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Proceedings of the IIBEC International Convention and Trade Show

September 15-20, 2021

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It's Not Raining—Where is the Water Coming From? Moisture Movement in Building Enclosures

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International Institute of
Building Enclosure Consultants



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ABSTRACT

Water damage is the most common reason for lawsuits against builders. In the springtime, the roof leaks, even though it has not rained for months. Where is the water coming from? I used high-permeable materials in the building construction, so why do I have moisture problems? I have been constructing buildings for decades, and I never had moisture problems in the past—why am I facing them now? This presentation explores the ways that moisture moves in buildings and why moisture problems are showing up in today's construction. The energy and moisture transport calculator is used to provide answers to these questions.

SPEAKER



Laverne Dagleish

Air Barrier Association of America | Walpole, MA

Laverne Dagleish has spent most of his life in the construction business. As the executive director of the Air Barrier Association of America (ABBA), he has been involved in all their research projects, starting with a major initiative to demonstrate the energy savings of airtight buildings. Dagleish is the coordinator for developing material specifications for air and water-resistive barriers as well as test methods to determine material properties. As the developer of ABAA's Site Quality Assurance Program, he saw the problems caused by water intrusion and poor workmanship.

It's Not Raining—Where is the Water Coming From? Moisture Movement in Building Enclosures

Ceilings can be a problem in cold climates, in both new and existing homes. One specific conundrum is water damage to raised cathedral and nonvaulted ceilings that is evident in the spring but not in the summer (**Fig. 1**). Roofing contractors who installed new roofs in the fall would be called back in the spring to fix roof leaks, even if the water leaks do not correlate to a rain event and the leaks no longer occur in the subsequent summer months. The contractor is always to blame, as “it didn’t leak before you installed the new roof.”

Sometimes it is the roofer’s fault because of installation deficiencies, but in many cases, water intrusion resulted even where proper installation in accordance with the design intent is confirmed (**Fig. 2**). And it is not just roofs that have issues: basements would have water “leaks” in the spring, which are speculated to be the result of a crack in the foundation until it is discovered that there are no cracks in the foundation, nor any rusting form ties that could leak.

In both cases, the moisture inside the building does not come from outside; it is caused by warm, moist air inside the building that leaks into unconditioned spaces and condenses, even turning to frost. In cold climates, the frost builds up over time and when the weather warms up and the sun shines brightly, the temperature in the unconditioned space would warm and the frost melts. The now-liquid water would show staining on the interior of the ceiling and water would show on the floor of the basement.

The moisture did not come from the outside, it is interior water vapor that condensed.

MOISTURE MOVEMENT IN BUILDINGS

Building physics tells us the answer. The nice thing about building physics is that it does

not change, no matter where the building is located or what materials are used.

Moisture always moves from wet to dry and high water vapor pressure to low water vapor pressure. Water is all around us in the form of a solid, liquid, or gas. Moisture moves by gravity, capillary action, diffusion, and air transport.

In many cases—but not all—water in the form of a solid or gas does not lead to problems in buildings that cause lawsuits and unhappy building owners and tenants. Instead, solid water melting to a liquid and water as a gas condensing to a liquid is where we get the problems in our buildings.

For example, a snowstorm in a northern climate can blow snow into the attic of a building with a peaked roof and gable-end vents. At that time, there is no problem; snow can be a good insulator. The problem with snow is that it does not stay snow, it melts (**Fig. 3**).

Water as a gas,

Figure 1. Water coming from roof.

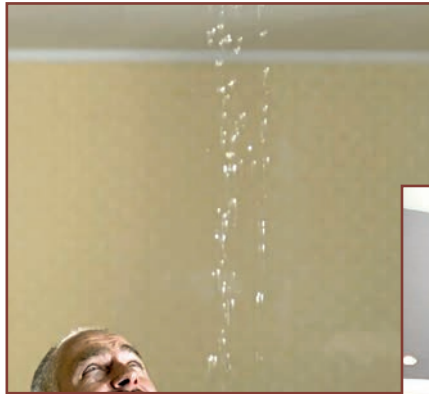


Figure 2. Water damage.



can lead to high humidity in a building. The humidity can be quite high and not cause a problem if the building enclosure has been properly designed and constructed. The problem is when warm, moist air touches a cold surface; this lowers the air temperature to the dew point where water vapor condenses to liquid water. The cold surface can be caused by cold temperatures outside or by an air-conditioning system inside.

Bulk (liquid) water is handled by roofing materials, shingles, water-resistive barriers, and flashing. The purpose of all these materials is to direct water down and

away from the building. Gravity then does its part, as long as the right materials have been installed in the right way. This is priority number one: if liquid water is not kept out of the building, nothing else matters.

In some parts of the country where there are high water tables, water can be wicked up the foundation by capillary action if the foundation is made of a porous material. The same occurs with many materials if part of the material is in liquid water: water will move up the material by capillary action.



Figure 3. Snow in attic.

Water vapor transmission or diffusion is when water vapor moves through a material. This is an important property to know, but this is where we get off track. Many designers feel that this is the most important property of a material. They design their building around permeable materials, so that the building “breathes.” Keep in mind these are molecules of water working their way through a material and for some materials, it can take months for enough water to work its way through to be able to measure the flow and assign a water vapor transmission rate. The permeability of a material is measured in perms. One perm is 57 ng per (m²·s·Pa) of water and a nanogram is one billionth of a gram. A drop of water is approximately 0.05 mL, so its mass would be 0.05 g. No matter how you look at this, it is not a lot of water; there are many nanograms of water in one drop.

Many design professionals focus on the water vapor transmission of a single material and they want a material that can

“breathe.” Materials that have a water vapor transmission rate of 10 perms (570 ng) or 30 perms (1710 ng) do not have a lot of drying potential. Characteristics of current materials allow water vapor transmission both ways: in and out. Water will always move from wet to dry, so whether moisture goes into or out of a building assembly depends on which side has a higher moisture content, not the material used.

Much of the water damage in buildings is not caused by a material having a water vapor transmission rate that is too high or too low. Moisture movement by air transport is often overlooked because the result is liquid water.

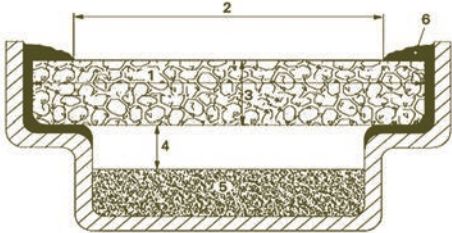


Figure 4. Specimen cup.

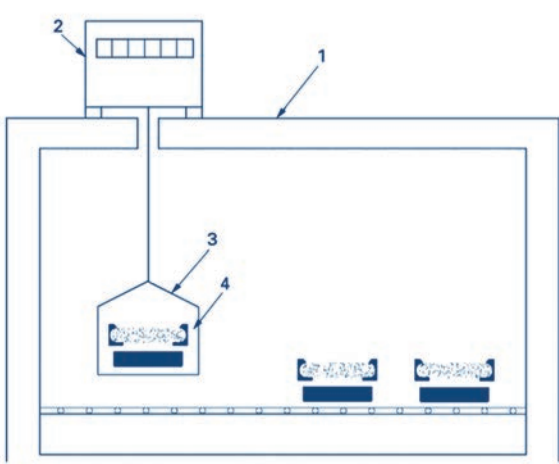


Figure 5. Oven.

When you see liquid water, you expect there is a leak, so you look for a breach or you may feel the material you used is not permeable enough to allow drying. It is important to understand the comparison of moisture movement by water vapor transmission rate through materials and moisture transported by air.

WATER VAPOR TRANSMISSION RATE OF MATERIALS

In simple terms, the water vapor transmission rate is how fast water can go through a material and exit on the other side. ASTM E96¹ defines the water vapor transmission rate as “the steady water vapor flow in unit time through [a] unit area of a body, normal to specific parallel surfaces, under specific conditions on temperature and humidity at each surface.” This definition is important because it means that a published water vapor transmission rate is only applicable to steady-state conditions at specific atmospheres. It also means that for thicker materials, it does not account for water that enters the material but does not go out the other side.

Understanding what this means requires understanding the test method. The basics are simple. There are two test methods: the desiccant (dry cup) method and the water (wet cup) method (Fig. 4). In the desiccant test method, a specimen is prepared with anhydrous calcium chloride in the bottom of a glass dish. The material being tested is then placed over the dish and sealed so that the only way for water vapor to get into the dish is through the material.

The water test method is almost the same preparation for the specimen, except that water is in the bottom of the dish instead of anhydrous calcium chloride. The water molecules then have to work their way through the material to exit the dish.

Self-Adhered	Desiccant method, ng	Water method, ng	Difference
Minimum water vapor transmission rate	0.572	0.572	0%
Maximum water vapor transmission rate	1763	2830	61%
Mean water vapor transmission rate	1.01	2697	5789%
Minimum percent difference	0	0	4%
Maximum percent difference	1.15	1.26	10%
Mean percent difference	1763	2380	65%

Source: Air Barrier Association of America website.

Table 1. Sampling of water vapor transmission rates for self-adhered sheet membranes; n = 59

Fluid-applied membranes	Desiccant method, ng	Water method, ng	Difference
Minimum water vapor transmission rate	0.572	0.572	0%
Maximum water vapor transmission rate	1763	2830	61%
Mean water vapor transmission rate	0.89	1.8	102%
Minimum percent difference	4.96	5.15	4%
Maximum percent difference	4.3	2034	47202%
Mean percent difference	418	870	108%

Source: Air Barrier Association of America website.

Table 2. Sampling of water vapor transmission rates for fluid-applied membranes; n = 11

This creates the driest and the wettest conditions possible inside the glass dish: for practical purposes, 100% relative humidity (RH) and 0% RH. For both the desiccant and water test methods, the specimens are then placed in an oven that is held at 23°C and 50% RH (Fig. 5).

For the desiccant method, the conditions are essentially 25% RH as there is 0% RH on one surface and 50% RH on the other surface. For the water method, the conditions are 75% RH as there is 100% RH on one surface and 50% RH on the other surface.

If the atmosphere changes on either side of the material, the water vapor transmission rate changes. The *International Building Code*² and the *International Residential Code*³ require that you meet a water vapor transmission rate using the desiccant method and the code and then identify three classes of vapor retarders.

Here is where the problem comes in. If the vapor retarder is installed in a wall assembly, how often during the year will the material be subjected to an atmosphere of 23°C and 25% RH? If it is installed on the interior, there may be times when the material is subjected to that atmosphere, but if it is installed on the exterior of the sheathing and under the cladding, the amount of time the material will be subjected to this environment will be minimal.

The water test method essentially involves an atmosphere of 23°C and 75% RH. These values are high for an interior application but probably better aligned with the atmosphere when installed on the exterior of a building under the cladding.

However, the point of a standardized test method is not to estimate the performance of a material in situ. It is to determine “the steady water vapor flow in unit time through unit area of a body, normal to specific parallel surfaces, under specific conditions on temperature and humidity at each surface.” A standard test method is simply a means of comparing materials under a specific set of conditions. An architect asked which test method should be used when designing a building: desiccant or water? It does not matter, as the test method is simply a way of comparing material and has nothing to do with installed performance of the material itself, nor the performance of the building assembly.

It is not possible to determine the difference between the desiccant and water test methods and apply that percentage to materials that only have desiccant method results to determine the water method results. Every material will have different percentages

Sprayed polyurethane foam (medium-density closed cell)	Desiccant method	Water method	Difference
Minimum water vapor transmission rate	1.13	56	4856%
Maximum water vapor transmission rate	68.9	241	250%
Mean water vapor transmission rate	49	90	84%
Minimum percent difference	68.9	74	7%
Maximum percent difference	24.87	217.36	774%
Mean percent difference	56	1021.13	1723%

Source: Air Barrier Association of America website.

Table 3. Sampling of water vapor transmission rates for sprayed polyurethane foam (medium-density closed cell); n = 16

Factory-bonded membrane	Desiccant method	Water method	Difference
Minimum water vapor transmission rate	1.22	1.1	10%
Maximum water vapor transmission rate	1459	1850	27%
Mean water vapor transmission rate	105.24	279.7	166%
Minimum percent difference	105.24	279.7	166%
Maximum percent difference	1.22	1.1	10%
Mean percent difference	1459	1850	27%

Source: Air Barrier Association of America website.

Table 4. Sampling of water vapor transmission rates for factory-bonded membranes to sheathing; n = 3

Adhesive-backed commercial building wrap	Desiccant method	Water method	Difference
Minimum water vapor transmission rate	6.68	8	20%
Maximum water vapor transmission rate	1763	2030	15%
Mean water vapor transmission rate	614	978	59%
Minimum percent difference	1600	3630	127%
Maximum percent difference	6.86	8	17%
Mean percent difference	614	978	59%

Source: Air Barrier Association of America website.

Table 5. Sampling of water vapor transmission rates for adhesive-backed commercial building wrap; n = 6

according to the two methods.

The Air Barrier Association of America (ABAA)⁴ website provides accredited laboratory results for materials tested according to ASTM E96 using both the desiccant and water methods (Tables 1 to 5). The results are surprising.

The website lists the following materials under the heading of assemblies as both

the material to be tested and as the material installed in a wall assembly and tested.

- self-adhered sheet membranes
- fluid-applied membranes
- sprayed polyurethane foam (medium-density closed cell)
- mechanically fastened commercial building wrap

The performance of the building assembly needs to be determined based on the total assembly and under the conditions the building assembly will be subjected to.

- boardstock (rigid cellular thermal insulation board)
- factory-bonded membranes to sheathing
- adhesive-backed commercial building wrap

Each of these materials has different water transmission rates when tested according to the desiccant and water method. The minimum, maximum, and mean water vapor transmission rates are listed for all materials. The percent differences listed are the results for the same material.

The data shown in Tables 1 to 5 help to understand two things. First, the results of the ASTM E96 desiccant test method used to determine the water vapor transmission rates of a material cannot be used to indicate the performance of a building assembly. Second, the amount of water that comes through a material or a building assembly is minimal in the big picture and in many cases can be ignored. In cold climates, when the outside air is heated, the RH drops and the air is very dry. In humid climates, if the outside air goes through the heating, ventilation, and air-conditioning (HVAC) system, the amount of water vapor in the air is normally reduced by the equipment.

The performance of the building assembly needs to be determined based on the total assembly and under the conditions the building assembly will be subjected to. If the building assembly will be subjected to high humidity most or all of the time (for example, an indoor swimming pool), or if the building assembly will always have a moisture drive in one direction (for example, a freezer), a vapor barrier can be critical.

Water vapor transmission needs to be determined for the whole building assembly and not just a single material. Each material layer has a different water vapor transmission

rate, so the placement of each material is important and will affect the overall building assembly performance. For example, in cold climates, a polyethylene sheet installed on the inside of a building over a fibrous insulation will have a very small amount of water vapor transmission through the material, while the fibrous insulation and

all the other materials outboard of the polyethylene material will be kept dry. But if the same polyethylene film is placed on the cold side of the insulation, there can be condensation on the polyethylene sheet if the temperature is at or below the dew point.

The water vapor transmission rate of a whole building assembly can be tested for water vapor transmission in a climate chamber, where a different atmosphere is placed on each side of the assembly. However, changing the construction of the assembly or changing the atmosphere on either side of the specimen will change the results. Testing a whole building assembly gives the overall performance of an assembly, but only at the atmospheres tested.

THE BIG MOISTURE PROBLEMS

Liquid Water

The measures to prevent big water problems in a building should be obvious. First, keep liquid water out. That applies both during and after construction. Correctly install the

shingles, avoid holes in a roofing membrane, cover the complete exterior with a water-resistive barrier (do not use an 8 ft sheet on a 10 ft wall), water drainage does not work that way. If the water-resistive barrier comes in rolls, overlap the top sheet over the bottom sheet. Flash every opening properly and have the flashing material direct the water to the outside of the exterior cladding, not just onto the water-resistive barrier. Avoid gaps between pieces of flashing; flashing should be continuous. Direct all water to the outside of the exterior cladding.

These measures are very basic, but many buildings have required hundreds of thousands of dollars' worth of repairs because the basics were not done.

Water Vapor Transmission

When it is determined that the water in the building is not the result of a leak, many people believe that the building assembly has not been allowed to dry out because the water vapor transmission rates of the material were too low. The tendency is therefore to use materials with increasingly higher water vapor transmission rates to solve the problem. Water damage may be blamed on a material with a low water vapor transmission rate and the solution is to use a material with a high water vapor transmission rate.

Materials available in the construction market allow moisture to move in both directions. A material with a high water vapor transmission rate allows water vapor to escape and also allows it to enter the building assembly. A good example is reservoir cladding, such as brick or stucco, where moisture can stay in the material for some time after a rainstorm. The cladding becomes saturated during a rain

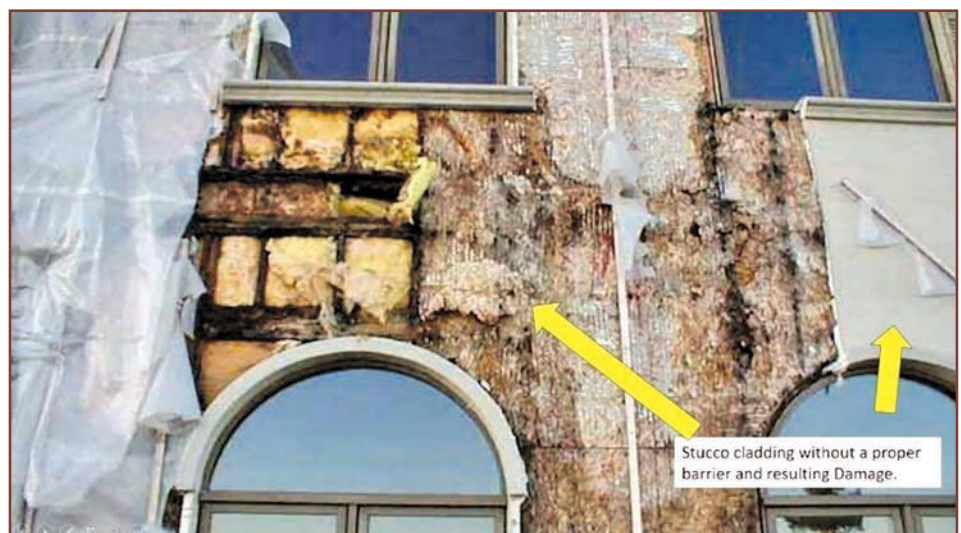


Figure 6. Wall damage.

event and then the sun comes out. The solar energy hitting the wall moves the moisture from wet to dry and from high to low humidity (Fig. 6). Moisture moves into the building assembly more rapidly than the drying rate. This will result in an increase in the moisture content of the building assembly. This can lead to mold, mildew, rot, or corrosion. The two-way movement of water vapor through the material needs to be considered when choosing materials for construction.



Figure 7. Frost in attic.

Water Vapor by Air Transport

Many people do not equate liquid water or frost can be caused by water vapor. When liquid water is evident in a building or in a building assembly, people look for a water leaks in the assembly or feel that the materials used should have a high water vapor transmission rate to allow the moisture to escape. The amount of water transported by air through the holes and cracks in the building assemblies is not considered (Fig. 7).

The ABAA website⁵ has an air and water transport calculator that provides this information. Many presentations have included a comparison of the amount of water vapor that goes through 1 m² of drywall in a heating season and the amount that goes through a 2 cm² hole. The National Research Council calculated this over a full heating season for a home in Ottawa, Ontario, Canada. These results are applicable to a single type of building in a single location.

The calculator allows the determination of moisture movement by air leakage for 52 cities the United States and five cities in Canada. The amount of water vapor going through a 1 in.² hole by air movement is compared

with a material subjected to conditions in the ASTM E96 desiccant test method. The test is conducted under steady-state conditions and the building is subjected to dynamic, continually changing conditions. The material

performs differently in a building than it does in a laboratory. The water vapor transmission amounts in Table 6 do not indicate field performance. Programs such as WUFI that calculate heat and moisture transport in multilayer building components provide

realistic numbers of water vapor transmission of a building assembly.

Table 6 compares the amount of water that moves through a 1 in.² hole in four cities representing different regions and atmospheres in the United States, based on water vapor pressure differences created for each city. The water vapor transmission through a material was calculated using ASTM E96 desiccant test method. This is not an apples-to-apples comparison, but it provides an approximation of the amount of water that moves by air transport compared with the amount of water that works its way through a material over a period of one year. Neither method indicates which way the moisture moves nor how much of the moisture remains in the building assembly.

The difference in air leakage from a mid-rise to a high-rise building is due to stack effect (and reverse stack effect) caused by the height of the building and the temperature difference between inside and outside the building.

When water is observed in a building assembly, there could be more than a single cause of water damage. Each potential

cause should be evaluated and its significance determined.

When basic building physics is used when water or water damage is observed, a workable solution can be found. Every building is different, but if it is not raining outside and there are no water leaks from a pipe, it's probably caused by water vapor movement (Fig. 8).

When the ceiling of a building leaks in the spring with no rain, it is caused by warm, moist air leaking into the ceiling or attic and condensing on the underside of the sheathing or on framing members in the attic in cold climates or ducts and pipes in the ceiling in warm and humid climates.

In cold climates, the solution normally used is to add attic ventilation. There are requirements in the code for ventilation and if problems occur, the solution is thought to be to add more ventilation. In many cases, that can aggravate the problem. The problem in most buildings is warm, moist air from inside the building leaking into the attic and condensing. There is an air-pressure difference between inside the building and the unconditioned attic caused by wind, stack, and mechanical effects. There can also be a pressure difference between the attic and outside. When we add more holes between the outside and the attic, we reduce the pressure different between the two spaces, but it could increase the air-



Figure 8. Mold on sheathing.

Location	Water vapor by air transport through a 1 in.-square hole, oz/gal.		Water vapor transmission through 39 × 39 in. of material,* oz/gal.		
	Mid-rise	High-rise	5.7 ng (0.1 perm)	57 ng (1.0 perm)	570 ng (10 perm)
Seattle, WA	5,543/34.64	18,120/113.25	0.166	1.66	16.6
San Francisco, CA	6,812/42.57	20,738/129.61	0.166	1.66	16.6
Chicago, IL	5,612/35.07	16,285/1010.78	0.166	1.66	16.6
Miami, FL	7941/49.63	17,577/109.86	0.166	1.66	16.6

* According to ASTM E96 desiccant test method

Table 6. Moisture movement: water vapor transmission through a material compared with air transport



Figure 9. Rotten, five-year-old walls.

pressure difference between the interior of the building and the attic space, which is now close to the outside pressure. This increase in pressure difference results in more moisture being drawn into the attic space.

When the problem is air leakage from the interior into the attic, rather than adding more ventilation, it makes more sense to fix the leaks. Fixing a boat with leaks by adding increasingly bigger pumps is not logical. The leaks should simply be sealed. The same applies to our attic: adding more ventilation does not seal the holes that are the root cause of the problem. The floor of every attic should be air sealed before any insulation is added to the attic.

THE PROBLEM WILL GROW

These problems have been around for decades. They became more pronounced in the 1960s and 1970s, when we started to add more insulation to our buildings. Up to that point, most buildings had little insulation and leaked like a sieve. That meant that the

moisture created inside our buildings had an easy way to escape to the exterior. The moisture was not around long enough to cause damage. As we add insulation, the insulation performs as intended: it slows down heat flow. That means there is not the same amount of energy to move the moisture from the building assembly to the exterior. The warm, moist air stays in the building assembly longer, where it is more likely to condense.

When some of the holes in the building are sealed, the warm, moist air travels to the next hole where the path through the building assembly may be longer (**Fig. 9**).

Low-energy homes are being constructed and this means more insulation is being added (as high as R -40 to R -50), making the building assemblies thicker. Any warm, moist air, either outside the building or inside the building, depending on the climate, will have a longer time to work its way through the building assembly and may reach the dew point temperature before it exits the building assembly.

Air barriers are required by many local codes, but they may not be installed continuously. This results in a smaller number of holes, which will result in a greater airflow through them. These concentrated leaks will introduce more water vapor to a small area, which may condense before it exits the building assembly.

Building as a system means nothing is simple: any change can affect other functions,

either for the good or to the detriment of a building. Both residential and commercial buildings need to have balanced supply and exhaust air to function properly. Unbalanced systems can increase pressure differences in parts of the building, resulting in greater air leakage in that part of the building. A properly sized air conditioner can remove a lot of moisture from the air, but an oversized air conditioner will not run long enough to dry the air out, which will affect the amount of moisture in the air.

Building performance is affected by the building enclosure, the HVAC system, the occupants, and the exterior environment. Getting them all to work together is not easy, but it is building science. 

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Moisture and Durability in Green Standards

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International Institute of
Building Enclosure Consultants



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ABSTRACT

Recent changes in building model energy codes include envelope criteria that minimize building enclosure thermal loads and, in turn, reduce a building's energy consumption. These changes require modifications in traditional building enclosure designs to meet evolving energy code requirements. Unfortunately, some code-compliant energy-efficient designs may adversely impact a building's durability. This paper compares how four green standards—the U.S. Green Building Council's LEED v4.1; the Green Building Initiative's Green Globes, version 2019; the International Living Future Institute's Living Building Challenge, version 4.0; and the International Code Council's *2018 International Green Construction Code* (IgCC)—address moisture durability of building enclosures across the project phases of material selection; design and procurement; construction activities; performance testing; operation and maintenance; and enclosure commissioning. Gaps and similarities in the rating systems are discussed, and strategies to use the best parts of each rating system to improve project performance related to moisture durability are recommended.

SPEAKERS



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Benjamin Meyer, AIA, NCARB, LEED AP, is a building and roofing science architect with GAF in Richmond, Va. His previous experience includes serving as an enclosure consultant principal, technical management for enclosure products, commercial design, real estate development, and construction management on a range of residential, educational, office, and DuPont industrial projects. He is a voting member of the ASHRAE 90.1 Envelope and Project Committees, LEED Technical Committee member, past technical advisor of the LEED Materials (MR) TAG, and director of the Air Barrier Association of America.



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GAF | Parsippany, NJ

Jennifer Keegan, AIAA, is the director of building and roofing science for GAF in Richmond, Va., focusing on overall roof system design and performance. She has over 20 years of experience as a building enclosure consultant specializing in assessment, design, and remediation of building enclosure systems. She is the chair of the ASTM D08.22 Roofing and Waterproofing Subcommittee, education chair for IIBEC, an executive board member of National Women in Roofing, and a board member of Women in Construction.

Moisture and Durability in Green Standards

There can be a perception in the market that a “green” building is a better building, and that the risks associated with “building differently” are inherently covered by the green certifications driving the industry forward from a sustainability standpoint. Both better buildings and risk mitigation can be accomplished through building green, and this paper will discuss some of the key principles to accomplish these objectives for building enclosures and roof assemblies.

Moisture durability of enclosure systems focuses on the interaction of the materials, assemblies, and their design configurations in the building. The goals of managing moisture durability are to establish performance expectations, and to allow enclosures to perform as intended, continue to perform through the project life cycle, and be serviced or maintained in a way that minimizes risk of damage to the enclosure and performance of other critical building systems. This discussion focuses on the moisture durability aspects of buildings and how those aspects relate to energy performance and life-cycle expectations. Although other aspects of resilience are also important, moisture durability targets risks that are not necessarily related to climate change but are related to the design of enclosure and roof assemblies directly.

MOISTURE DURABILITY IN CONTEXT

The American Institute of Architects (AIA)¹ defines resilience as “mitigating risk for hazards, shocks, and stresses and adapting to changing conditions.” Resilience goes beyond the minimum code requirements to address issues that influence long-term performance. The “hazards, shocks, and stressors” can come from external sources as well as from the design decisions of the built environment. Some external sources can be extreme events such as tornadoes and wildfires, and some are common and per-

sistent adverse events from design decisions, resulting in moisture risks in the building enclosure. This perspective of moisture durability as a risk fits within many existing terms and goals that stem from sustainability, resilience, adaptability, and mitigation initiatives; moisture durability fits within these goals and is not separate from them, as demonstrated in **Fig. 1**.

ENERGY EFFICIENCY AS A MOVING TARGET

The minimum or baseline energy efficiency in the code requirements and owner’s performance expectations has been a moving target over time. The American National Standards Institute (ANSI), American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), and Illuminating Engineering Society (IES) update ANSI/ASHRAE/IES Standard 90.1² (one of the primary national energy standards) every three years, and each new edition has increased the cost-effective and validated ener-

gy savings. The Pacific Northwest National Laboratory³ validated that ANSI/ASHRAE/IES 90.1-2019² provides an additional 5% of energy savings over the previous 2016 version.

Compounding the energy savings, Green building rating systems generally require additional energy savings beyond the baseline and provide points for exceeding the baseline. In addition, the energy performance requirements within green certification systems are also improving. As highlighted in **Fig. 2**,^{2,4-6} the same energy savings that would have contributed 10 points to the Leadership in Energy and Environmental Design (LEED) v3 rating system is roughly equivalent to the starting energy savings required in LEED v4.1,⁶ which was in the pilot phase at the time this paper was published.

Not every local jurisdiction adopts the same base model codes and standards at the same time and rate, which leads to additional confusion in the design and construction industry.

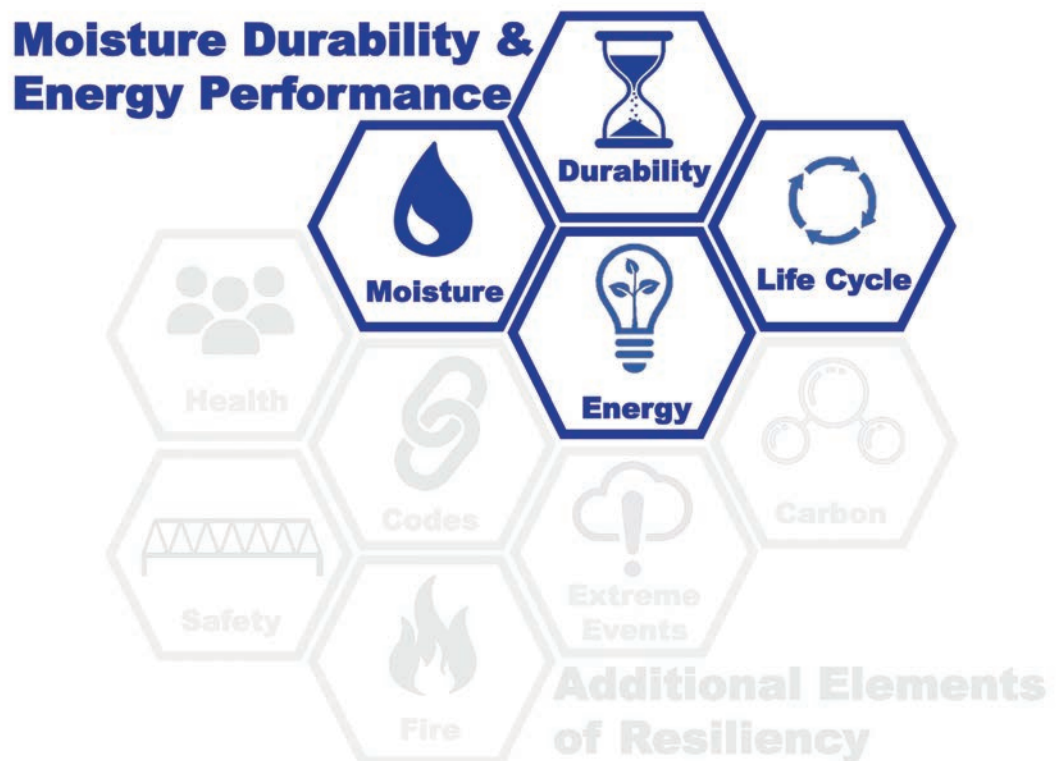


Figure 1. Moisture, durability, and energy efficiency are part of resilient design.

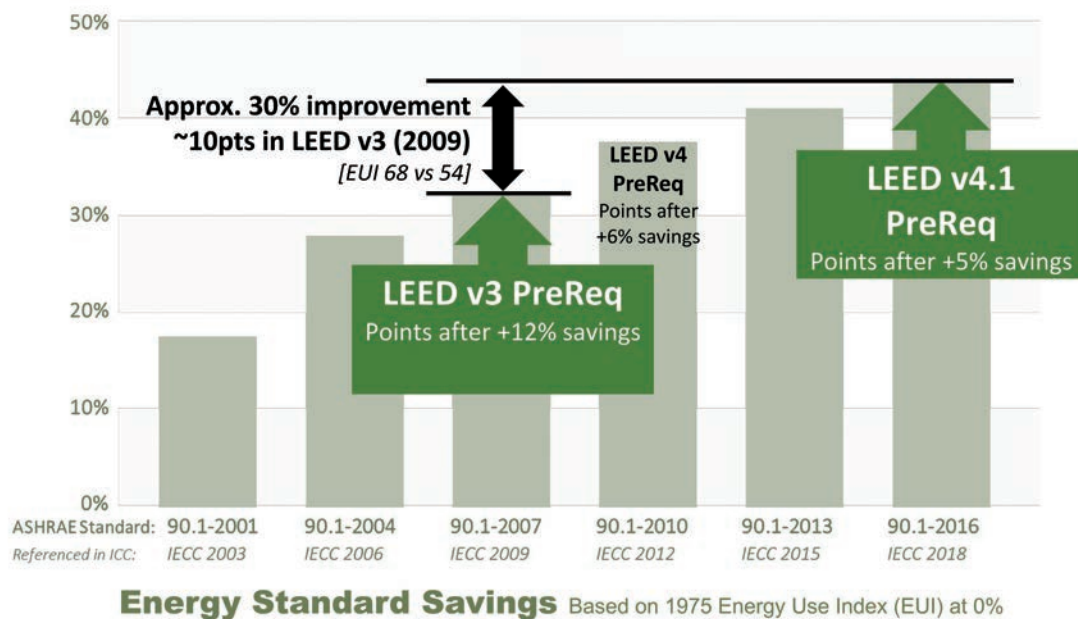


Figure 2. Increasing efficiency requirements are compounded by green rating systems.^{2,4-6}

INTERACTIVE COMPLEXITY AND TIGHT COUPLING

In *Normal Accidents: Living with High-Risk Technologies*, Charles Perrow explains how significant technological advancement can lead to failures.⁷ He describes two main components of “normal accidents.” The first component, “interactive complexity,” is a function of the number and degree of system interrelationships; when this factor is high, surprises are to be expected. The second component is “tight coupling,” the degree at which initial failures can concatenate rapidly to bring down other parts of the system; when failures are highly linked, surprises are not easily isolated and resolved. Perrow explains that if a system has only one of these two components, the risk of accidents is more easily managed. However, when “interactive complexity” and “tight coupling” are combined, accidents could be considered “normal” or expected.

As more materials and additional requirements are added to enclosures, it is important to recognize when materials and assemblies must be changed to achieve higher energy performance. In a broad sense, as energy efficiency is improved in building enclosures, moisture risks can increase from decreased heat flow across the assemblies, as shown in Fig. 3. The changes in enclosures can manifest as

generally lower exterior surface temperatures (during heating months) as the exterior is less dependent on the interior space conditioning. As we improve energy efficiency, we may also be increasing moisture risks in building enclosures. And the risk of “normal accidents” may increase as the result of more complex designs that are *more tightly coupled* to the building’s HVAC operations, structural elements, and occupant-use conditions.

Consider the following real-world example of the “normal accidents” concept in practice and how it relates to a client’s awareness of or willingness to accept this risk for an innovative building. This relevant example comes from the first-ever LEED platinum building and a recently closed legal case.⁸ The example demonstrates the building enclosure’s technical complexity and tight coupling across various

processes to manage the unanticipated moisture risks as early as possible. It is important through this green rating system assessment to recognize the options and limitations that exist with the rating systems and their actual coverage to mitigate moisture risks in the face of complexity and system coupling.

MOISTURE MANAGEMENT ACROSS THE PROJECT PHASES

Although it is tempting to assume that the building enclosure will work perfectly and water will not go where it does not belong, such a belief can lead to a lack of risk mitigation for a very likely hazard (water) throughout the useful life of the building. A more realistic assumption is moisture intrusion cannot be completely avoided, so it must be managed. Enclosures should be designed and installed

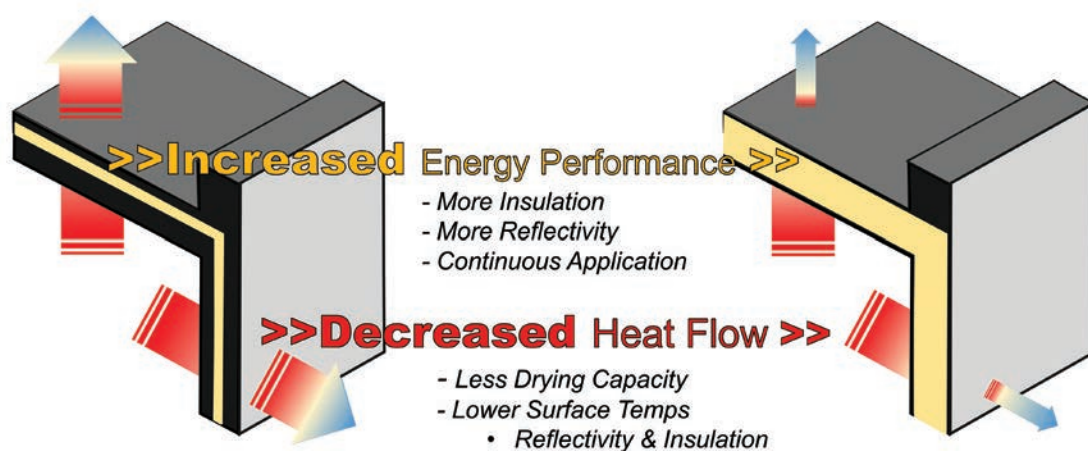


Figure 3. Energy efficiency improvements can lead to increased moisture risks in a building enclosure.

not only to keep out bulk water and drain it away but also to manage incidental water with minimal long-term impact. The key is for the enclosure design to have a greater capacity for drying than its risk of wetting.⁹

Figure 4 illustrates six primary categories for moisture durability assessment of an enclosure. Roughly working across the project life-cycle, such an assessment can identify aspects moisture risk management that green building rating systems can address in specific phases. The following is a brief summary of the elements highlighted in this assessment.

Material Selection

The material selection phase can start early in the project process. It can often carry over into a firm master specification, or even be dictated as a line-item budget before the schematic concept is complete. Material selection improvements can include above-code specification requirements, such as exceeding minimums for attachments and roof edges, dedicated air barriers, and material properties like solar reflectivity. Single-source manufacturer systems for building enclosures does not mean only one manufacturer must be specified per product; rather, it involves considering together the bids for all components within an enclosure system, like a roof, and their ability to properly integrate with adjoining systems. In a roof system, all of the components, such as the membrane, cover board, insulation, air/vapor retarder, and structural deck, are tested by third parties as a system, and they should really be specified as a system, not separately. Coordinated manufacturer systems can be key to installed performance, such as prior system testing and single-source responsibility for future service and repair. Third-party product certifications, such as health product declarations and environmental product declarations, can be useful in the product selection process for green building ratings, but unless the product certification addresses performance in specific applications, it may not address moisture durability.

Design and Procurement

In the design and procurement phase, project teams solidify design decisions and look for unexpected building-system interactions. When designing an enclosure, it becomes very important to understand the

Moisture Management Elements

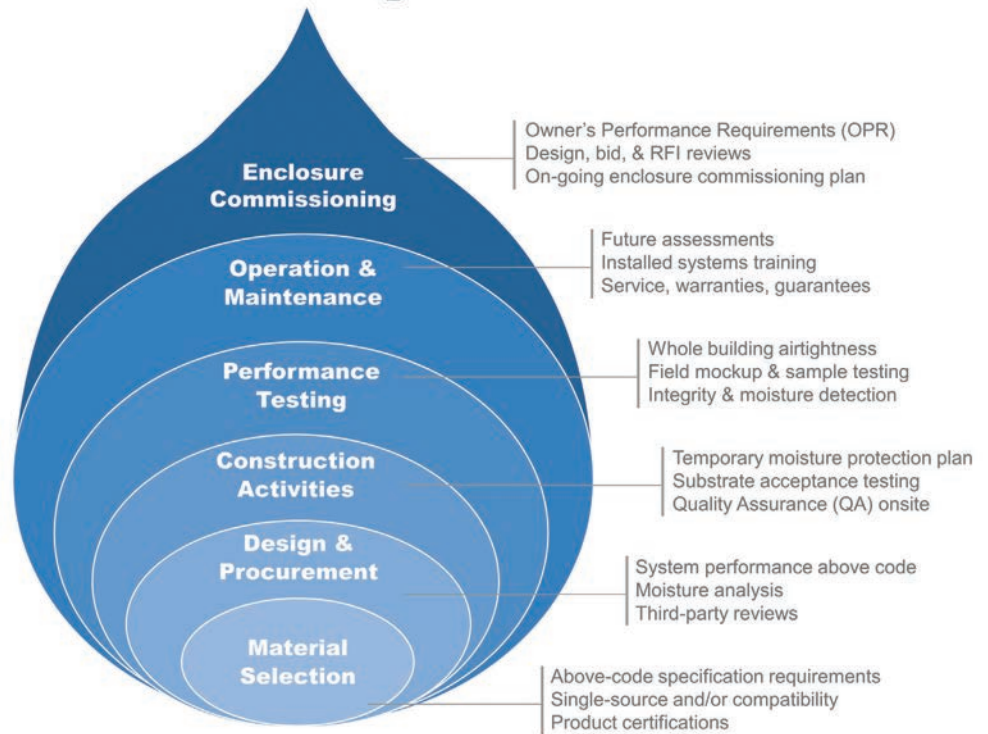


Figure 4. Moisture durability elements and assessment project life-cycle details.

overall system performance, such as expected resistance to anticipated extreme weather events, and clarifying the expected enclosure system service life. Rather than relying on heuristics and rules of thumb for long-term moisture performance of the building enclosure, it is preferable to perform a moisture analysis to identify areas where “tight coupling” of moisture mechanisms may be occurring in the building. Specifically, performing ASHRAE 160¹⁰ hygrothermal analysis early in the design process allows data and the outcomes to inform the project team.¹¹ Also, it is important to engage professionals with specific expertise in moisture risk mitigation for third-party reviews such as consultant constructability reviews, manufacturer reviews for conformance with published requirement, and contractor shop drawing reviews across the enclosure systems.

The inclusion of performance testing can lower the risks related to moisture durability. When these tests are specified with defined pass/fail criteria, the project team can vet performance at the intersection of design and construction. Potential risks, including air and water leaks, are identified early and can be addressed before the building is occupied.

Construction Activities

In the construction phase, project teams bring designs to reality. During the lengthy construction process, moisture can find its way into areas where it was never intended. To protect the building and the integrity of the enclosure, a temporary moisture protection plan is important. The plan should include measures for material storage and specifications for in-process protection during the many weeks or months when the enclosure systems, like roofs, are being applied. When installing materials on site, rather than in a controlled environment, it is important to identify that conditions are appropriate to proceed. Site conditions can be qualified by substrate acceptance testing such as adhesion tests, compatibility qualification, and fastener withdrawal resistance methods. In addition to the general contractor's quality control efforts, using a third-party quality assurance program—whether it is a system-based verification or involves specific third-party auditors, like the Air Barrier Association of America's ABAA Quality Assurance Program¹² or the IIBEC Registered Roof Observer (RRO) programs¹³—can also contribute to managing moisture risks.

Across the project phases, the project team can coordinate BECx efforts with the owner's performance requirements through documentation reviews, installation observations, guiding performance testing, and establishing the ongoing commissioning plan for the enclosure.

Performance Testing

When performance testing is required, it is important that the owner's expectations are taken into account early in the design and carried through to the trades in the field. The point of performance testing is not to make buildings "fail" after they're built, but to ensure the constructed building meets the initial minimum performance targets set by the owner and design team when they started the project. A whole building airtightness test is a good example of this point. The test does not attempt to "overpressurize" the building; the objective is to uniformly pressurize the enclosure to identify inconsistencies in the overall construction. Stopping these air leaks can enable the mechanical systems to perform as designed during the use phase of the building, limiting leakage and potential occupant discomfort. Testing can also be performed on a smaller scale with field mock-up and sample tests. These can be useful to establish acceptable installation and sequencing methods on site and provide representative results, while avoiding the expense of comprehensive testing. Another set of moisture durability tests are integrity and moisture detection testing, such as infrared scans, electronic leak detection, or nuclear moisture surveys. These can be useful to demonstrate a moisture protection plan was

successfully implemented—that there is no concealed moisture, and that systems are continuous where they are intended to manage rain, like in a roof or waterproofing system and at interfaces.

Operation and Maintenance

It is important to begin recognizing the operational challenges early in the design phase. For example, the project team might wish to consider climate projections, such as the likelihood that the intensity of rainstorms will increase in the future, or explore how the project can adapt for changed uses at the end of the building's expected life, such as capturing rainwater for irrigation.

After the building is completed and the use phase has begun, installed systems training is important for occupants and facility managers; they will

need to understand how enclosure systems are expected to operate and the associated maintenance requirements, such as the clearing of roof drains and care for rooftop solar installations. Use-phase training can also include the handoff of warranties and guarantees from the construction process to the building operators. This is important because it can help inform facility management of ongoing inspection schedules and long-term maintenance contracts necessary to meet the initial design expectations. Like most things, roofs and enclosure systems need to be maintained, and service contracts can be a critical part of scheduling and performing inspections to ensure that long-term guarantees are not voided.

Building Enclosure Commissioning

Unlike the previously described elements, building enclosure commissioning (BECx) is not a separate project phase. Rather, BECx is a holistic process that starts in predesign and continues through to the use phase of the completed building.¹⁴ Along the way, the commissioning process can manage moisture risks by identifying system complexities and helping the project team take steps to manage the tight coupling of the enclosure and related systems. Across the project phases, the project team

can coordinate BECx efforts with the owner's performance requirements through documentation reviews, installation observations, guiding performance testing, and establishing the ongoing commissioning plan for the enclosure. When incorporated into the project, BECx can be a great tool to manage moisture durability and the associated risks.

MOISTURE MANAGEMENT IN GREEN BUILDING RATING SYSTEMS

For the moisture durability assessment, we have compared the four most common green building rating systems available for new construction projects against the six construction phase categories, as shown in **Fig. 5**. The green building rating systems reviewed are:

- The U.S. Green Building Council's LEED v4.1⁶
- The Green Building Initiative's Green Globes, version 2019¹⁵
- The International Living Future Institute's Living Building Challenge (LBC), version 4.0¹⁶
- The International Code Council's 2018 *International Green Construction Code* (IgCC)¹⁷

SUMMARY OF GREEN RATING SYSTEM ASSESSMENT

Compiled across the typical project life-cycle phases, the following is a summary of the notable factors that apply to moisture assessments across the highlighted green building rating systems.

Material Selection

In terms of material selection, there is some consistency across all four rating systems. Starting with above-code specifications in the top row of Fig. 5, all four are shown in yellow (partially or indirectly addressed). This is because all four have requirements for improved energy efficiency over the code minimum, including light-colored or reflective roofing. The enclosure is generally above the code minimum, but the rating systems do not consider direct above-code measures related to moisture durability mitigation. None of the four rating systems have measures that encourage comprehensively sourced products to mitigate future risks within and across enclosure systems. Though none of the ratings systems refer specifically to material moisture certifications, all four systems provide a mechanism to reward products for third-party certifications; in the last row of the material selection part of

Fig. 5, this is shown in blue, indicating this element is clearly addressed in the green standards.

Design and Procurement

The design phase is where project specifications can enable success mitigating moisture throughout the later project phases and help align the design with the owner's performance requirements. A number of items in this phase including moisture analysis and third-party reviews, are "partially or indirectly addressed" by LEED v4.1 and Green Globes through enclosure commissioning credits (see additional discussion in the "Building Enclosure Commissioning" section later in this paper).

The Green Globes rating system addresses system performance by providing credit for performing a building risk assessment of the design to resist extreme events. Green Globes also touches on moisture control design analysis; the credit is focused on managing interior-generated moisture, but it indirectly includes building enclosure components as part of an ASHRAE Standard 160 moisture analysis when interior moisture is expected.

The 2018 IgCC addresses moisture control design analysis directly by requiring all designs to perform dynamic heat and moisture analysis, including ASHRAE 160, of the enclosure and across interior space conditions. The LBC rating system does not provide specific or prescriptive moisture mitigation requirements for many aspects of the design and procurement process.

Construction Activities

The construction phase is a period of the building's life that is often not designed to manage moisture, although it can lead to a reduced life cycle if it is not performed well. All green rating programs except for LBC include measures to address temporary moisture protection during construction. None of the rating systems have minimum substrate acceptance to provide "stoplight conditions" for enclosure installations, such as moisture on the roof deck. The project specifications and the various construction trades are left to manage these acceptance handoffs.

Notably, Green Globes provides direct measures for onsite quality assurance and verification, whereas LEED v4.1 indirectly captures this scope in its enhanced enclosure commissioning credit. The previous version of Green Globes also included the RRO program by reference but its measures are now described generally as elements of a third-party observations verification program.

Performance Testing

The IgCC is the only one of the four green rating systems to directly address field performance testing by providing enhanced guidance on whole building airtightness testing. The comprehensive testing of the built enclosure can have broad performance impacts on achieving the intended energy efficiency from the design to the field, mitigating ongoing moisture accumulation caused by air leakage condensation, and enabling the HVAC design to deliver a comfortable space to the occupants.

	 LEED v4.1	 Green Globes v2019	 LBC v4.0	 IgCC 2018
Material Selection				
Above-code specifications				
Single-source / compatibility				
Product Certification				
Design & Procurement				
System Performance				
Moisture Analysis				
Third-Party Reviews				
Construction				
Temporary Protection				
Substrate Acceptance				
Quality Assurance				
Performance Testing				
Whole Building Airtightness				
Field Mockup & Sample Testing				
Integrity Detection				
Operations & Maintenance				
Future Assessments				
Systems Training				
Service, Warranties, Guarantees				
Enclosure Commissioning				
BECx				

Assessment Color Key	
	Not Addressed
	Partially / Indirectly Addressed
	Addressed

Figure 5. Project life-cycle phases of moisture durability assessment in green building rating systems.

Green Rating Systems & Moisture Management

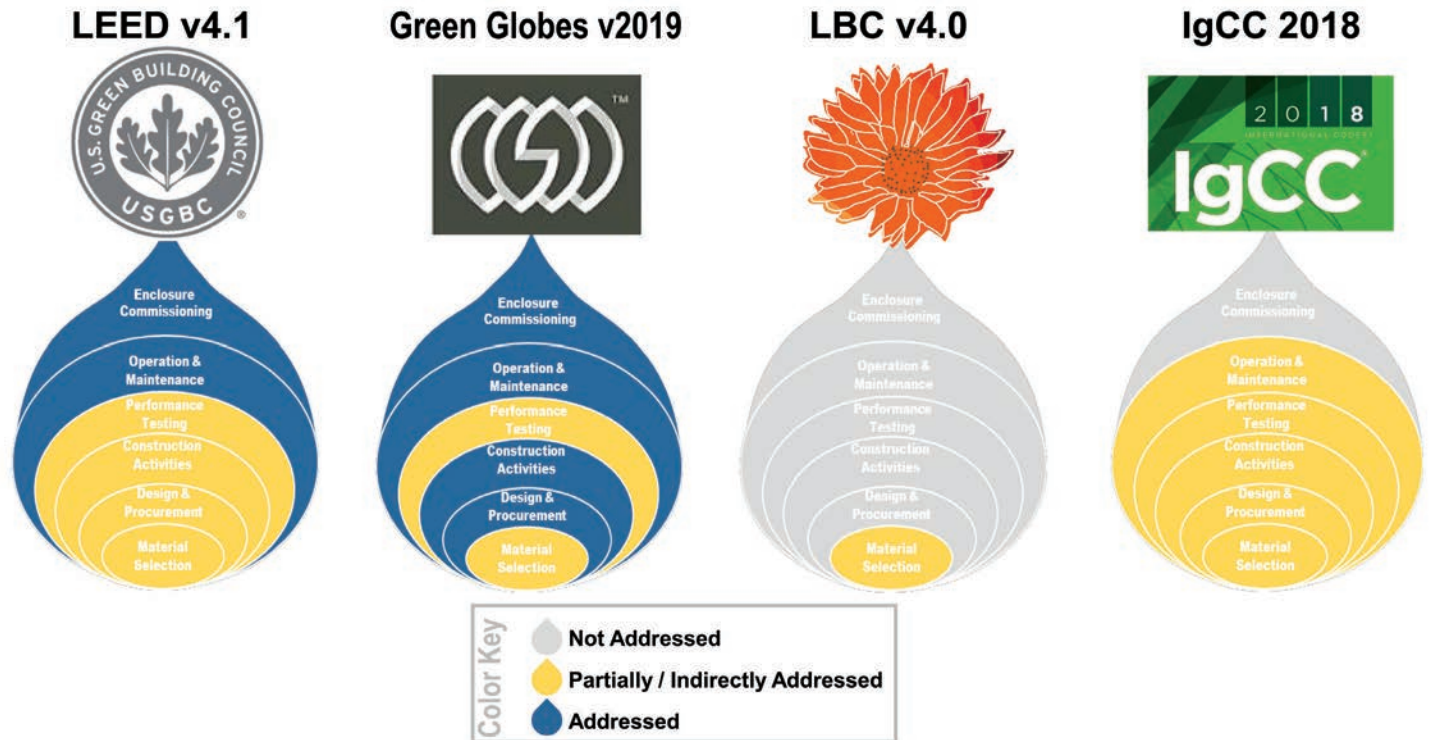


Figure 6. Comparison of moisture durability aspects in green building rating systems.

LEED v4.1 and Green Globes do not include specific measures for performance testing, but such testing can be a part of the Enhanced Commissioning credit of the Building Enclosure; (see additional discussion in the “Building Enclosure Commissioning” section later in this paper). Because scope is not identified in the LEED and Green Globes enclosure commissioning credits and minimum performance requirements, field testing can lead to substantial variation in actual built outcomes. For this reason, Fig. 5 shows field testing to be “partially or indirectly addressed” by these rating systems. The LBC rating system does not provide specific or prescriptive requirements for performance testing.

Operation and Maintenance

LEED v4.1 includes occupant training directly in the Enhanced Commissioning credit for the building enclosure. However, the inclusion of future assessments and specifically addressing manufacturer system documentation are left up to the project team.

Green Globes provides additional points for evaluating the building’s operational continuity or for a recovery assessment in the event of extreme weather conditions. Green Globes also provides specific credit for enclosure systems training in the use phase. However,

similar to LEED, it leaves manufacturer system documentation up to the project team.

The IgCC includes requirements for a detailed service life plan (10.3.2.3), which includes documenting, planning, and providing access to the enclosure elements based on their expected service life. It does not, however, deal with future-use assessments or specific service, warranty, or guarantee documents of the building enclosure.

The LBC rating system does not provide specific or prescriptive requirements for the operations and maintenance of the building’s use phase.

Building Enclosure Commissioning

Although LEED v4.1 and Green Globes provide additional points for enclosure commissioning, it is important to clarify that even though points are being given for enclosure commissioning, there are very few minimum tasks for project teams to accomplish. For many critical moisture durability aspects, decisions about how to proceed are left up to the project team. Compared to LEED v4.0, LEED v4.1 is notably improved by referencing ASTM E2947, *Standard Guide for Building Enclosure Commissioning*,¹⁴ which provides an exhaustive list of optional performance tests. It is incumbent upon the designer to establish

a minimum scope to vet project performance and achieve credit for the enhanced commissioning credit.

The LBC and IgCC do not include requirements or credits to include enclosure commissioning in the rating systems. The IgCC does have a commissioning requirements section (IgCC 10.3.1.2.1), but, unfortunately, the building enclosure is not included in the list of systems to be Commissioned.

Figure 6 summarizes each of the six individual detailed assessments reviewed across the project life-cycle phases. There is quite a range of results across the green building rating systems assessed.

KEY TAKEAWAYS

Overlooking one of the project phases may result in unmanaged risk for the long-term building performance. Therefore, when designing for moisture durability and energy efficiency in enclosures and roof systems, consider all project phases. This includes utilizing the building enclosure commissioning process to more formally ensure that an enclosure professional assesses the relevant moisture durability risks.

Some of the green rating systems have direct coverage of individual elements of moisture risk mitigation, but reliance on the

certification frameworks may not be sufficient to provide comprehensive moisture durability mitigation. In particular, all four rating systems have mandatory energy efficiency improvements beyond code-minimum requirements, but they all lack a complete set of mandatory credits to accommodate the increased moisture risk associated with the added enclosure complexity.

To accomplish long-term durability, risk management is recommended when interactive complexity and tight coupling are inherent in a roof and enclosure system design. This assessment provides a framework for applying enclosure moisture risk elements that can be used to either supplement any of the green rating systems or just enhance a project's performance. To shore up any project's specification, using or borrowing the best features from each system is recommended. And if the owner is seeking a specific green rating system certification, be sure to look across the alternative rating systems to fill in any gaps regarding enclosure moisture durability. 

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Water Penetration and Air-Leakage Testing of Flanged Commercial Windows

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ABSTRACT

Flanged windows are typically considered a product for low-rise residential buildings, and unflanged window systems (curtainwall, window wall, storefront) are typically considered products for commercial and high-rise construction. However, a new type of window system is becoming more common on high-rise construction: flanged, aluminum windows designed for high-rise buildings. Though numerous industry standards exist to guide the installation of flanged windows in low-rise construction, there is virtually no guidance to inform best practices for the installation of higher performance flanged windows in high-rise construction. Terracon Consultants Inc. and JE Dunn Construction partnered in 2017 to perform water penetration and air leakage testing of flanged window details, which resulted in a chapter in ASTM's Whole Building Air Leakage: Testing and Building Performance Impacts (<https://doi.org/10.1520/STP1615-EB>). Although that collaboration achieved valuable conclusions, the team was limited in their testing capability. Therefore, Terracon and JE Dunn have now partnered with Tremco to expand upon our previous research efforts. Tremco has a large, sophisticated testing facility in Cleveland, Ohio, where we can increase the accuracy and volume of testing. This research and collaboration effort regarding window details is part of a greater effort to establish a high-rise detailing manual, which is badly needed by our industry.

SPEAKERS



Keith Simon

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Keith Simon joined Building Exterior Solutions Inc. (a division of Terracon) in April 2014. He has over 15 years of experience in architectural design and building enclosure consultation, including peer review, design assistance, durability analysis, construction administration, testing, and forensics of building enclosure issues. Simon was the founder of the Austin Building Enclosure Council (BEC: Austin). He currently serves as a board member for BEC: Austin as well as the Passive House Austin Chapter, and he is secretary of the national executive committee for the Building Enclosure Technology and Environment Council. Simon serves as Terracon's subject matter expert for hygrothermal modeling and building enclosure commissioning.



John Posenecker

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John Posenecker joined Terracon in March 2015. A registered mechanical engineer, he is on the Building Enclosure Council (BEC) National Board and is a board member and Technical Committee cochair for the Air Barrier Association of America. His experience includes the design, construction, testing, and forensic investigation of building enclosure systems. Posenecker has participated in a wide variety of projects associated with enclosures, including containment systems for commercial nuclear power plants, noise control systems for commercial and institutional projects, and waterproofing systems for a wide variety of commercial high-rise and low-rise buildings.

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Water Penetration and Air-Leakage Testing of Flanged Commercial Windows

Flanged windows are typically considered a product for low-rise residential buildings and unflanged window systems (curtainwall, window wall, storefront) are typically considered products for commercial and high-rise construction. However, a new type of window system is becoming more common on high-rise construction: flanged, aluminum windows designed for high-rise buildings. While numerous industry standards exist to guide the installation of flanged windows in low-rise construction, the only guidance that exists to inform best practices for the installation of higher-performance flanged windows in high-rise construction comes from manufacturers for their specific systems (**Fig. 1**).

Terracon Consultants Inc. and JE Dunn Construction partnered in 2017 to perform water-penetration and air-leakage testing of flanged window details, which resulted in a chapter in the ASTM International publication *Whole Building Air Leakage: Testing and Building Performance Impacts*.¹ For the purposes of this paper, the results of this 2017 testing will be referred to as round 1 testing. While valuable conclusions resulted from that collaboration, the team was limited in their testing capability. Therefore, Terracon and JE Dunn have now partnered with Tremco to expand upon our previous research efforts. Tremco has a large, sophisticated testing facility in Cleveland, Ohio, that provides controlled indoor laboratory testing capability and the capacity for a much greater quantity of tests compared with the initial 2017 study (**Fig. 2**). Our 2020 research efforts, for the purposes of this paper, will be referred to as round 2 testing. This research and collaboration effort regarding window details is part of a greater effort to establish a high-rise detailing manual greatly needed by our industry.

Research methods for both round 1 and



Figure 1. Examples of commercial aluminum flanged windows.



Figure 2. Tremco testing facility in Cleveland, Ohio.

round 2 testing consisted of construction of full-scale wall mock-ups with window “blanks” installed with distinct integration details with the surrounding air- and water-resistive barrier system(s). The window blanks and air- and water-resistive barrier (WRB) system(s) act as controls within the testing and therefore allow the integration details themselves to be isolated and quantified in terms of water- and air-leakage performance. The round 1 testing utilized a mechanically fastened WRB system and the round 2 testing utilized a fluid-applied WRB system. Both rounds of testing utilized the same six mock-ups/integration details. Test methods used for the round 2 testing were ASTM E331, *Standard Test Method for Water Penetration of Exterior*

Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference,² and ASTM E283, *Standard Test Method for Determining Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors*

However, a new type of window system is becoming more common on high-rise construction: flanged, aluminum windows designed for high-rise buildings.

Testing	Research team	Air-leakage test method	Water-leakage test method	Mock-ups 1-6
Round 1 (2017-2018)	Terracon, JE Dunn	ASTM E783 (field test)	ASTM E1105 (field test)	Mechanically fastened WRB system
Round 2 (2019-2020)	Terracon, JE Dunn, Tremco	ASTM E283 (lab test)	ASTM E331 (lab test)	Fluid-applied WRB system

Note: WRB = water-resistive barrier.

Table 1. Summary of the two rounds of testing

Under Specified Pressure Differences Across the Specimen.³ **Table 1** summarizes the two rounds of testing.

A significant amount of testing and data within the building industry is available for air barrier systems (e.g., mechanically fastened WRB, fluid-applied WRB, sheathing board with integral WRB). There is also a great amount of testing and data within the building industry for manufactured products, such as windows, doors, and louvers. However, there is a lack of knowledge within the building industry of how these products are integrated into air-barrier systems to prevent air infiltration and water penetration. The goal of the ongoing research project described in this paper is to use test methods to evaluate detailing at the integration between fenestration products and air- and water-resistive barrier (WRB) systems. This study will not evaluate or compare air-barrier systems or products. However, it aims to specifically evaluate the integration details with respect to both air and water, and how well products are designed and integrated with the building's primary air- and water-resistive barrier systems.

Multifamily construction has seen tremendous growth in recent years and is projected to continue growing for at least the near term. Flanged windows are a dominant window type in multifamily construction. In round 1, the research team tested flanged windows integrated with a mechanically fastened WRB system and determined the conclusions listed as follows. **Table 2** presents the results of the round 1 testing. It should be emphasized that these conclusions are relevant to low-rise, wood-framed construction only and more study was required to determine best practices for high-rise installations.

Round 1 testing conclusions (Table 2):

- Testing showed that the open at sill installation method manages water better than the barrier at sill installation method. Open at sill indicates there is not sealant behind the window sill flange and there is not tape/membrane over the window sill flange. Barrier at sill indicates that there is sealant behind the window sill flange and also there is tape/membrane over the window sill flange.

- Testing showed that while the barrier at sill installation method may be more airtight than the open at sill method at 300 Pa (typical of high-rise construction), the open at sill method can be very airtight (close to zero air leakage) at 75 Pa (typical of low-rise construction) if foam or sealant is installed from the interior around the full perimeter of the windows.
- The test results showed that the low-rise foam or backer rod and sealant that is typically installed from the interior of flanged windows around the full perimeter of the windows is extremely important to both air and water performance.

While the round 1 testing made recommendations for low-rise construction very clear (use the open at sill method and install foam or sealant from the interior around the full perimeter), it was determined that further testing would be required to be able to make recommendations for high-rise construction. That determination led to our partnership with Tremco and round 2 testing.

SUMMARY OF GUIDING INDUSTRY STANDARDS, INSTALLATION INSTRUCTIONS, AND TEST METHODS

Installation Standards

AAMA (American Architectural Manufacturers Association) Standard 100, *Standard Practice for the Installation of Windows with Flanges or Mounting Fins in Wood Frame Construction*,⁴ states, "This

Mock-up information			Mechanically fastened WRB		
Mock-up no.	Installation method	Interior air seal	Air leakage through specimen, ASTM E783, cfm/sf	Air leakage through specimen, ASTM E783, cfm/sf	Water leakage through specimen, ASTM E1105 (cyclical) at 10 psf (23 total minutes)
1	Open at sill	Nothing	300 Pa	75 Pa	Summary
2	Barrier at sill	Nothing	1.37	0.33	10 seconds (480 Pa)
3	Open at sill	Foam	0.35	0.23	19 minutes (480 Pa)
4	Barrier at sill	Foam	0.15	0	Pass (480 Pa)
5	Open at sill	Sealant	0	0	23 minutes (480 Pa)
6	Barrier at sill	Sealant	0.12	0	Pass (480 Pa)
			0	0	13 minutes (480 Pa)
			(0.04 is pass)	(0.04 is pass)	(No water observed is pass)

Note: WRB = water-resistive barrier.

Table 2. Summary results of round 1 testing (mechanically fastened WRB system)

standard practice includes procedures for the installation of windows into buildings of no more than three stories in height.”

ASTM E2112, *Standard Practice for Installation of Exterior Windows, Doors and Skylights*⁵ states, “This practice covers the installation of fenestration products in new and existing construction. For the purpose of this practice, fenestration products shall be limited to windows, sliding patio-type doors, swinging patio type doors, and skylights, as used primarily in residential and light commercial buildings.”

Note that while both of the aforementioned standards serve as the most common installation methods within the multifamily building industry, neither standard is designed for high-rise construction. Therefore, as a research baseline, it was determined to use a major water-resistive-barrier manufacturer’s installation instructions for multifamily high-rise construction.⁶ Note that the installation instructions for high-rise construction generally align with Method A1 installation procedures as noted in Table 8 of ASTM E2112.

Air-Leakage Standards

ANSI/NFRC 400-2014, *Procedure for Determining Fenestration Product Air Leakage*,⁷ states that ASTM E283³ shall be the only method used to measure product air-leakage rates. The standard also states, “A differential pressure of 300 pascals (6.24 psf) shall be acceptable if the North American Fenestration Standard (NAFS) is used for products obtaining an HC or AW rating.”

However, while 300 Pa is an appropriate pressure to test as representative of high-rise construction, the research team decided to also test all of the mock-ups at 75 Pa, which is the metric used by the *International Building Code* (IBC) as well as the Passive House Institute US (PHIUS) and is more representative for low-rise multifamily construction. In other words, all mock-ups were tested for air leakage at both pressures—75 Pa and 300 Pa—during air-leakage testing.

Water-Penetration Standards

Table 2 of AAMA/WDMA/CSA 101/IS.2/A440-08, *NAFS – North American Fenestration Standard/Specification for Windows, Doors, and Skylights*,⁸ indicates the following: “Gateway Requirements” lists AW (architectural window) with the highest PG (performance grade) of 40, corresponding to a minimum design water resistance test pressure of 8.00 psf. AW windows can be rated as high

as PG 60 (corresponding to a 12.0 psf water resistance laboratory test pressure).

Note that our research team initially chose to water test at 10.0 psf as a typical high-rise value from our experience with common high-rise construction products and methods for the round 1 testing and a value a bit higher than the corresponding AW window pressure of 8.00 psf. However, during round 2 testing, we used ASTM E331, which gradually works up to 25 psf and therefore will be used with any future testing as a more rigorous method.

Two test methods for water penetration were evaluated to determine which would be the most appropriate: ASTM E331² and ASTM E547, *Standard Test Method for Water Penetration of Exterior Windows, Skylights, Doors and Curtain Walls by Cyclic Static Air Pressure Difference*.⁹ ASTM E547 was identified as a method developed more recently and is noted to be more realistic with regard to actual atmospheric conditions experienced on a building site, according to Bob Braun’s article “Building Wall Assemblies: Focus on Testing for Water Leakage and the Role for Sealants and Adhesives.”¹⁰ Initially, the research team decided to test per the corresponding field testing standards (i.e., ASTM E783¹¹ and ASTM E1105¹²) in lieu of the laboratory standards as more representative of our mock-up conditions during round 1 testing. However, after partnering with Tremco, the team’s expanded testing capability led us to perform the round 2 testing, using a fluid-applied WRB system, with the corresponding lab tests (i.e., ASTM E331 and ASTM E283). The change in test method did make it somewhat harder to compare the results of the two rounds of testing, as round 1 testing utilized field test methods with a mechanically fastened WRB system and round 2 testing utilized laboratory test methods with a fluid-applied WRB system.



Figure 3. Mock-up 1, round 2 testing, fluid-applied WRB system. Note: WRB = water-resistive barrier.

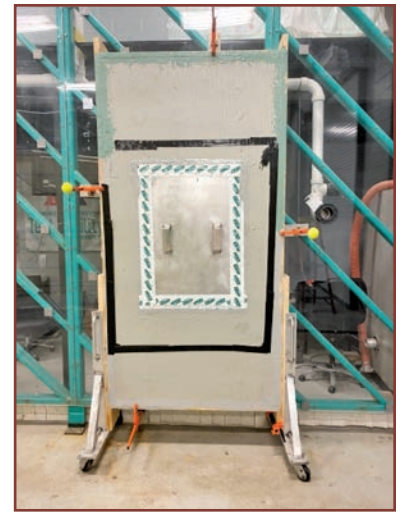


Figure 4. Mock-up 2, round 2 testing, fluid-applied WRB system. Note: WRB = water-resistive barrier.

METHODOLOGY

For each round of testing, six mock-ups with the following identical construction were built:

- Metal stud framing
- 4 ft × 8 ft sheet of gypsum sheathing with a 24 in. × 36 in. rough window opening
- Wood palette base with castors, 4 ft × 4 ft

Window “blanks” were constructed from 24-gauge metal with soldered corners. The goal of the blanks is to simulate flanged windows and to prevent air or water penetration through the blank itself. The air- and water-resistive barrier (WRB) was installed on mock-ups by a manufacturer’s representative in accordance with the manufacturer’s installation instructions (round 1 testing with a mechanically fastened WRB system and round 2 testing with a fluid-applied WRB system). While the window blanks were designed not to allow any air leakage, the blanks typically measured a negligible amount (typically 0.1 cfm of air leakage, but results ranged from 0.0 cfm to 0.2 cfm). The window blanks were then installed by the authors in general accordance with ASTM E2112 Method A1 but with specific sill modification details designed by the research team:

- Mock-up 1: open at the sill, no interior air seal (**Fig. 3**)
- Mock-up 2: barrier at sill, no interior air seal (**Fig. 4**)
- Mock-up 3: open at sill with low-pressure foam installed from interior side (**Fig. 5**)

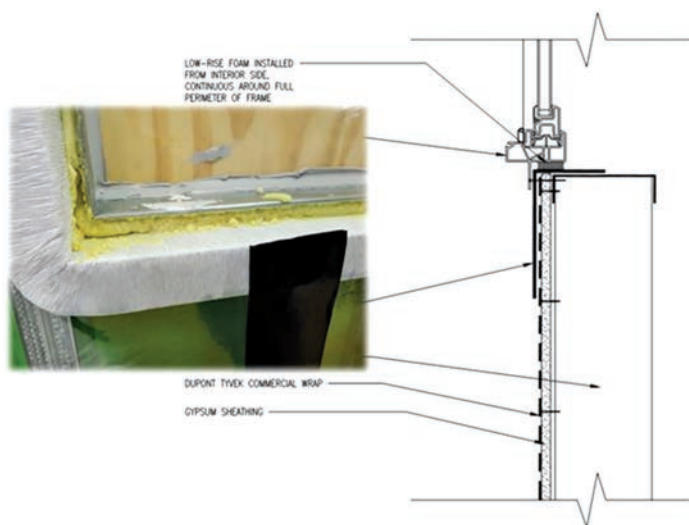


Figure 5. Mock-up 3, round 1 testing, mechanically fastened WRB system. Note: WRB = water-resistive barrier.

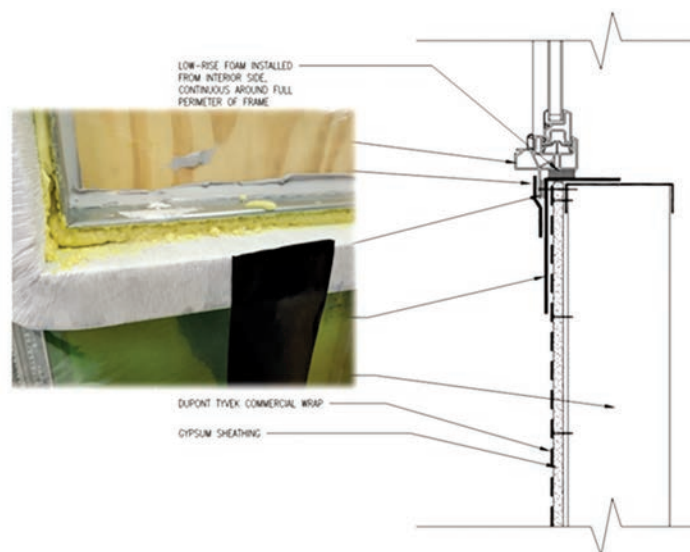
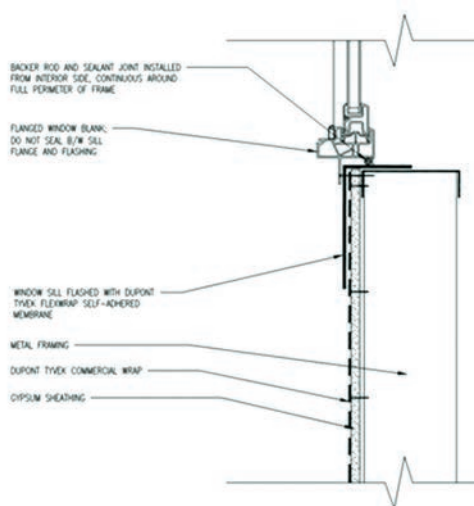


Figure 6. Mock-up 4, round 1 testing, mechanically fastened WRB system. Note: WRB = water-resistive barrier.



Figure 7. Mock-up 5, round 1 testing, mechanically fastened WRB system. Note: WRB = water-resistive barrier.



- Mock-up 4: barrier at sill with low-pressure foam installed from interior side (Fig. 6)
- Mock-up 5: open at sill with backer rod and sealant installed from interior side (Fig. 7)
- Mock-up 6: barrier at sill with backer rod and sealant installed from interior side (Fig. 8)

Figure 9 shows a summary of the mock up constructions. The jamb and head conditions were kept consistent (excluding the foam/sealant installed from the interior). Only the sill condition was detailed differently on each of the mock-ups. A 4 ft × 8 ft test chamber was built from dimensional lumber, sheet vinyl, and tape sealed to the backside of each mock-up. A vacuum was attached with an airflow meter, and a manometer to read pressure differentials. Each mock-up was tested for air leakage in general accordance with ASTM E783 (round 1 testing) or ASTM E283 (round 2 testing). The air-leakage tests were performed at both 75 Pa and 300 Pa pressure differential per the standards noted previously. For each mock-up, three air-leakage tests were performed:

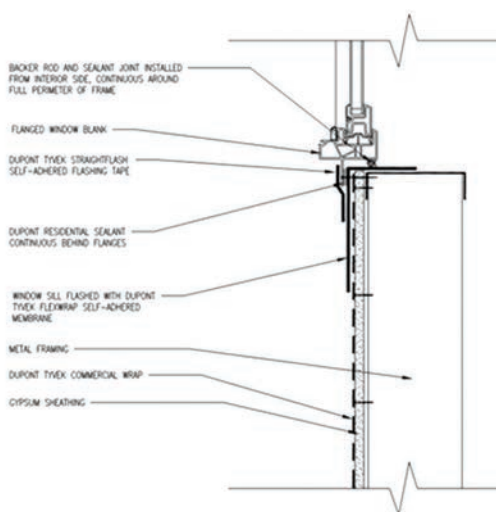
1. Air test 1: Fully isolated—a 3 mil sheet of plastic was taped over the entire front face of each mock-up.
2. Air test 2: Blank isolated—a 3 mil sheet of plastic was taped over the window blank only (Fig. 10).
3. Air test 3: No isolation (Fig. 3).

Subtracting the results of air test 1 from those of air test 3, the resulting value determined air leakage through the air-barrier assembly. Subtracting the results of air test 3 from those of air test 2, the resulting value determined air leakage through the window blank.

After the air-leakage testing, the mock-ups were



Figure 8. Mock-up 6, round 1 testing, mechanically fastened WRB system. Note: WRB = water-resistive barrier.



Mockup no.	Installation method	Interior air seal
1	Open at sill	Nothing
2	Barrier at sill	Nothing
3	Open at sill	Foam
4	Barrier at sill	Foam
5	Open at sill	Sealant
6	Barrier at sill	Sealant

Figure 9. Summary of mock-up construction.



Figure 10. Mock-up 3, round 2 testing during blank isolation air-leakage testing.

(round 2 testing) utilizing custom-built spray racks. The pressure differential used during the testing was 10 psf for the ASTM E1105 field round 1 testing and increasing pressures up to 25 psf were used for the ASTM E331 laboratory round 2 testing (Fig. 12).

RESULTS

Test results are summarized in Tables 2 and 3. The air test procedures were repeated on each mock-up typically at least three times, resulting in a significant margin of error for the measured results. However, a relative hierarchy for airtightness was clear:

1. For the round 1 testing (mechanically fastened WRB system) at 75 Pa, mock-ups 3, 4, 5, and 6 exhibited zero air leakage. Mock-up 2 leaked 1.4 cfm and mock-up 1 leaked 2.0 cfm.
2. For the round 1 testing at 300 Pa, mock-ups 4 and 6 exhibited zero air leakage. Mock-up 3 leaked 0.9 cfm and mock-up 5 leaked 0.7 cfm. As expected, mock-ups 1 and 2 exhibited the most air leakage (8.2 cfm and 2.1 cfm, respectively).



Figure 11. Air-leakage testing equipment (manometer, airflow meter, commercial vacuum).

tested for water penetration leakage in general conformance with ASTM E1105 (round 1 testing) or ASTM E331

3. For the round 2 testing (fluid-applied WRB system), all air-leakage testing at both 75 Pa and 300 Pa resulted in negligible values close to zero.

While water-penetration testing is typically used as a pass/fail method, a test pressure of 10 psf was selected for the round 1 testing with the intent of determining a hierarchy of water penetration resistance.

Round 1 testing (mechanically fastened WRB system):

- Mock-up 1: Water infiltration was observed within 10 seconds.
- Mock-up 2: Water infiltration was observed at approximately 9 minutes. Upon retest, water infiltration was observed at 19 minutes.
- Mock-up 4: Water infiltration was observed after completion of the 23-minute test when the testing chamber was removed.
- Mock-up 6: Water infiltration was observed at approximately 13 minutes.
- Mock-ups 3 and 5: No water infiltration was observed during nor after completion of the 23-minute test.

Round 2 testing (fluid-applied WRB system):

- Mock-up 1: Passed testing through 15 psf, water infiltration observed at 18 psf
- Mock-up 2: Water infiltration observed at 1.57 psf
- Mock-up 3: Passed testing through 25 psf

- Mock-up 4: Passed testing through 1.57 psf, water infiltration observed at 6.2 psf
- Mock-up 5: Passed testing through 25 psf
- Mock-up 6: Passed testing through 25 psf



Figure 12. ASTM E1105 water testing of mock-up 2, round 1 testing.

Mock-up information			Fluid-applied WRB		
			Air leakage through specimen, ASTM E283, cfm/sf	Air leakage through specimen, ASTM E283, cfm/sf	Water leakage through specimen, ASTM E331
Mock-up no.	Installation method	Interior air seal	300 Pa	75 Pa	Summary
1	Open at sill	Nothing	0.005	0.002	860 Pa
2	Barrier at sill	Nothing	0.015	0.015	75 Pa
3	Open at sill	Foam	0.049	0.019	Pass (1200 Pa)
4	Barrier at sill	Foam	0.015	0.015	300 Pa
5	Open at sill	Sealant	0.005	0.002	Pass (1200 Pa)
6	Barrier at sill	Sealant	0.017	0.015	Pass (1200 Pa)
			(0.04 is pass)	(0.04 is pass)	(No water observed is pass)

Note: WRB = water-resistive barrier.

Table 3. Summary results of round 2 testing (fluid-applied WRB system)

CONCLUSION

A common flanged window installation (Fig. 13) often used on multifamily construction is ASTM E2112 Method A1 with low-pressure foam installed from the interior. However, Method A1 with a barrier modification at the sill is being used more frequently due to increasing airtightness requirements. For high-rise construction, the industry is seeing more and more flanged aluminum window systems with little guidance for installation best practices. The following lessons learned were gleaned from our research:



Figure 13. Commercial flanged window installation.

- Test results for both low-rise (round 1 testing) and high-rise (round 2 testing) show that the low-pressure foam or backer rod and sealant installed around the full perimeter of the windows from the interior side is very important for both increased air-leakage and water-penetration performance. The research team was not able to determine any increased performance from foam as opposed to sealant, but at least one of those strategies is always recommended. It should be noted that architectural drawing sets frequently omit the low-pressure foam (or backer rod and sealant) in the window section details, despite the importance of this component. Note that our research methods do not account for the relative abilities of foam and sealant to withstand long-term building movement, which may be a reason to consider backer rod and sealant instead of low-pressure foam, as the foam will shrink and may lose adhesion to the substrates, decreasing system performance over the long term.
- Test results indicate that the open-sill approach generally appears to manage water better than the barrier approach for both low-rise (round 1 testing) and high-rise (round 2 testing) construction. This recommendation is clear for low-rise construction, but more testing would be required to clarify recommendations for specific high-rise construction conditions, such as hurricane-force winds or coastal areas. It should also be noted that the open-sill approach plans for drainage from windows that may fail in the future and allows for more installation error on the part of the installer.
- Testing indicated that the barrier approach is generally more airtight than the open-sill method. However, the open sill can be very airtight (due to the foam or sealant installed from the interior side). At 75 Pa (low-rise construction, IBC requirements, PHIUS requirements), the open-sill approach is sufficient for airtightness (zero or negligible air leakage measured). For most high-rise conditions, the open-sill approach (with an interior air seal) is sufficiently close to zero air leakage, as well when a fluid-applied WRB system is utilized.
- Based on our test results, the recommendation for low-rise construction with vinyl flanged windows and a mechanically fastened WRB is the open-sill approach with either low-pressure foam or backer rod and sealant. More testing is required to clarify recommendations for specific high-rise construction conditions, such as hurricane and coastal zones.
- Test results indicate that the change from a mechanically fastened WRB system to a fluid-applied WRB system demonstrated a marked performance improvement in terms of both air- and water-leakage performance (i.e., the same or less air leakage and the same

or less water infiltration for all mock-ups). All projects should consider the change from a mechanically fastened WRB system if possible. However, this change/upgrade becomes significantly more critical for high-rise construction and the associated increase in pressures from wind, rain, and sun. 

The research team intends to test the following in future rounds of testing:

- Variation: backer rod and sealant at the sill and only 6 in. up the jamb.
- Traditional head detail with mechanically fastened WRB flapped up versus reverse-lapped head detail (window head flange sealed outboard of WRB, but then taped and sealed at the top edge with compatible sealant).
- Repeat all tests with a self-adhered membrane WRB system.
- Repeat all tests with a mechanically fastened WRB system, but per test methods used in round 2 testing (ASTM E283 and ASTM E331).
- Repeat all tests with a board stock WRB system.
- All future testing will follow ASTM E331 and E283 to facilitate comparison of metrics and results as well as to utilize greater pressure differentials.

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Proving Ground: Performance Mock-Ups as Proof of Concept and Constructability Tools

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ABSTRACT

Design solutions must be buildable in the real world. Facade design intent, geometry, and materials must come together in a way that allows structural loading, environmental protection, and optimal long-term performance. Performance mock-ups bridge the gap between conceptual design and construction and allow project teams to test expectations and fine-tune plans prior to installation. This step is particularly important when working with innovative facade designs that incorporate new materials or complex integrations between various standard assemblies.

A performance mock-up is commonly understood as a tool to test previously untested cladding and glazing assemblies. However, it can also be a valuable tool for understanding constructability, sequencing, and integration detailing. Transition detailing, in particular, is unique to each project. Although the design may include transition concepts and shop drawings may be carefully detailed, getting the systems to work together can be a challenge and result in unintended design changes, as well as schedule and cost impacts during construction.

In this paper, I will explore how performance mock-ups translate design intricacies into constructable assemblies, and ultimately, a successful project. I will discuss laboratory and on-site mock-ups and how to make the most of each, including strategies for planning, timing, testing, and follow-through.

SPEAKER



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Proving Ground: Performance Mock-Ups as Proof of Concept and Constructability Tools

Design solutions must be buildable. Facade design intent, geometry, and materials must come together in a way that allows structural loading, environmental protection, and optimal long-term performance. Performance mock-ups (PMUs) bridge the gap between conceptual design and construction and allow project teams to test expectations and fine-tune the design prior to installation. This step is particularly important with innovative facade designs that incorporate new materials or complex integrations between assemblies, as well as with simple designs and traditional assemblies.

A PMU is a tool to test performance of cladding and glazing assemblies. It is also a valuable tool for understanding constructability, sequencing, and transition detailing. Transition detailing is unique to each project, and while the design may include transition concepts and shop drawings may be carefully detailed, getting the systems to work together can be a challenge and can result in unintended design changes, as well as schedule and cost impacts, during construction.

This article discusses types of PMUs and how to make the most of each type; strategies for planning, timing, testing, and follow-through; how to avoid pitfalls in design, construction, and testing; and ultimately how PMUs translate design intricacies into constructible assemblies for a successful project.

MOCK-UP DESIGN, CONSTRUCTION, TESTING, AND EVALUATION

Mock-up Types

A mock-up is defined as a “full-size model built to scale for study, testing, or display.”¹ Construction mock-ups vary in scope and complexity depending on what they are intended to accomplish. Common types of mock-ups include visual, component, system, and performance. A visual mock-up allows for aesthetic review of components, colors, finishes, and workmanship (Fig. 1). Component mock-ups are small scale and can be used to study pieces of a larger assembly, such as a complex sheet metal shape or unique mullion profile (Fig. 2). A system installation mock-up, such as a window installation or initial waterproofing application, helps confirm preparation and installation prior to full production, and allows initial quality assurance testing (Fig. 3). While these types of mock-ups are useful, they are limited. A PMU combines the visual, component, and system mock-ups into a single installation and allows testing of various performance metrics, as well as a more comprehensive evaluation of construction detailing, sequencing, and discovery of unanticipated conditions (Fig. 4).



Figure 1. Visual mock-up.



Figure 2. Component mock-up.



Figure 3. System installation mock-up.



Figure 4. Performance mock-up.

Figure 6. On-site performance mock-up.

Figure 5. Laboratory performance mock-up.



PMU Considerations

A PMU can be built, evaluated, and tested in a laboratory (Fig. 5), on site or near the project (Fig. 6), or in situ within the building construction (Fig. 7). Project conditions (complexity, schedule, budget, and available space) generally dictate which location is most appropriate. Evaluate each alternative for intent, scheduling, and cost-effectiveness. Assess design complexity, previous performance history, and combinations of products and materials. Appraise the need or desire to validate performance expectations through testing and the potential need for rework or retesting of all or part of the assembly if the PMU does not initially perform as intended.

The type and extent of testing desired drives decisions about the PMU type and location. A laboratory setting allows the most extensive testing because it has prebuilt testing chambers, available testing equipment, and designated space. Some tests, such as the effects of simulated building movement, can only be performed in a laboratory setting. Most other tests, such as air and



Figure 7. In situ performance mock-up.

water infiltration tests, can be performed with on-site mock-ups. In situ testing is generally the most limited option, due to building constraints. Laboratory and on-site testing can be completed before or at early stages of construction so that the results can be used to inform the design or construction process prior to

full implementation on the building. The results of in situ testing, which occurs during construction, necessarily limits the type and extent of modifications that can be made because materials have been ordered and work is ongoing.

Consider the convenience of available PMU construction and testing spaces. A nearby laboratory testing facility will be reasonably easy for the design and construction teams to access, and it allows PMU construction to be performed by the builders who will be performing the final work. A testing facility that is farther away limits access and makes coordination more difficult—builders performing the final work may not be able to work on the PMU or they may require special accommodations to do so, which affects cost and scheduling. An on-site PMU requires open space, such as plaza, landscape, or parking areas. A constricted and busy site may not accommodate an on-site PMU. There may be nearby space available in parking lots or other open spaces, but permission or leasing arrangements may be required to use them. An in situ PMU requires no special facilities or space and can potentially become a part of the finished work; however, fabrication schedules and construction sequencing may restrict the extent of the mock-up and limit one's ability to conduct desired testing (for example, it may not be possible to perform water testing in an in situ mock-up over work in progress below).

Consider the project schedule. A PMU should be constructed and tested prior to construction of the relevant components. Laboratory testing facilities have a finite amount of space, which may be reserved already. If laboratories are unavailable, testers must rely on on-site or in situ PMUs. A particularly aggressive project schedule may not allow for laboratory or on-site mock-up construction and evaluation, whereupon an in situ mockup may be the only viable option.

Consider the project costs. PMU construction, testing, and evaluation should be included in early construction cost estimates to allow evaluation by the owner, design, and construction teams to avoid unexpected costs. A laboratory PMU is typically the most expensive, followed by on-site and in situ. Costs will be impacted by the complexity and extent of the PMU, intended testing and evaluation, and the need or desire to rebuild or retest.

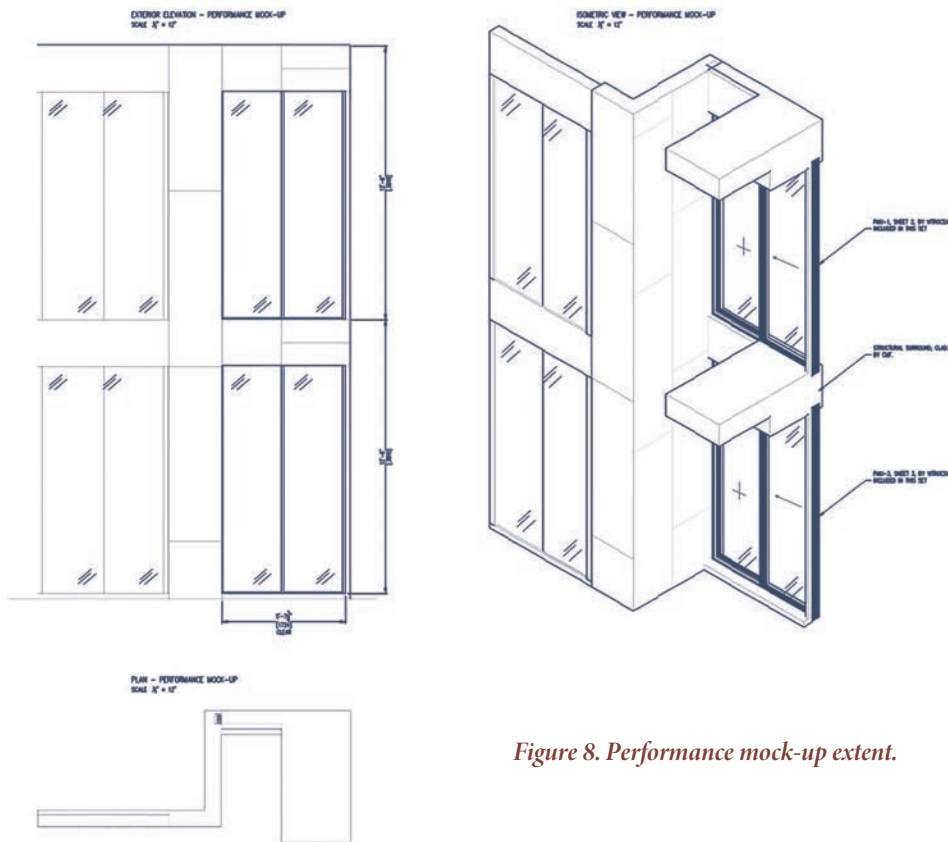


Figure 8. Performance mock-up extent.

PMU Design

Design the PMU to represent project-specific conditions. Evaluation reports of components or assemblies by manufacturers or fabricators are useful to understand expected performance, but they typically do not evaluate adjacent assemblies, transitions, or concealed conditions. As the finished building is ultimately intended to perform holistically, it is important to confirm that the various components will function adequately together.

Include typical elements of the exterior wall system in the PMU, and evaluate whether mock-up of nontypical conditions provides value to the project. Mock-ups vary in size and should be coordinated with specific testing requirements. Consider how much space for the PMU can be accommodated by the laboratory or on site. In some cases, multiple PMUs may be necessary to consider all relevant conditions. Generally, the PMU should include the following (Fig. 8):

- One or more typical vertical and horizontal bays, enough to represent repetitive components
- Typical vertical and horizontal conditions and transitions
- Inside and outside corners, if appropriate

Mock-up of project-specific concealed conditions is particularly important, as a failure on

for convenience to expedite cladding installation, the specified clips cannot be evaluated for installation and weather barrier continuity.

For laboratory or on-site mock-ups, while the PMU should be project specific, multiple representative sample conditions can be included in a single PMU. However, it is important to understand that the edges of the PMU are likely a non-project-specific condition; thus, details and components that are intended to be tested should not be located too close to the edge. The design and construction teams must consider not only which assemblies and transitions will provide the most benefit to mock-up but also how to transition them, including non-building conditions. Although not part of the building design, these transitions will essentially be required to pass PMU testing; however, they generally cannot be isolated, and testing failures can be difficult to attribute to a non-building condition only.

PMU Construction

To the extent practical, construct the PMU to mimic building construction. Account for logistics, sequencing, crating, staging, and other factors that mimic building field conditions. This process may reveal special requirements that might otherwise cause delays or increase costs. Ideally, the same forepersons and crews in the trades responsible for the work on the building will construct the PMU (Fig. 9). This allows the builders to practice and help identify and resolve unforeseen



Figure 9. Performance mock-up in construction.

Quality assurance evaluations during PMU construction will help eliminate construction deficiencies that could lead to PMU testing failure.

conditions, special sequencing, or special techniques required, which in turn reduces the risk of delays and improves quality assurance during construction.

While the PMU should represent building construction, there will be challenges to simulate project-specific conditions on a steel testing chamber at a laboratory or a stand-alone wall assembly on site. Consider

designed to allow simulated drift testing.

As part of the construction process, consider in-progress observations of the PMU by the design team and product manufacturers for quality assurance, as might be performed on the building. Before installed materials are covered by subsequent materials, review the installed materials and workmanship for compliance with the design documents and manu-

facturers' requirements. Similarly, consider performing quality assurance testing, such as material bond strength testing or thickness measurements. Quality assurance evaluations during PMU construction will help eliminate construction deficiencies that could lead to PMU testing failure.

Consider "pretesting" partially installed assemblies to identify

areas that require remediation, redesign, or reinstallation that might otherwise contribute to PMU testing failure after these components are concealed. For example, it may be advisable to perform water testing on a wall assembly that includes weather barrier and penetration detailing before covering by finish cladding; the test results may provide early indications of whether installation is successful, while it is still relatively easy to make repairs or changes.

Performance Testing

Performance testing checks the wall assembly's ability to meet design performance expectations. Evaluate and select testing in the context of previously tested or untested assemblies, the transitions between assemblies, anticipated environmental conditions, performance expectations, and level of acceptable performance risk. When selecting performance tests, consider other factors noted previously, including available laboratories and space, schedule, and cost.

Evaluate test methods and required test values for project-specific conditions. Consider whether the proposed tests are valid for project conditions, and if the values are appropriate for the project requirements. Require test loads for the PMU based on local conditions and building code and jurisdictional requirements. Coordinate the required test values with the specified products and assemblies. The tests and values can be more (or less) stringent than standards published by ASTM International, American Architectural Manufacturers Association, or other industry organizations, provided they comply with regulations and meet the owner's performance requirements.

Laboratory PMU testing is guided by



Figure 10. Laboratory testing.



Figure 11. On-site testing.



Figure 12. Failed original joint installation.

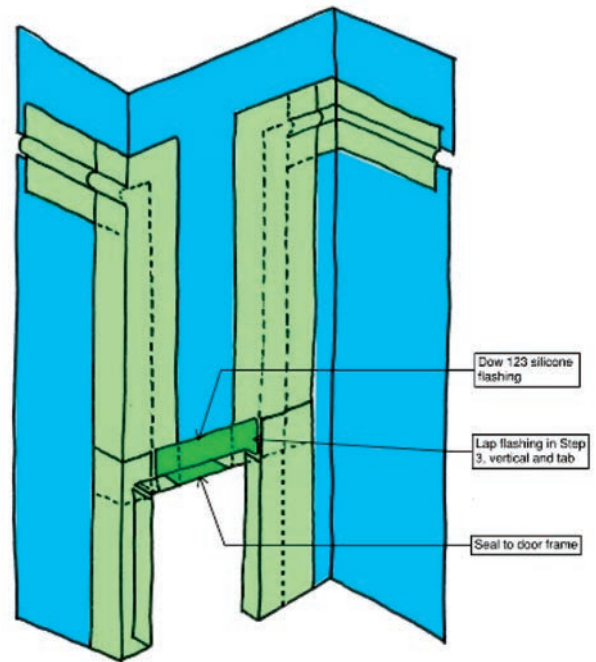


Figure 13. “Re-engineered” joint.

ASTM E2099, *Standard Practice for the Specification of Pre-Construction Laboratory Mock-ups of Exterior Wall Systems*,² which covers testing for air and water infiltration before and after the application of building design loads, effects of wind pressure, and vertical and horizontal movement between stories (Fig. 10). At the project team’s discretion, more (or less) testing can be performed. Air and water infiltration and structural testing are generally required, but optional tests include thermal performance, condensation risk, acoustic performance, and window washer anchorage.

On-site and in situ PMU testing are not currently guided by a singular industry standard. As noted previously, some, but not all, of the testing that can be done on a laboratory PMU can also be done to on site or in situ PMUs (Fig. 11).

Failures, Rebuilding, Retesting, and Deconstruction

Evaluate testing failures to determine when portions (or all) of the PMU should be reconstructed to implement revisions based on initial construction and testing results, and when the revised PMU should be retested. ASTM E2099 generally does not require retesting upon failure (although there are certain exceptions), so it is incumbent on the design team to specify the intent and requirements for retesting after failures.

To obtain the greatest value from a PMU, evaluate failure modes, make repairs, and retest to confirm the efficacy of the design or construction methodology; acceptance of testing failure does not generate proof of concept. “Band-Aid” repairs to make a mock-up artificially pass testing should be used with caution; they are only allowable if they do not influence the performance of adjacent components, if the cause of failure is known with certainty, and if the remediation for the building is proven. For example, adding sealant to prevent water entry into the glazing pocket of a PMU curtain wall assembly that is not intended to be installed during fabrication, can result in a false pass, which may fail on the building. In general, make PMU repairs to comply with the design intent of the construction documents, as modified by lessons learned from the original PMU, or redesign and rebuild the failed component to meet expected performance criteria (Fig. 12–14).

While it is easy to suggest repeated repairs and retesting, there is a cost and schedule implication to doing so. If initial testing fails and subsequent testing continues to fail after repairs are made, it may be tempting at some point to accept the test failures and move on to building construction. Before moving on, it may be prudent to reconstruct sections of the PMU



Figure 14. Successfully reinstalled joint installation.



Figure 15. Deconstruction of performance mock-up components.

rather than trying to continue to make repairs. As a last resort, failures could be accepted. This decision should be made carefully on a case-by-case basis; conditions should be evaluated by the design, construction, and ownership teams to understand the most likely failure modes and if they can realistically be resolved in situ, as well as to understand the potential performance risk. In such cases, it is advisable to conduct follow-up in situ testing to confirm performance.

Documented deconstruction of a PMU is advisable in some circumstances. Suspected failure at concealed conditions or of an isolated component may require further analysis to develop an effective, repeatable remediation, which may require partial deconstruction to understand a flaw in the design, fabrication, or installation (**Fig. 15**). Similarly, if test failure is accepted as noted previously, observations of the suspected failure mode may provide some confidence in the proposed repair without additional testing.

COORDINATION AND SCHEDULING TOOLS TO REDUCE UNFORESEEN CONDITIONS

Unforeseen Conditions and Common Pitfalls in Design, Construction, and Testing

As discussed previously, a PMU can be used to flush out unforeseen issues in design, fabrication, or installation prior to full implementation on a building. When using a PMU,

thorough coordination, scheduling, observation, and communication will reduce such issue, improving the likelihood of testing success and minimizing costs, if any, for follow-up reconstruction and retesting.

Common pitfalls in design include inadequate consideration of transition areas. This is particularly true of areas that combine complicated geometries, movement requirements (seismic, expansion, drift), or both with multiple materials and components, which may be installed by different trades. Communicating design intent in two-dimensional plan and section drawings is often not adequate to fully develop transitional design. Isometric or sequence detailing is necessary to understand complex transitions.

Common pitfalls in construction include the incorporation of unspecified materials and components and non-project-specific conditions. Unspecified materials and components are sometimes used in concealed conditions for convenience or to expedite installation or testing. Detailing around these unspecified components allows a testing failure or pass that is not fully applicable to the building. As noted earlier, a PMU may include non-project-specific conditions, such as perimeter/support conditions that are unique, to allow construction and testing of multiple assemblies on a single PMU. These conditions are typically not detailed in the design documents, but they are nonetheless required to pass testing if they cannot be isolated. In addition, many

PMU test failures are not due to design flaws; rather, they are caused by incorrectly installed components, which must be removed and reinstalled for additional testing.

Common pitfalls in testing include insufficient coordination and equipment failure. “Wet” components, such as sealant, must fully cure before testing. Pretesting, or even full testing, is occasionally performed on uncured components, resulting in failure and the need to reinstall, cure, and retest. If PMUs are subjected to rain or water from adjacent testing or cleaning and not fully dried before testing, it is difficult to accurately assess the source of water leaks. Misplaced testing gauges do not provide accurate measurements, resulting in misdiagnosis. Furthermore, misplaced gauges can cause damage to PMU components, such as glazing, that might require replacement before retesting. Finally, if test equipment such as a propeller or water spray rack fails to operate properly on the day of the test, a retest may need to be scheduled.

Coordination Tools

Coordination among the owner, design team, contractors and trade partners, and testing agency is necessary to get the most value from the PMU process and to minimize PMU costs and schedule delays. The PMU purpose execution, evaluation, and expectation must be commonly understood by the project team. Although the design team is generally responsible for specifying PMUs, testing, values, and pass/fail criteria, the PMU effort should be collaborative. Define the roles of the project team early in the process: the owner defines the performance requirements (meets or exceeds jurisdictional requirements); the designer designs to meet the performance requirements and establishes the PMU parameters; contractors and trade partners provide feedback on constructability, performance expectations, and costs for the owner and designer to consider; and the testing agency provides final proof of concept by conducting specified testing.

Identify the type of PMU, conceptual PMU assemblies, extent, and testing early in the design phase. As PMUs and testing affect costs and schedules, the design team should identify the intended mock-ups and testing during the design phase, obtain owner buy-in, and include the mock-ups in construction cost estimates. This may require discussions of costs versus benefits and risks to define the PMU process.

Identify the assemblies to be included in the PMU in the construction drawings. As

noted in ASTM E2099, the assemblies should be identified either by designating an area or areas on the architectural elevations or by providing separate mock-up elevation drawings that may combine various typical parts of the wall systems into a single mock-up. Evaluate the building geometry and various components to determine which is the most appropriate approach. In addition to elevations, provide wall sections and details, or references, as necessary. As discussed previously, a composite PMU may require transitions that are not included in the building; detail these areas to reduce risk of testing failure. Finally, identify critical points in the assembly, such as stack joints and transitions, where special viewing access may be needed.

The construction specifications indicate required testing, performance values, and more. Specifications include many individual sections that will be part of the PMU; however, specifications are not always fully coordinated. In addition, required testing described in any given section may be questioned as to its applicability to components of another section. As such, consider a stand-alone PMU specification section, or, alternatively, a comprehensive exterior cladding system specification, that references the various related sections and also provides a single place to define the PMU type, testing regimen, evaluation protocol, performance values, and other mock-up requirements, which can be noted as a catch-all to “govern” in the event of discrepancies among other specification sections. In addition, clarify if only specific components of the PMU are being evaluated or if all components including transitions, terminations, etc. will be evaluated.

Require material product data and shop drawing submittals for the PMU. The shop drawings should fully detail materials and components, transitions to adjacent assemblies, edge conditions, and viewing platforms. Consider requiring coordinated shop drawings that integrate various trades’ work into a single coordinated drawing set. Coordinate with the testing facility for the location of temporary supports and mounting locations for gauges. In addition, require submittal of test procedures and evaluation protocol for confirmation.

Conduct a PMU preconstruction meeting that includes all relevant parties to review approved shop drawings, testing procedures, and anticipated sequencing and schedule. Use the meeting as a tool to coordinate trades, understand cure times, and identify areas that may need further development or input by the design team.

Coordinate construction with the design team and manufacturers’ representatives to make periodic observations for compliance with design intent and manufacturers’ requirements. Make observations to document each “layer” of construction before it is covered by subsequent components. Have multiple parties review “final” construction and test setup before testing, with enough time to make minor repairs or adjustments.

Evaluate PMU construction as it is built to provide feedback on areas that work as intended or need further modification and evaluation. The contractor should maintain a record of as built mock-up construction, indicating in detail any changes or modifications to the PMU. Following successful testing, the design team should incorporate any changes to the design as a result of the PMU process into updated construction documents. Because PMU modifications may need to be interpolated to various assemblies on the building, relying only on as-built drawings or notes of the PMU to document design changes risks overlooking an important modification.

Scheduling Tools

The most important aspect of scheduling the PMU is that it be completed, tested, and approved before procurement and construction for the building (or relevant components), and with enough time to incorporate any design modifications. If the PMU process is completed after facade construction is underway or after cladding components are already in fabrication, it could be infeasible to incorporate modifications. For laboratory or on-site PMUs, coordinate the PMU schedule with the laboratory facility or on-site space requirements. In addition, consider accounting for time in the schedule to repair and retest the PMU; most PMUs will not pass the testing the first time for a variety of reasons. Remember, the PMU is intended to be a problem-solving tool, not a formality.

Understand the critical path to a successful test relative to component procurement and building construction. Establish a milestone schedule for the PMU, accounting for submittals and shop drawings, and in-progress reviews to observe components before they are covered. In addition, keep in mind that many concealed materials are not intended for long-term exposure to ultraviolet light and may degrade over time. Delays in cover, repairs, or testing can lead to testing failures from material degradation, potentially requiring additional repairs and testing.

HOW CONSTRUCTION PROCESS AND TESTING CALIBRATE FINAL DESIGN AND CONSTRUCTION

Construction Process

The purpose of a PMU is to provide proof of concept for the design performance intent and the construction means and methods. The PMU construction process can identify many potential design and construction issues on a small scale, allowing the opportunity for modifications prior to full implementation, which reduces the risk of schedule and cost increases on the building.

Previously untested assemblies or combinations of materials and components include some risk of performance failure, either due to design, fabrication, or installation. A PMU allows practice installation, which can in turn help to identify deficiencies and develop remediations to allow the design to perform as intended.

Design integration between materials or components may not be well developed in the construction drawings. Alternatively, design intent may be clear enough in two-dimensional plan and section drawings but underdeveloped across complex three-dimensional geometries. Even with building modeling software, small-scale transitions can be overlooked or misunderstood until visible, creating an unforeseen condition. A PMU allows discovery of underdeveloped transitions, as well as input from subcontractors on constructability at these transitions, so that solutions can be prepared and tested.

Along with transitional design details, complicated assemblies may require multiple attempts to build correctly. The PMU provides the opportunity to develop efficient means and methods for complicated transitions and best practices for specific conditions. The efficiencies learned on the PMU can be applied to the building. Any number of construction oversights may occur, such as noncompliance with design detailing, insufficient laps, or unrepaired damages. As these issues are identified on the PMU, special attention can be emphasized for these same areas on the actual building.

The need to install one product or component before another is not always clear in the design drawings. Alternatively, sequencing may be clear enough but may require one trade’s scope to be interrupted by another’s. A PMU helps clarify sequencing requirements, allowing for better planning and scheduling, or identifies areas that may be more efficiently constructed with alternative detailing.

Type	Pros	Cons
Laboratory	• Allows testing not possible with other PMUs • Allows modifications to design, fabrication, or construction to be implemented (potentially)	• Most expensive • Requires the most coordination • Requires a laboratory testing facility, and team members must travel to and from the facility
On-site	• Allows some of the testing that can be done in laboratory • Allows modifications to design, fabrication, or construction to be implemented (potentially)	• Moderately expensive • Requires moderate coordination • Requires space to build and test • No structural movement testing • No air/water infiltration testing following movement testing
In situ	• Least expensive • Requires the least coordination • The PMU may potentially remain as part of the finished work	• May required multiple mock-ups to review all areas of interest • Only allows limited testing and observation • Only allows minor modifications to design or construction, more in line with quality assurance

Table 1. Pros and Cons of Performance Mock-ups (PMUs)

A PMU allows discovery of timing or scheduling impacts. Necessary modifications to components or alternative components could have lead times that impact the overall schedule. Early discovery of such issues can potentially mitigate delays or at least provide information to make informed decisions about delays versus performance.

Testing

Successful performance testing provides the final proof of concept for both design and construction. Successful testing proves the design, materials, and methods will work as intended. However, the process of achieving successful testing is how the design and construction are fine-tuned. Testing failures offer the design and construction teams the opportunity to evaluate the cause of failure and implement changes to achieve success. Multiple rounds of testing may be required to confirm that the changes work as intended.

To get the most value from the performance testing process, only “engineered” changes to the design or construction should be completed, and these changes should be done in the same manner that they would be implemented on the building. Retesting short-term or “nonengineered” repairs that are made only to expedite PMU testing success will not fine-tune the final design or construction and will leave some doubt as to proof of concept.

Documentation and Implementation

Because the PMU is a tool to evaluate design and construction prior to full implementation, it is critical that modifications to the design and lessons learned in the construction be incorporated in the project. If the

mock-up is performed too late to make meaningful changes, or if there is no documentation of changes and plans for implementation, the PMU becomes a mere formality and may not add substantial value to the project.

ASTM E2099 generally requires as-built drawings of the PMU showing any changes to the design, as well as a final test report. However, simply meeting these requirements may not be enough to get the full value of the PMU process. Methodology and responsibilities should be established for documenting design changes and construction means and methods, and for how design changes will be implemented. In addition to as-built drawings, photographic documentation of the overall process and detail assemblies allows a virtual deconstruction and analysis of areas in the event of localized test failures. Written observations and analysis of pretesting, full testing, and retesting, or acceptance of failures, and any design, means, or methods modifications create a narrative for further evaluation and an additional basis for implementing changes on the building.

EVALUATING THE COSTS AND BENEFITS OF PMUS

Table 1 summarizes pros and cons of laboratory, on-site, and in situ PMU types. This information can be useful when performing a high-level cost-benefit-risk analysis for the PMU types, including not providing a PMU at all. The potential results of a PMU do not always justify the expense; however, stakeholders may consider the cost of a PMU to be a relatively low-cost investment to reduce the risk of relatively high-cost performance failure, unforeseen conditions, and schedule and con-

struction cost changes while in full production on the building.

Laboratory PMUs are generally of most value to projects with complicated geometries, transitions with multiple materials and components, previously untested assemblies or combinations of assemblies, and custom fabrications—particularly if capacity for differential movement is also required. In addition, laboratory testing may benefit projects with potentially high costs or substantial risks associated with failures, such as loss of use or litigation. A nearby laboratory maximizes the value of this PMU type by easy access for the design and construction teams. Although testing at a remote laboratory may be costlier, it can still be beneficial in some cases.

Compared to laboratory PMUs, on-site PMUs may provide a better value for projects with limited differential movement, comparatively simple geometries and transitions, limited components, and traditional combinations with a history of similar installation and good performance. Previous performance history might negate the need to test for movement and post-movement air and water infiltration, with relatively low risk. However, the on-site PMU will still allow for fine-tuning and adjustments for project-specific conditions. Lack of a nearby laboratory may increase the value of an on-site PMU, which could provide many of the same benefits as laboratory testing without excessive cost for travel or loss of interpretation between builders. An on-site PMU could also be considered a compromise to accommodate space, schedule, or cost constraints while still allowing more testing and evaluation prior to fabrication or construction than could be achieved with an in situ PMU.

In situ PMUs are most appropriate for projects with simple geometries, materials and components with proven track records of performance, and simple and limited transitions. Although the in situ PMU provides performance validation for design and construction, it is more of a quality assurance test for installed components to confirm performance is the same as it was in the past. An in situ PMU may be appropriate in situations where there is little reason to anticipate performance failure and it is unlikely that design or construction changes will be necessary.

Omission of any type of PMU can increase risks for cost increases, schedule delays, performance failures, and undesirable aesthetic changes. In addition, omission of a PMU may limit the owner's, design team's, and builder's

confidence in the project success, which may, in turn, have insurance or future litigation implications.

SUMMARY

Facade designs range from simple to complex, but regardless of the level of complexity, they are expected to fulfill an aesthetic vision and provide a safe environment for users over the course of the building's life cycle. PMUs allow testing of design solutions for constructability, sequencing, transition and integration detailing, and expected performance. Lessons learned as part of the mock-up construction and testing process can be incorporated into the final design and construction to reduce the risk of unintended design changes, schedule, and cost impacts during full implementation.

Successful mock-up construction and testing provides a proof of concept for the design itself as well as the construction means and methods, and should provide the owner, design team, and contractor a high level of confidence in project success. 

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A Tale of Two Masonry Facade Rehabilitations: When Preservation Standards, Codes, and Client Expectations Are at Odds

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ABSTRACT

Facade rehabilitation projects require design professionals to manage and balance a complex combination of varied and sometimes opposing factors, including historic preservation issues and considerations, code requirements, and client expectations. This presentation will focus on preservation, restoration, and rehabilitation, and the differences among these processes as they relate to historic building facades and other aspects of a rehabilitation project. Unnecessary repairs and beautification in the name of restoration are often some of the most difficult challenges faced by the preservation industry. Historic preservation involves constant efforts to determine the appropriate scope of repairs, justify replacement of undamaged original fabric, decide when it is okay not to repair, and manage the client's expectations with regard to a historic building not looking shiny and new. The balancing act between these priorities becomes even more challenging when incentives—including tax benefits or other financial means—are at stake.

SPEAKERS



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A Tale of Two Masonry Facade Rehabilitations: When Preservation Standards, Codes, and Client Expectations Are at Odds

Facade rehabilitation and restoration projects require design professionals to manage and balance varied and sometimes opposing factors, including historic preservation philosophical issues and considerations, code requirements, client expectations, and available funds. This paper will focus on the terms preservation, restoration, and rehabilitation, and discuss the differences between each process as they relate to historic building facades and how they are interpreted relative to the two case studies presented. Successful historic preservation balances developing an appropriate scope of repairs, based on the treatment, which may require justification of additional removals and replacement of original fabric, and an understanding of when no intervention is deemed appropriate. These factors must always be considered in combination with managing the client's expectations and budget constraints. These conversations become even more challenging when incentives include tax benefits and other financial influences. This paper reviews the four Secretary of the Interior's Standards for the Treatment of Historic Properties and compares and contrasts the implementation of the Standards and the balance of many factors for two large-scale historic masonry facade repair projects.

THE SECRETARY OF THE INTERIOR'S STANDARDS FOR THE TREATMENT OF HISTORIC PROPERTIES

The Secretary of the Interior's Standards for the Treatment of Historic Properties (Standards) are practical historic preservation principles that use nontechnical language. They promote historic preservation best practices. The Standards offer four distinct approaches to the treatment of historic properties—preservation, rehabilitation, restoration, and reconstruction—with accompanying guidelines for each. Inevitably, more than one of these standards will apply to a property

undergoing repairs, depending on the property's significance, existing physical condition, the extent of documentation available, and interpretive goals. Most facade projects combine aspects of more than one of these approaches, depending on the condition and significance of specific elements.

The Standards are a series of concepts about maintaining, repairing, and replacing historic materials, as well as designing new additions or making alterations. The Guidelines offer general design and technical recommendations to assist in applying the Standards to a specific property. Together, they provide a framework and guidance for decision-making about work or changes to a historic property. The Standards and Guidelines can be applied to historic properties of all types, materials, constructions, sizes, and uses. They include both the exterior and interior and could also extend to a property's landscape features, site, environment, as well as related new construction. The Guidelines are advisory, not regulatory, but are often used to guide and influence decisions regarding tax credit evaluation. For the purposes of this paper, the Standards will be referenced according to how they are applied for historic masonry facades.

As part of any historic facade preservation project, selecting an appropriate treatment among the four outlined in the Standards is critical to help guide the decision-making process for the suitable scope of repairs. The following list summarizes the four philosophical approaches of the Standards.

- Preservation focuses on the maintenance and repair of existing

historic materials and retention of a property's form as it has evolved over time.

- Rehabilitation acknowledges the need to alter or add to a historic property to meet continuing or changing uses while retaining the property's historic character.
- Restoration depicts a property at a particular period of time in its history, while removing evidence of other periods.
- Reconstruction recreates nonsurviving portions of a property for interpretive purposes.

Choosing the most appropriate approach for a component of a building, or the entire building, requires careful review of the building's historical significance, as well as a number of other considerations, including relative importance in history, physical condition, proposed use, and mandated code requirements.

As part of any historic facade preservation project, selecting an appropriate treatment among the four outlined in the Standards is critical to help guide the decision-making process for the suitable scope of repairs.

As outlined in the exemplars below, many historic preservation projects fit into more than one of the categories of treatment, but use the principles set forth in the Standards. Certain federal and other high-profile historic preservation projects, where a specific period of significance is established, will require a stricter interpretation of the Standards. National Historic Landmarks, designated for their “exceptional significance in American history,” or many buildings individually listed in the National Register, often warrant Preservation or Restoration. Buildings that contribute to the significance of a historic district but are not individually listed in the National Register more frequently undergo Rehabilitation for a compatible new use.

Preservation may be appropriate if distinctive materials, features, and spaces are essentially intact and convey the building’s historical significance. If the building requires more extensive repair and replacement, or if alterations or additions are necessary for a new use, then Rehabilitation is probably the most appropriate treatment. These key questions play major roles in determining what treatment is selected. Regardless of the intervention, applicable code requirements will need to be taken into consideration.



Figure 1. Photo of original construction of Old Cook County Hospital in Chicago, IL, circa 1913. Source: Photograph taken on December 24, 1913, before the building’s completion (from “The Man on Five” website - <http://themanonfive.com/page/59>).

EXEMPLARS

The following facade repair projects highlight the combination of many varied and sometimes opposing factors. Each case study illustrates the process used for evaluating and determining an appropriate scope of repairs using the appropriate Secretary of the Interior’s Standards for the Treatment of Historic Properties while managing the client’s expectations. The Old Cook County Hospital facade is considered a combination preservation and rehabilitation project, while the 30th Street Station facade project would be considered a combination of preservation and restoration.

OLD COOK COUNTY HOSPITAL (CHICAGO, ILLINOIS)

The Cook County Hospital Administration Building, designed by Paul Gerhardt (County Architect) in the Classical Revival style, exemplifies the influence of the Ecole des Beaux-Arts in its design traditions on American architecture of the 19th and early 20th centuries. The Old Cook County Hospital is regarded as one of Chicago’s grandest public buildings and illustrates the importance of local Cook County government in the care and welfare of its citizens through its high-style architecture.

The eight-story Old Cook County

Hospital Administration building and penthouses commenced construction in 1912 and was completed in 1916 (Fig. 1). The Cook County Hospital Administration Building as it exists today has a long, rectangular footprint that is relatively narrow given its block-long length. Its main-street facades, facing north, east, and west, are clad with tan clay brick and ornamented with white glazed terra-cotta. The building’s base has a granite water table and a granite-look course of terra-cotta. The primary north facade of the building fronts Harrison Street. The

east facade fronts Wood Street and the west facade once abutted the Fantus clinic (since demolished), which was also vacant. The south (secondary) facade fronts a surface parking lot. The main portion of the building is approximately 110 ft tall and penthouses extend to 146 ft. The building, as it currently exists, is generally rectangular in plan, as the four projecting rectangular wings with hexagonal bays extending from the south facade were previously demolished, which reportedly occurred circa 2010. The overall plan dimensions are approximately 555 ft (east-west direction) by 75 ft (north-south direction).

The great scale of the building is softened on the street facades through a tripartite division of a two-story base, five-story shaft, and one-story top. It is symmetrical and balanced, and has a visually rhythmic appearance, with the building’s central and end sections set back slightly. Separated by midsections extended forward also help to reduce the scale of the imposing masses. The south facade is much simpler and is clad with tan clay brick, except for the returns and the east and west ends, which mimic the detailing of the other three facades. A three-story projecting porch exists at the center of the south facade and is clad with tan clay brick and terra-cotta. Two light wells, also clad with tan brick masonry and terra-cotta, flank the central projecting porch.

The front facade has classical-style ornament of various sorts, including pairs of “giant-order” terra-cotta-clad columns that are three stories in height, cartouches, swags, decorative sills with brackets, window grilles, and moldings. Although the facade has an overall decorativeness, ornament is most concentrated around the building’s main entrance, set in the center of the facade, within recesses that define floors four through six, above and around many windows and other building openings, and at the building’s roofline, especially where the facade projects forward. Most of the windows are aluminum-framed replacement windows to match the configuration of the original wood frame, double hung and single glazed. Large multi-lite monumental arched windows exist at the second, third, and fourth floors on the north facade. Additional unique features include the eight operating room skylights at the eighth floor centered on the north facade, as well as the two large sloped skylights (since roofed over with sheet-metal roofing) over the original operating theaters at the east and west ends of the north facade.

The building structure is a steel frame clad with structural clay-tile fireproofing

with a combination of clay-tile arched floors and reinforced concrete floor slabs. The exterior walls are multiwythe header bonded brick masonry with architectural terra-cotta ornament with interior extruded clay-tile backup. Vertical chases existed between the exterior masonry cladding and the backup clay tile for ventilation and mechanical chases, with multiple voids between the clay-tile backup and floor slabs as well as between floors. Various combinations of steel beams, plates, angles, bars, rods, and J-hooks support the masonry cladding. Brick masonry is supported at each floor by continuous steel shelf angles, typically riveted to the main building structure. Terra-cotta units are either supported by shelf angles similar to the brick or the units are independently supported by a system of steel components that are also riveted to the main structural system.

The Old Cook County Hospital was closed in 2002 and maintenance of the exterior enclosure before that was limited. Additionally, the building stood vacant and unconditioned until 2018 with little effort to limit air and water infiltration. Temporarily stabilization of portions of the exterior facade had been installed throughout the period of vacancy to minimize hazards to public safety. Unfortunately, the previous stabilization interventions did not provide weather protection for the interior or substrate portions for the structural support and anchorages (Fig. 2).

The evaluation of the Old Cook County Hospital exterior facade consisted of three phases. The initial phase was a Code-mandated City of Chicago Facade Examination. This limited visual assessment was performed to prepare a Critical Examination report and to familiarize ourselves with the general construction and design of the building, particularly the exterior facades. The second phase was a due diligence investigation to gain a general sense of the con-

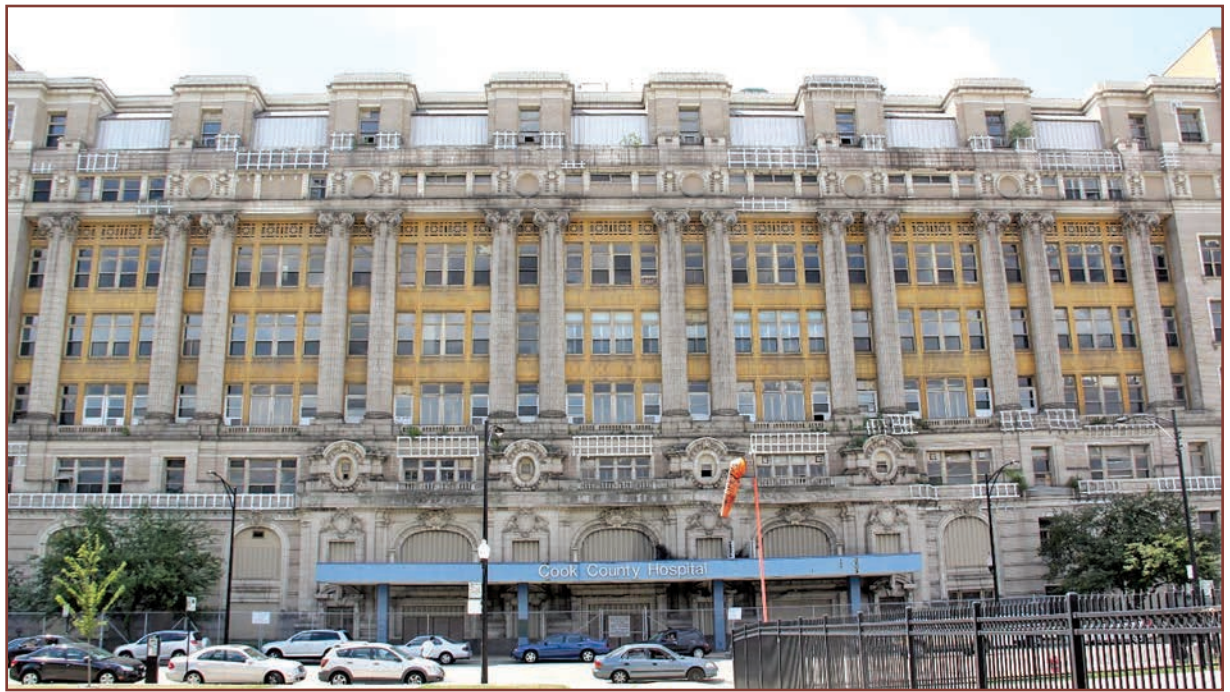


Figure 2. Old Cook County Hospital north facade prior to redevelopment circa 2012.

dition of the facades and the causes of distress, as well as gain a general sense of the order of magnitude of costs for the recommended repairs. The third phase included testing and trials to gain more knowledge of the physical characteristics of representative facade materials, as well as cleaning trials, reviewing existing conditions of the monumental windows for restoration and the existing roofing to provide information for the design of appropriate repair scope.

During Phase 1, which commenced in 2011, a limited on-site assessment of the exterior masonry walls and windows was performed, as required by the City of Chicago Facade ordinance and requested by the county ownership. The assessment included a close-up inspection at representative areas using industrial rope access and review of limited inspection of openings to observe and document concealed conditions from a personnel lift. During the inspection, temporary stabilization and additional site restrictions were recommended to address the hazardous conditions that were observed.

During Phase 2, which was conducted in 2016, a due diligence investigation of the exterior masonry walls and windows, as requested by the redevelopment team, was performed. The investigation included a close-up inspection at representative areas of the north, east and west facades using suspended scaffolding, and limited inspection openings at significantly distressed areas to review and document concealed conditions. At that time,

it was thought that the south facade would be removed and replaced in its entirety with a new wall system.

During Phase 3, which commenced in 2018 as the initial phase of the redevelopment, a review of cleaning systems for the brick and terra-cotta was performed and trials were implemented from grade. A cursory visual assessment was performed of the south facade to determine the extent of masonry repairs, due to design modification and subsequent need to retain and restore the existing cladding on the south facade. Additionally, as part of Phase 3, a review of the existing monumental windows was performed to determine the scope of repairs for restoration of the windows. Phase 3 also included review of the existing roofing and various roof conditions to determine appropriate roofing repairs for main roof, skylights, balcony areas as well as the integral terra-cotta gutter.

Investigation Findings *Terra-Cotta and Brick*

Generally, the investigation revealed that the majority of terra-cotta and brick exhibited deterioration consistent with a cladding material that has been in service for more than 100 years and minimally maintained due to vacancy of the building for the last 15 years and lack of appropriate funding. As expected, distress and deterioration were most pronounced at high-exposure area locations with unrestricted water infiltration resulting in corrosion of supporting steel. These areas included the third floor terra-

Figure 3. Distressed terra-cotta window head unit caused by corrosion of steel anchorages and support at Old Cook County Hospital as viewed during 2011 Phase 1 assessment.



Figure 4. Distressed terra-cotta window seventh floor head units below previously replaced cornice caused by corrosion of steel anchorages poor detailing of retrofit at Old Cook County Hospital as viewed during 2016 Phase 2 assessment.



cotta gutter, projecting balconies, hung terra-cotta elements, and parapets (Fig. 3).

Some of the cracking in the masonry cladding was not exclusively related to corroding steel anchors or shelf angles, but more related to original moisture expansion of the existing masonry and a lack of expansion provisions. Related distress included vertical cracking near the southeast and southwest corners of the south facade, as well as vertical cracking of the terra-cotta clad monumental columns on the north facade.

In addition, distress was occurring at locations of previous incompatible or poorly designed repairs and stabilization efforts, such as the terra-cotta cornice at the seventh floor. The cornice had been previously removed and replaced with a terra-cotta flat spandrel and poor detailing relative to historic sensitivity and water management. The removal process included cutting steel elements flush with the plane of the wall and installing brick and poor replacement terra-cotta around the existing steel. Water management considerations were not taken into account with the detail, thus allowing excessive water infiltration and subsequent corrosion of the supporting steel of the facade components below the repair area (Fig. 4). This approach provided a short-term solution to falling material, but poor detailing resulted in additional water infiltration into the “repaired” wall areas and subsequent development of distress and deterioration.

Some of the additional distress to the brick and terra-cotta was caused by the previous installation of temporary stabilization without sensitivity for eventual restoration of the building. The stainless-steel straps and mesh were installed with ferrous anchors

and through the face of the terra-cotta units and brick elements rather than through mortar joints or other means to limit distress to the masonry units. Corrosion of the ferrous anchors for the stabilization resulted in excessive cracking and spalling of many of the terra-cotta units and brick masonry that could otherwise have been salvaged (Fig. 5).

Mortar

Significant deterioration was observed at the majority of mortar joints between terra-cotta units and the brick masonry, including bond line



Figure 5. View of distress at the terra-cotta masonry exacerbated by previous stabilization efforts with corroding fasteners causing cracking and spalling of the terra-cotta units.

separations, cracking, significant erosion, and missing mortar. Visual evidence of previous repointing at limited areas existed, but no consistent pattern was observed. Most of the horizontal and sloped mortar joints had been previously covered with sealant that had been applied directly over the mortar without proper preparation of the joint.

Rehabilitation Program

The building sits in a prominent visual location along the expressway that provides access to the City of Chicago from the west. In its earlier days it had provided the backdrop for notable films such as the *Fugitive* and the *Dark Knight*, but due to its vacancy and long-awaited fate due to obsolescence as a hospital facility for the county, the building had become an eyesore. Significant atmospheric soiling and organic growth exacerbated by the expressway traffic as well as previous stabilization efforts created a “Frankenstein” appearance and provided a canvas for the local graffiti artists. These factors contributed to the need to repair and clean the exterior facade to restore its original grandeur. Restoration cleaning was limited to the street-facing facades (north, east, and west) while the south facade was “cleaned up” due to the washing of the wall after the numerous masonry repairs and the replacement of the corrugated metal paneling at the old wings with an insulated metal panel curtainwall.

Based on the findings of our investigation and the intent of the adaptive reuse of the building to become a hotel and offices, an exterior repair program was developed. Some of the major challenges with the facade rehabilitation included the significant deterioration and numerous concealed conditions at the brick and terra-cotta cladding due to the lack of previous maintenance and the fact that the building had been vacant for more than 15 years. The challenges also included that the entire adaptive reuse was occurring at the same time and was supposed to move in a west to east direction, based on different turnover dates for certain portions of the building, similar to new construction. This meant that all trades (interior and exterior) were generally trying to work in the same area of the building at the same time. Window and roofing replacement occurred at locations of ongoing masonry repairs, which was further complicated by the long lead time of procuring replacement terra-cotta. An added challenge included coordination of two subcontractors for each aspect of the exterior enclosure repairs due

to county hiring requirements, including one masonry restoration contractor for the repairs on the north, west, and east facades, a different masonry restoration contractor for the south facade, a window replacement contractor, as well as a window restoration contractor and two roofing contractors. This was particularly challenging when considering the work also included typical construction challenges such as maintaining consistent compliance with the restoration approach and approved mock-ups, weather, material availability, and a compressed schedule. It should be noted that for the purposes of this paper, the program described herein only includes the masonry portion of the project. The exterior enclosure rehabilitation also included restoration of monumental wood windows at the north facade, removal and replacement of the double hung wood windows with new aluminum-framed windows to match the historic configuration on the main facades, as well as replacement of all roofing including balconies.

At the direction of the Owner and as defined by the Secretary of the Interior’s Standards for Rehabilitation, the repair approach for Old Cook County Hospital facade rehabilitation was to develop a design that would address the most significant deterioration, create a watertight building, and provide restoration of certain historically significant elements as outlined by the City of Chicago Department of Landmarks and the National Park Service, along with the Illinois Historic Preservation Agency and the state historic preservation office to receive tax incentives. It was understood that lower-priority repairs and maintenance would be completed when the building was occupied and able to generate revenue to pay for future repair expenditures. As such, the approach taken by the rehabilitation designers was to address the visible repairs and existing distress conditions, rather than the preferred comprehensive repairs to address detailing at similar locations. This approach helped to limit the amount of replacement material but did not address concealed conditions at areas currently not exhibiting distress; therefore, a more rigorous regular maintenance was

recommended on the building enclosure than had a more proactive comprehensive approach been undertaken.

Repair recommendations typically corresponding to the scope of work below were presented to ownership based on the conditions observed during our investigations, the expected rate of continued deterioration, and the appropriate repair and restoration approaches according to the Secretary of the Interior’s Standards for Rehabilitation, given the historical significance of the building. The high-priority repairs were considered critical repair issues to address the significant deterioration observed. The lower-priority repairs were conditions that were addressed to minimize the potential of future distress to develop into conditions that endanger public safety, as well as improve the overall appearance of the building when required for historic preservation incentives.

Based on the multiphased investigation, the defined rehabilitation intent, and the historic preservation incentives, as well as the need to address applicable concealed conditions where distress was observed, the following scope of work was completed as part of the exterior facade rehabilitation. The repair scope was divided based on different priorities, including addressing hazardous conditions, reducing water infiltration, addressing fire and life safety code requirements, and improving aesthetics.



Figure 6. Installation of terra-cotta units at monumental columns at the north facade during rehabilitation in 2019.

Hazardous Conditions

- Repaired the brick, stone, and terra-cotta masonry on all facades. The brick, stone, and terra-cotta units that were deteriorated beyond repair were replaced in-kind. This also included the removal and rebuilding of select areas with salvaged units. Approximately 10,000 ft² of brick were removed and replaced or reinstalled. Granite units were replaced at the base of the building as necessary. Approximately 4000 terra-cotta units were removed and replaced. Approximately 10,000 additional units were removed and reinstalled as part of the repairs to address the underlying steel (Fig. 6).

- Reconstructed terra-cotta gutter at the third floor of the building on the north, east, west, and south return facades. This included replacing steel shelf angle and all anchorages, replacing deteriorated terra-cotta with new replacement terra-cotta, reinstallation of salvaged terra-cotta, and installation of a new gutter liner (Fig. 7).
- Rebuilt deteriorated brick masonry on south facade with salvaged or replacement brick.



Figure 7. Reconstruction of the third floor gutter and installation of terra-cotta units at the north, east, and west facade during rehabilitation in 2018–2019.

Reduction of Water Infiltration

- Full repointing of the north, east, and west facades.
- Zone repointing the south facade, which included approximately 40% of the area (that with the most significant deterioration).
- Installed new roofing at all roof and balcony areas.

Code Requirements

- Repaired/replaced entrances on north, east, and west facades to closely match configuration and profiles of the original doors and sidelights, and replicated any missing doors at those entrances based on historic drawings and photographs.
- Introduced two new entrances that closely match historic configuration and profiles within existing openings on north facade to accommodate new retail and commercial uses.
- Introduced new entrances as needed on the south facade to accommodate new retail and commercial uses.
- Replaced wood windows, which were either missing (i.e., previously infilled or with significant alterations to the sash) or deteriorated beyond repair with new aluminum windows that match the historic windows in configuration, size, and profiles.
- Removed masonry infills from historic window openings to restore fenestra-

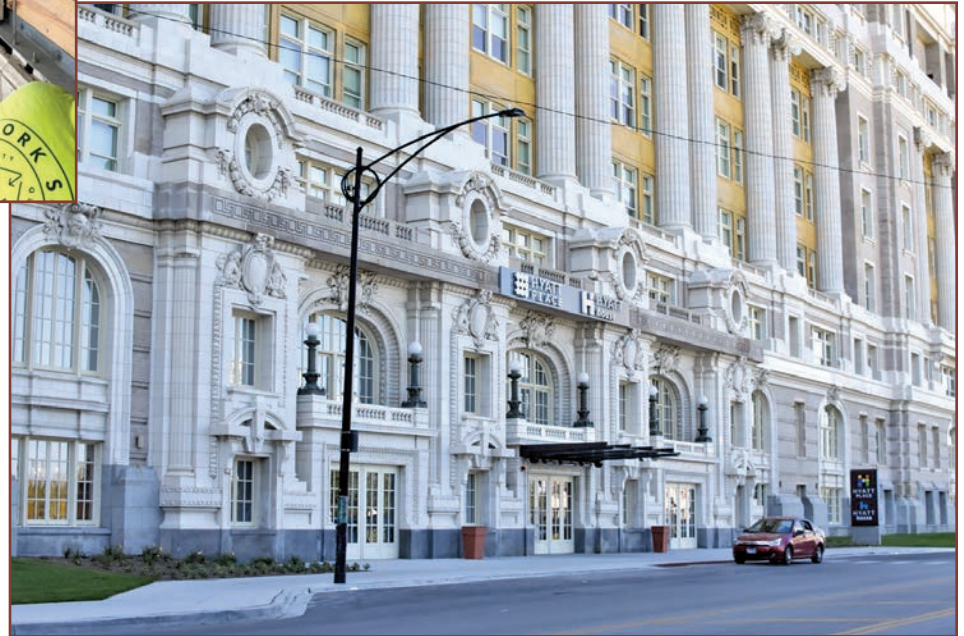


Figure 8. Overall view of main entrance on the north facade following completion of the rehabilitation. Note the restored monumental windows and the salvage and reinstallation of the terra-cotta lanterns.

tion pattern and installed new aluminum windows in the original openings.

- Restored monumental wood windows on the north facade at the second and third floors (Fig. 8).
- Removed interior clay-tile backup at exterior walls to address mechanical, electrical, and plumbing code issues, which required adjustments to provide code-required anchorages for the replacement window installation.

Improvement of Aesthetics

- Cleaned the existing brick, terra-cotta, and stone masonry with a two-part chemical cleaning system on the north, south, and west facades (Fig. 8).
- Removed nonhistoric metal paneling at the former pavilion locations and nonhistoric 1959 infill on the south

facade, and installed new metal panels and windows in these areas.

- Added new architectural accent illumination and reused existing historic fixtures as appropriate.

30TH STREET STATION (PHILADELPHIA, PENNSYLVANIA)

Built during the Great Depression, 30th Street Station once housed the headquarters of the Pennsylvania Railroad and has served as Philadelphia's principal rail passenger station since its completion in 1934 (Fig. 9). The neoclassical design of the building's exterior reflects a "modern" interpretation of the classical style. This structure is one of the last surviving American "gateway" transit buildings.



Figure 9. Photo of original construction of 30th Street Station in Philadelphia, PA.

Situated on the west bank of the Schuylkill River, the station was planned during the mid-1920s by the Pennsylvania Railroad Company in partnership with the City of Philadelphia. As constructed, the building is cruciform in plan, with the long axis running north to south, parallel with the Schuylkill River for 640 ft. The rectangular volume of the Main Passenger Concourse, 135 ft wide, nearly 330 ft in length, and over 100 ft high, bisects the north-south axis in line with John F. Kennedy Boulevard, and presents an imposing facade to downtown Philadelphia. The structure is a steel and concrete frame with brick masonry infill walls, faced with coursed, buff colored Alabama limestone that sits on a continuous horizontal base of pink granite. The station is built entirely on an elevated deck, which allows the Amtrak rail lines and the adjacent Schuylkill Expressway to pass freely underneath. Caissons support the entire structure, transferring the loads of the station and parking deck through isolation pads down to bedrock, some 80 ft below.

The original main pedestrian entrances are located at either end of the concourse, screened behind the six composite order columns of each portico. The entrances consist of paired copper alloy and glass doors framed by decorative granite surrounds. The verticality and scale of the limestone clad portico columns is complemented by the repetition of glass, steel window, and cast-iron curtain wall bays that punctuate the limestone walls at regular intervals. The facades are further unified architecturally by an entablature composed of a classically proportioned architrave, frieze, dentil band, and block cornice, and crowned by substantial attic walls. A coffered terra-cotta soffit defines the ceiling space of the east and west porticos.

The cross-axis volume of the concourse rises above the height of the main north-south section of the building and is further defined by a second, more decorative modillion cornice and deeper attic walls, which rise to form the parapet for the roof above. The north and south faces of the upper attic have a series of false terra-cotta screens just above the cornice. The four long axis corners of the building are emphasized by slight articulations of the facade, wider window bays, and the integration of secondary pedestrian entrances.

The north and south facades duplicate the design and rhythm established on the primary facades, including the repetitive curtain wall bays and classical entablature. The outer face of the viaduct walls at the north end of the

building is treated in much the same manner as the rest of the building, punctuated in a regular pattern with sections of cast iron, steel, and glass curtain wall and crowned with a classical entablature, but rising only two stories in height and lacking the attic walls above.

Two internal light courts exist immediately adjacent to the north and south walls of the Main Passenger Concourse. The light courts extend from the second floor to the fifth floor and are clad with beige header bonded brickwork, hung limestone lintels, and limestone sills, with solid steel double-hung windows in punched openings. The adjacent concourse facades are characterized by clerestory bays of cast-iron curtain wall set between brick clad piers.

The south, east, and west facades of the building are constructed of Alabama limestone that is supported at each floor line by steel shelf angles riveted to steel clips that are in turn riveted to the perimeter spandrel beams. The wall system is solid masonry and typically consists of limestone units that were laid integrally with the brick backup wall or to the concrete encasement around the steel columns and spandrel beams. There are typically several courses of limestone units between shelf angle locations. The thickness of each of these ashlar courses alternates between 4 in. and 8 in. with the thicker units keyed into the brick backup wall. This system, by using 8-in.-thick units, provides lateral restraint for the flat portions of the limestone walls. Decorative projecting courses near the top of the building are also thicker and intermittent lateral steel strap anchors were used to restrain the pieces from rotating during installation. Historic research suggests that the cladding stone used in the construction of the station is a domestic oolitic limestone in two color-tones: "buff" and variegated, of either "standard" or "select" grade.

Limestone soffits are located between piers throughout the building. These soffits are hung from continuous steel members that span between the piers. The configuration of the steel varies, but generally consists of built-up beams, channels and angles. The soffits are hung from a series of eye-bolts in the head joints between units with rods that span between adjacent units. The eye-bolts extend through horizontal legs in the steel members above.

The north facade is constructed with a similar system, but in general the unit thickness is thinner than the other walls, resulting in the shelf angles and lateral straps being closer to the exterior surface of the units. A continuous shelf angle extends at approximately

the midheight of the piers and above the hung soffit units on the north facade. Two lateral stability anchors were installed in the units supported by the shelf angle. The remaining courses presumably alternate thickness similar to the other areas of the facade. The interior surface of the north facade is exposed to the train platform, creating a false wall.

The evaluation of the 30th Street Station exterior facade consisted of three primary phases. The initial phase was intended to understand the construction and design of the building, particularly the exterior facades. The second phase was an on-site investigation to gain a general sense of the condition of the facades and the causes of distress. The third phase was a testing phase to gain more knowledge of the physical characteristics of representative facade materials to provide information for the design of appropriate repairs. The following is a more detailed description of the various tasks performed during each of the three phases described above, specifically related to the stone cladding.

Phase 1 included tasks to become familiar with the general composition of the exterior cladding systems and any specific work previously performed on the exterior enclosure. During this phase we performed the following tasks.

- Reviewed available original drawings provided by Amtrak.
- Reviewed available previous pertinent reports and repair documents provided by Amtrak.
- Performed research at the Philadelphia Historic Commission regarding previous projects related to the exterior of the building. No significant documents were found during our research.
- Performed a limited search of historic architectural journals for published articles pertaining to the design and construction of 30th Street Station. Limited information was found, primarily dealing with the interior of the building and general facade information.
- Performed archival research at the Chicago Historical Society, the depository of many of the drawings by Graham, Anderson, Probst & White. No additional drawings beyond those in Amtrak's archive were found.
- Performed archival research to identify historical materials and building components, including stone, brick, windows, and the curtain wall.

During Phase 2, an on-site investigation of the exterior masonry walls, steel windows, and cast-iron curtain wall system was performed. The investigation included a close-up inspection at representative areas and inspections of openings at selected areas to observe and document concealed conditions.

The investigation was performed using a combination of access techniques. Suspended scaffolding was used to access the interior light courts. Personnel lifts were used to access the portico ceilings and accessible areas of the primary limestone facades. Inspection of less accessible areas of the light courts was performed using industrial rope access.

Masonry inspection openings were made to understand the condition of the concealed materials and in the development of appropriate repairs. Material samples were extracted at this time for laboratory testing during Phase 3.

A review of potential cleaning systems was also conducted and included trial cleaning of the limestone facade from a penthouse roof on the southeast fifth floor roof, on grade at the viaduct, and on grade at the West Portico, to determine the effectiveness of various cleaning techniques.

Phase 3 consisted of limited laboratory analysis of various materials performed to identify likely causes of distress and to ensure that appropriate repairs are recommended that will not damage, alter the appearance of, or reduce the potential for performing future work on the building's facades. Testing included limited petrographic analysis and physical testing of the face brick and limestone to define material characteristics. A limited petrographic and chemical analysis of mortar samples was also performed to determine the mortar's composition and character and to assist in designing an appropriate proportion for repointing and setting mortar.

Investigation Findings

Limestone and Brick

Generally, the investigation revealed that the majority of limestone and brick exhibits deterioration consistent with a cladding material that has been in service for more than 80 years. As expected, weathering of the limestone is most pronounced on horizontal surfaces such as the tops of copings and projecting cornice elements. Some cracking exists in the limestone that is not related to corroding steel anchors or shelf angles. These areas include vertical cracking in the limestone on the east and west pavilions. In addition, cracks in some of the other ashlar units were noted with no

discernable pattern throughout the rest of the facade areas. The majority of the large hung soffit panels in the light court areas are cracked near the bearing points at the piers. The typical soffit arrangement consists of three individual hung units. The center unit is supported from the structural system above, while the end units are hung from this same structure, but also bear on the adjacent pier. Spalling was also identified at shelf angles and lateral anchor locations. The majority of this spalling was observed on the north facade adjacent to Arch Street and the units directly below the projecting cornice units around the perimeter of the main portion of the building. Some spalling corresponded to wood shims that had been left in place during the original construction. Spalling at shelf angle locations corresponded to the toe of the horizontal leg of the shelf angle where the edge of the angle ("toe") was relatively close to the face of the limestone and the presence of some corrosion scale.

Petrographic analysis of the limestone revealed that the stone is an oolitic-fossiliferous stone with calcite, minor amounts of quartz, and traces of clay. Physical testing of the limestone revealed that, based on the density of the limestone and water absorption, the limestone conforms to a category II, medium-density limestone.

Isolated areas of dark "crusts and dirt accumulation" existed on the limestone at projecting assemblies such as the cornice and other concealed areas (i.e., dentils, brackets, and column capitals). Dark microbiological algae growth was identified near the parapet walls and the horizontal portions of the limestone cornice. Several iron inclusions and stains were observed at isolated areas throughout the limestone facades.

The brick exhibited cracking and displacement in the light courts as a result of corrosion of supporting shelf angles corresponding to the top of the windows at each floor. These conditions also extended to the light court parapets. The inside wythe of brick at the majority of parapets exhibited indications of freeze-thaw damage.

Mortar

General deterioration was observed at the majority of mortar joints between limestone units including bond line separations, cracking, and missing mortar. Visual evidence of previous repointing at limited areas was noted, but no consistent pattern was identified. Most of the horizontal and sloped mortar joints had been previously covered with sealant. The sealant was

applied directly over the mortar and the joint was typically not properly prepared. Chemical testing of the mortar revealed that the mortar consisted of a mixture of slag cement, hydrated lime, and sand, consistent with slag cement-hydrated lime mortars of the period.

Restoration Program

Based on the findings of our investigation and the application of the Secretary of the Interior's Standards for Restoration, a phased prioritized restoration program was developed. One of the major challenges with the facade restoration at the building was that the entire building was to remain open throughout the work. This included offices, restaurants, commercial spaces, and, most significantly, full train operations for three different rail lines that interfaced with the station. This was particularly challenging when considering the work also included typical construction challenges such as weather, noise, and dust, as well as hazardous material abatement for the masonry work (including removal of lead paint for the cast-iron recoating and sealants containing PCBs for the window restoration), odors from new coatings and sealants, and removing windows for restoration as well as areas of window replacement. It should be noted that for purposes of this paper, the following program description includes only the masonry portion of the project. The restoration also included restoration of the cast-iron curtain wall and steel windows on the main facades and concourse as well as window replacement in the light courts.

At the direction of Amtrak, the approach for 30th Street Station facade restoration was to develop a 50- to 75-year design. The potential for ongoing maintenance and the likelihood of additional funding in the near-term for repairs were generally recognized to be improbable. As such, unlike the previous case study, the approach taken by the designers was to address the repairs based on details rather than visible and existing distress. Thus, if distress was noted at specific shelf angle elevations, the entire length of angle would be repaired rather than only areas exhibiting distress. This approach helped to limit issues related to matching existing stone, provided a more uniform appearance, and reduced the amount of long-term maintenance that would be required.

The following prioritization of the recommendations was presented to Amtrak based on the conditions observed during our investigation, expected rate of continued deteriora-

tion, and appropriate repair and restoration approaches given the historical significance of the building. The highest-priority repairs are those that were considered critical repair issues. The second-highest-priority repairs are conditions that were addressed to minimize the potential of future distress to develop into a condition that endangers public safety. Finally, the lowest-priority repairs were considered maintenance and aesthetic issues. These repairs will minimize the potential of future distress developing and improve the overall appearance of the building.

Based on the investigation, the following scope of work was considered the highest priority:

- Spalled areas of limestone adjacent to corroded steel lateral straps. For smaller units, the repair included removing the limestone unit with the spall. Following removal of the stone, the remaining area of the lateral anchor was ground flush with the surface of the backup brick. A new matching limestone unit was installed with new stainless-steel anchorage components. Spalled areas on larger units were repaired in a similar fashion, except that the spalled area was removed over the height of the unit and a dutchman, or partial unit, was installed with stainless-steel lateral anchors.
- Spalls, displacements, and cracking of limestone at shelf angle locations. This repair included removing the limestone units that bear on the shelf angle. The existing shelf angle was cleaned and painted with a corrosion-inhibiting system, or the angle was replaced if the corrosion resulted in significant loss of cross-section area. For shelf angles that remained in situ, the mortar joint below the horizontal leg of the angle was ground out to provide access to the bottom side of the horizontal leg of the shelf angle. Replacement limestone units, or the existing limestone, was installed on the repaired or replaced shelf angle with stainless-steel lateral anchorage. The angles were protected by applying both a corrosion-inhibiting coating as well as a flexible membrane flashing (Fig. 10).
- Cracked limestone soffits were repaired by removing the limestone units set on the shelf angle before removing the units that are hung from the steel structure above. The existing

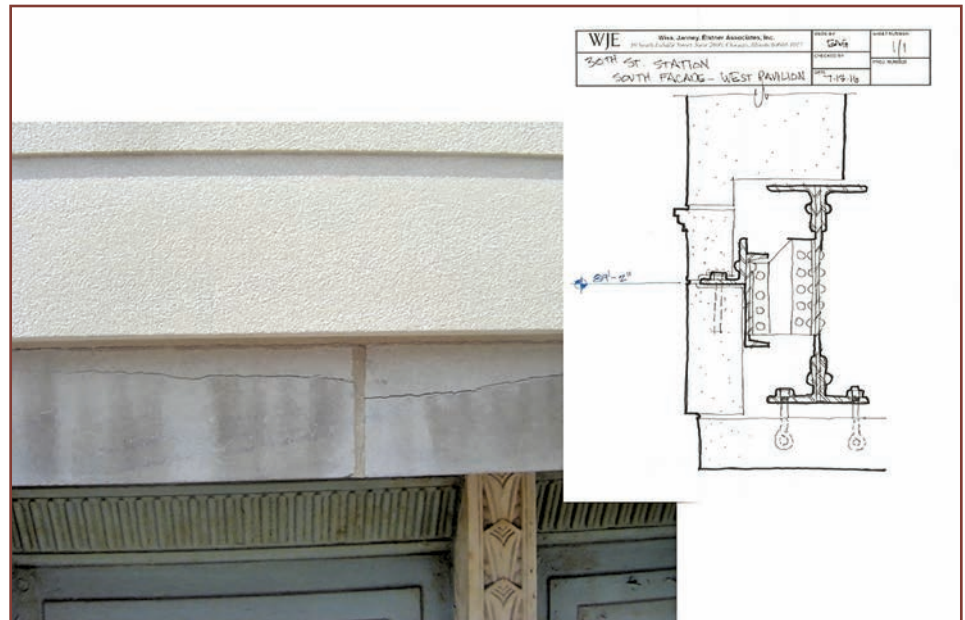


Figure 10. Typical cracked condition at the limestone soffit units at 30th Street Station, including field sketch of the existing condition.

shelf angle and exposed areas of the supporting steel were treated as previously discussed and a new unit was installed supported by stainless-steel anchors (Fig. 11).

- Deteriorated and displaced brick and the limestone lintels at the continuous shelf angles at the top two floors of the light courts were removed and replaced. Substrate steel was cleaned and painted, and a flashing system was installed on the shelf angles. Matching brick and new limestone lintels were installed with stainless-steel anchors.
- Light court parapets were reconstructed, including installing through-wall flashings below the coping and cleaning and painting concealed supporting roof beams.
- Deteriorated brick on the inside wythe of the south parapet wall was replaced and similar repairs were also performed on the brick piers on the other parapets at main roof areas.

Based on the investigation, the following scope of work was considered medium priority:

- Cracks that were not related to corrosion in the limestone were repaired by routing the crack and installing mortar into the joint in three ¼-in. lifts of mortar.
- Cracks that were related to thermal or structural movements in the limestone on the main facade were routed and

backer rod and sealant installed with ground limestone broadcast into the finished surface of the sealant to minimize visual impact.

- Cracks related to thermal or structural movements in the limestone that were not on the primary facades were routed as previously described, and a backer rod and sealant installed in the joint.
- Cracks related to corrosion of underlying steel supports or anchors were partially or completely replaced following repair of the underlying corroded steel.



Figure 11. Installation of replacement stone at shelf angle location at 30th Street Station.



Figure 12. Repointing effort at the limestone at the 30th Street Station.

Figure 13. Water misting cleaning at the limestone soffits at the main facades of 30th Street Station.



- Mortar joints between limestone units were all repointed (Fig. 12).
- Sealant and lead tees were installed in upward-facing mortar joints between limestone units.

The following scope of work was considered maintenance and the lowest priority:

- The limestone was cleaned using a water misting system in combination with biocide treatment to minimize accelerated limestone deterioration and improve the appearance of the building's primary public facades (Fig. 13).

- Inclusions in the limestone are being monitored as part of the ongoing maintenance of the facade. No repairs or treatment of the inclusions is determined to be necessary until a crack or spall has manifested itself.

Initially, Amtrak requested that the facade restoration work be phased based on priority because funding potential was not known and frequently varied based on emergency needs at other Amtrak facilities. Funding finally

became available in 2012, more than seven years after the documents were prepared. A follow-up inspection was performed to update and reprioritize the repairs as necessary. Based on the conditions observed during the follow-up inspection, numerous conditions that had been considered medium priority in 2005 were reprioritized to high priority in 2012. In

addition, some of the conditions that had previously been classified as high priority had deteriorated to a point that sidewalk protection was recommended and installed around the majority of the publicly accessible areas of the exterior of the station (Fig. 14).

CONCLUSION

Regardless of the extent of investigation and inspection in a facade project, all repairs cannot be anticipated, and all distress cannot realistically be observed and documented. As such, unanticipated conditions are inevitable. These can include concealed conditions that



Figure 14. Overall view of completed rehabilitation of the east facade of the 30th Street Station in 2018.

differ from the original contract documents, concealed distress, and load redistribution resulting in distress from repair operations. These conditions can be anticipated to some extent based on experience with similar buildings, but surprises are inevitable. Contractually, unanticipated conditions can be addressed by including unit costs and potential quantities for anticipated repairs and including a lump-sum contingency. In the case of Old Cook County Hospital, a contingency was recommended, but was controlled and used at the discretion of the general contractor, rather than the design professional and masonry subcontractor. By contrast, establishing a lump-sum contingency was not allowed for 30th Street Station because Amtrak is a quasi-governmental entity. Therefore, unit prices, potential quantities, and contingency unit prices were included in the bidding process.

As shown by the two exemplars presented, preservation of masonry facades requires design professionals to manage and balance a combination of many considerations, including existing conditions, historic preservation issues, code requirements, budget, unforeseen conditions, client expectations, and available funding. The selection and application of an appropriate treatment as defined by The Secretary of the Interior's Standards for the Treatment of Historic Properties, including the varied approach between preservation, restoration, and rehabilitation as illustrated in the examples presented herein, is another consideration in determining an appropriate scope of repairs. The application of specific treatments requires the preservation professional to understand when it is appropriate to replace undamaged original fabric to minimize future distress, while managing the client's expectations with regard to budget and tax incentives. Nevertheless, as demonstrated, there are multiple approaches to working within the Standards while meeting client's expectations, to provide successful rehabilitation or restoration facade projects that require the ability to prioritize, balance, and reassess goals as necessary throughout the project (Fig. 14 and 15). 

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Figure 15. Overall view of completed rehabilitation of the north facade of the Old Cook County Hospital in 2020.

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It Takes a Village: Building Enclosure Mentoring of Architecture Students

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International Institute of
Building Enclosure Consultants



2021 IIBEC International Convention & Trade Show

Phoenix, AZ | September 15-20, 2021

ABSTRACT

Architecture students need individualized support from faculty and mentors to learn about building enclosures in preparation for internships and practice. While imparting this knowledge is challenging in the best of times, it is even harder during a pandemic. In this paper, I recount the process and outcomes of the IIBEC Mid-Atlantic and Virginia Chapters' Student Design Competition held at Virginia Tech's School of Architecture + Design (SA+D) immediately after the shift to online learning in March 2020. Surprisingly, this seventh competition of its kind produced the most-detailed work yet. This result is likely due to the unprecedented dedication of IIBEC members serving as mentors and jurors, the individual attention afforded to each student, and the pointed interaction of students and mentors through the marking up of drawings in real time. I share two final student submissions along with insights gleaned from the mentoring sessions. While SA+D values self-directed learning, the students greatly benefited from the specific input from mentors on their design projects, conveying knowledge that they would not have otherwise gained in school. These insights will be of interest to building enclosure consultants, emerging professionals, and IIBEC chapter leaders looking to initiate similar student competitions as service and outreach efforts.

SPEAKER



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Elizabeth Grant, PhD, RA, is an associate professor at the School of Architecture + Design at Virginia Tech. She is a registered architect, a member of IIBEC, and the associate director of the Center for High Performance Environments. Grant's book, *Integrating Building Performance with Design: An Architecture Student's Guidebook*, was published by Routledge in 2017. She has also published in *Interface*, the *Journal of Architectural Engineering*, the *Journal of Green Building*, *Professional Roofing*, and *Architectural Science Review*. She holds two patents for an omnidirectional roof vent and is active in research critical to roofing design.

It Takes a Village: Building Enclosure Mentoring of Architecture Students

BUILDING ENCLOSURE EDUCATION IN ARCHITECTURE

In my 12 years as a full-time architecture professor at Virginia Tech, as well as my 10 years as an architecture student, I have become aware of a troubling lack of focus on the building enclosure in architectural education. As exemplary evidence of this, I offer the following excerpt from an email I received about an assignment I recently gave to third-year undergraduate architecture students. In this assignment, I asked students to present a design project, ideally their current design laboratory project, using plans, elevations, sections, details, and renderings or photographs sufficient to depict its form, general program, and materiality. They were asked to focus particularly on describing the thermal enclosure and its thermal characteristics. In response to this charge, one student emailed me the following, late one evening:

In short, I feel like it's such a DIFFICULT assignment. And I certainly need some help. In my past projects, I found myself putting little concern towards insulation and thermal comfort factors. So if I choose to work with [a past project], I need to put a lot of effort into the alteration of the building. (And it could be a BIG alteration.)

As for my current project, it's still in the very beginning stage of design. I am not sure if I am able to pull off the final design and get the drawing and rendering done when it's due....I indeed prefer to work with my current project. This assignment will really benefit the design in the end. But I am worried about the amount of work I need to do to make it possible.

This student was not merely trying to “get out” of the assignment; I subsequently met with him via video conference and he was genuinely concerned about his capacity to understand thermal, moisture, air, and vapor control layers sufficiently to depict them, even in a schematic form, for a small preschool building he was designing for an assignment

due some three weeks hence. His concern is not unique, and is the result of an architectural education system that does not prioritize this form of knowledge.

Students Avoid the Building Enclosure

Students often avoid drawing wall sections or details until required to do so by professors, and I hypothesize that this is because they are embarrassed about their lack of knowledge about building assemblies and would prefer not to draw attention to this shortcoming. In addition, they are flooded daily with images from websites such as Dezeen, ArchDaily, Architizer, and even *Architectural Record* that show walls and roofs as black poché, in articles that showcase chiefly the broader contextual and aesthetic features of architectural projects rather than their material characteristics. I am beginning to believe that many architecture students think, perhaps quite fairly given their cultural and institutional influences, that they are in school primarily to learn how to create atmospheric images of buildings, rather than drawings intended to convey critical information about how buildings are to be built. Both are surely important, but the former capacity is increasingly suffocating the latter.

I recently had a conversation with a faculty colleague who sympathizes with the need for more education about building enclosures. I told him that I teach third-year undergraduate students about Joe Lstiburek's “perfect wall”;¹ for instance, in my Environmental Building Systems course I compel them to read the “BSI 001: The Perfect Wall” article in class and ask them test questions about it. He and I agreed that these same third-year students, when asked to apply these concepts to their own designs, throw what they

have learned out the window in frustration because they have no idea how to do so. As my colleague remarked, when looking at a high-performance wall detail in an IIBEC conference proceeding, an *Interface* article, or John Straube's *High Performance Enclosures*,² students say, “but that's not *my* building.” There is a strong bias, particularly amongst the senior faculty of the school, against adapting even well-vetted details from other sources, in favor of creating one's own designs from scratch. Some professors have gone as far as mocking those who use Francis Ching's *Building Construction Illustrated*³ and other helpful sources, calling these “crutches.” Fortunately, this is not a consensus opinion, and I and some of my fellow faculty have been able to advocate for such “crutches” as support for creative activity, not a stifling of it.

I am beginning to believe that many architecture students think, perhaps quite fairly given their cultural and institutional influences, that they are in school primarily to learn how to create atmospheric images of buildings, rather than drawings intended to convey critical information about how buildings are to be built.

No.	When competition was held	Mentors	Convention or other forum for presentation
1	Fall 2012 semester	Mario Cortes, Elizabeth Grant, Matthew Innocenzi, James Jones, Michael Violette	Mid-Atlantic Chapter Educational meeting, November 8, 2012; 30th RCI International Convention and Trade Show, San Antonio, Tex.
2	Fall 2013 semester	Elizabeth Grant, Matthew Innocenzi, James Jones	30th RCI International Convention and Trade Show, San Antonio, Tex.
3	Spring 2015 semester	Elizabeth Grant, Matthew Innocenzi, Mark McConnel, Michael Violette	33rd RCI International Convention and Trade Show, Houston, Tex.
4	Spring 2016 semester	Patricia Aguirre, Derek Cundiff, Matthew Innocenzi, Peter Ozolins, Michael Violette	33rd RCI International Convention and Trade Show, Houston, Tex.
5	Spring 2018 semester	Derek Cundiff, Michael Hebert, Julie McDonald, Richard Wagner	
6	Spring 2019 semester	Derek Cundiff, Daniel Lemieux, Michael Violette	
7	Spring 2020 semester	Derek Cundiff, Matthew Schofield, Sam Zalok, Derek Ziese	2021 IIBEC International Convention and Trade Show, Phoenix, Ariz.

Table 1. The seven RCI/IIBEC MAC and VA Chapters' Student Design Competitions to date

THE IIBEC MID-ATLANTIC AND VIRGINIA CHAPTERS' STUDENT DESIGN COMPETITIONS

The IIBEC Mid-Atlantic and Virginia Chapters' Student Design Competition is the latest manifestation of a competition that has been steadily evolving since its inception in 2012. The competition was first envisioned by members of RCI Inc. who hoped to inculcate a special interest in the building enclosure in college students by exposing them to RCI members in a mentoring capacity. An initial meeting at the 27th RCI International Convention and Trade Show, in Dallas, Texas, led to a collaboration amongst Elizabeth Grant, Matthew Innocenzi, and Michael Violette to develop a competition prompt and determine how best to share the work with RCI members and others.

Table 1 details the timing of past competitions, the mentors who contributed each year, and the papers and presentations that have been generated to relay the outcomes of the competitions to RCI (and subsequently, IIBEC) members and the university community. Gaps in the sequence occurred when I could not hold the competition because I was not teaching an appropriate group of students, which needed to be third- or fourth-year architecture students. Over the years, some continuity was preserved amongst jurors, while introducing fresh faces. There has been an ongoing effort to balance consultants with training primarily as professional engineers with those who have been trained as architects, as well as to provide gender balance in the mentoring team whenever possible. In 2016, I dropped off the mentoring team to avoid any conflicts of interest involving the grading of the overall architectural design lab in which it was situated. When the Virginia Chapter of IIBEC was established in 2019, the subsequent competition was supported by both the IIBEC Mid-Atlantic and Virginia Chapters, as Virginia Tech students are frequently connected with regions served by both.

This paper focuses specifically on the outcomes of the

AND I MYSELF ON A SWIFTLY TILTING PLANET

IIBEC Mid-Atlantic and Virginia Chapters Student Design Competition • Architecture III • Spring 2020

In this competition you will revisit the Research Center for Climate Change and Sea Level Rise you designed in the first half of the semester, expanding on your initial ideas about a high school designed to support and complement the collaborative effort required by all individuals involved in research related to climate and sea level rise.

In this next phase of the work, you will further investigate and express the building's integrity in a physical and a metaphorical sense.

Judging Criteria

- Articulation of the building section
- Coordination and consistency of the drawings individually and collectively
- Clear rendering of materials
- Constructability and consideration of the forces of gravity and nature
- Accessibility and code compliance

Site

Your site is bounded by College Avenue, Draper Road (less the TOTS building), W. Roanoke Street, and Oley Street.

Presentation Format

(3) 36" x 20.25" PDF boards (16:9 ratio for widescreen presentation), combined into one PDF document; total file size 100 MB maximum. Each student will present on Zoom for 5 minutes, with 2 minutes for juror questions.

Sponsor

This competition is supported by the IIBEC Mid-Atlantic Chapter and the IIBEC Virginia Chapter, both Affiliated Chapters of IIBEC. The International Institute of Building Enclosure Consultants (IIBEC) is an international association of professionals who specialize in roofing, waterproofing, and exterior wall specification and design.

Required Drawings and Photographs

- Wall Section(s) at 3/4" = 1'-0" minimum
- Building Section(s) at 1/8" = 1'-0"
- Floor Plan(s)
- Roof Plan
- Elevations
- Building details at 3" = 1'-0"
- Photographs of existing model at 1/32" = 1'-0"

"When you design a building, you start from a general philosophy, and you come down, and you start from detail and come up. Only the theoretical architect believes that you can make the concept and then sometime, somebody will come to build it." —Renzo Piano

STAND BEFORE A GLASS AND TIE MY TIE

Figure 1. The brief for the seventh competition, held in spring 2020.

Note: 1" = 1 in. = 25.4 mm; 1' = 1 ft = 0.305 m.

seventh competition, which was anomalous in that it was conducted completely online.

THE SEVENTH COMPETITION

The seventh competition (**Fig. 1**), held in the spring of 2020, was titled “And I Myself on a Swiftly Tilting Planet,” a quote from a poem by Conrad Aiken called “Morning Song From ‘Senlin,’”²⁴ and featured an image of a swirling hurricane hovering off the coast of the United States. This was intended as a visual manifestation of climate change, but ended up being more symbolic of a different kind of maelstrom. When envisioning this competition, I had no way of knowing a virus of pandemic proportions was about to change the way it, as well as most other aspects of life, would be conducted starting in March of 2020.

The competition called for students to revisit the schematic designs for a Research Center for Climate Change and Sea Level Rise that they had developed in the first half of the spring semester as part of a competition held by the Virginia Chapter of the Association for Learning Environments (VA4LE). This initial VA4LE competition was focused on the creation of a high school designed to support and complement the collaborative effort required by all individuals involved in research related to climate change and sea-level rise. The school in question was a theoretical project with some practical underpinnings, thanks to the development of a program by members of the VA4LE. It was described as a research center: a specialized facility that would serve as a regional site for exploration and research, serving all local high schools. It was intended as a facility geared to specific study by a group of 160 students per semester, students who would apply to the program and who would have to meet certain criteria for enrollment.

The site for the competition was in downtown Blacksburg, in one of the liminal spaces between Virginia Tech and the town itself. It was bounded by College Avenue, Draper Road (minus a building containing a popular student bar, which of course was off-limits for virtual demolition), West Roanoke Street, and Otey Street. It comprised 6.12 acres as bounded in yellow in **Fig. 2**. Part of the site fell within a Special Flood Hazard Area, subject to inundation by the 1% annual chance flood, though no base flood elevations were identified within the site. The students had to address this parameter in their responses. The existing buildings on the site could be demolished, preserved, or modified as the students preferred.

The envisaged school was much smaller

than the typical high school in the region, at 24,150 gross square feet. While it lacked a gymnasium, auditorium, and large cafeteria (containing a small café instead), it did include dedicated lab spaces and classrooms for global warming, atmospheric pressure research, and marine and limnology research. The brief also called for spaces that encourage individual, small-group, and large-group creative activity, as well as collaboration amongst students. Spaces were to allow for impromptu interaction of students within the program, and be flexible and support a variety of activities. The resulting school buildings developed by the students for the VA4LE competition were expressive and creative, and in many cases addressed the stream currently buried in stormwater drainage pipes beneath the parking lot, daylighting it and making it accessible to the high school students for study. To enhance their understanding of flood protection, students attended an educational session titled “Floodplain Design, Construction, and Impacts on Flood Insurance” by Kurt Luecke of Smart Vent Products Inc. As a result of a review of the site during that session, their designs were constructed at an elevation at or above 2051 ft, at least 1 ft above the lowest adjacent grade to remain safely out of the 100-year flood zone.

The IIBEC Mid-Atlantic and Virginia Chapters' Student Design Competition required students to expand on their initial ideas about the school. This entailed their further investigating and expressing the building's integrity in the physical and metaphorical sense. More specifically, they were asked to consider the following parameters, which also served as judging criteria for the jury at the competition's close:

- Articulation of the building section
- Coordination and consistency of the drawings individually and collectively
- Clear rendering of materials
- Constructability and consideration of the forces of gravity and nature



Figure 2. Site plan for the seventh competition.

- Accessibility and code compliance

The deliverables for the competition were changed slightly when the competition moved to an all-online format. While a massing model of the project was initially required at a scale of $\frac{1}{32}$ in. = 1 ft 0 in., this was deemed impractical due to the fact that many students had to move home quickly and lacked access to modeling materials during quarantines in their home states. The massing model was made optional. Some did attempt a model from materials on hand, and these efforts helped both students and mentors better envision the overall design ideas the students presented. The revised requirements for virtual presentation boards were as follows:

- Three 36 in. $\times$ 20.25 in. PDF boards (16:9 ratio for widescreen presentation), combined into one PDF document; total file size 100 MB maximum
- Required:
 - Wall section(s) at $\frac{3}{4}$ in. = 1 ft 0 in. minimum
 - Building section(s) at $\frac{1}{8}$ in. = 1 ft 0 in.
 - Floor plan(s)
 - Roof plan
 - Elevations
 - Building details at 3 in. = 1 ft 0 in. (the number is up to you)
- Optional:
 - Photographs of massing model at $\frac{1}{32}$ in. = 1 ft 0 in.

THE WORK OF THE COMPETITION WINNERS

Figures 3 through 5 show the final boards of the competition's first place winner, Isaiah Ho.

This is how Isaiah described his project:

Following the fabric of the original sixteen squares of Blacksburg, the building forms a push and pull relationship with Virginia Tech and the Blacksburg community. The rectilinear form is carved away to create outdoor learning spaces and reflect the give and take of resources between the high school and the university. Collaboration and presentation spaces invite the community inside onto the public floor while learning and exploration happens on the upper two floors. Large light wells pierce the form, bringing daylight deep into the space and creating a unique experience for students and guests. The light wells also serve as circulation and lounge space, inviting students to explore and not just view the space. Every aspect of the building is catered to creating a fun and desirable experience. A welcom-

ing and diverse floor plan with many nooks and cutaways allows students to interact and socialize outside of the classroom while maintaining the flow of circulation. High flexibility in the lab allows for intimate and group collaboration, traditional teaching situations, and one-on-one interactions. A constant connection to the outside is formed through the outdoor learning spaces, including one located directly beside the floodway.

Figures 6 through 8 depict the final boards of the second-place winner, Erika Jacobs.

The following is Erika's project abstract:

The ethos of a climate research center calls for sustainable building material. Cross-laminated timber produces significantly less carbon emissions than concrete or steel construction. Revealing the structure provides an opportunity to teach students about the relationship between architecture and climate change.

The project site is on a growing college campus which poses unique challenges. This center will serve high

school students during the day and college students at night. The learning and administration wings close after school hours to allow college students to occupy the semi-public central area to prevent safety issues. Providing these multi-use spaces makes for a more feasible building proposal.

To encourage community involvement and education, the school has a community garden that sits adjacent to the local farmers' market. Increased community interaction provides opportunities for education on climate change and strategies to minimize ecological impact.

Light wells in the learning wing corridor ensures that classrooms are provided with sufficient daylight. The interior walls of the classroom have a clerestory at the top of the wall to allow the light to penetrate the space while maintaining privacy.

BEHIND THE CURTAIN: INTERACTIONS WITH MENTORS

The competition began on March 23, 2020, after a week's delay due to COVID-19. Two sets of mentoring sessions were scheduled, during the weeks of April 6 and April 24,

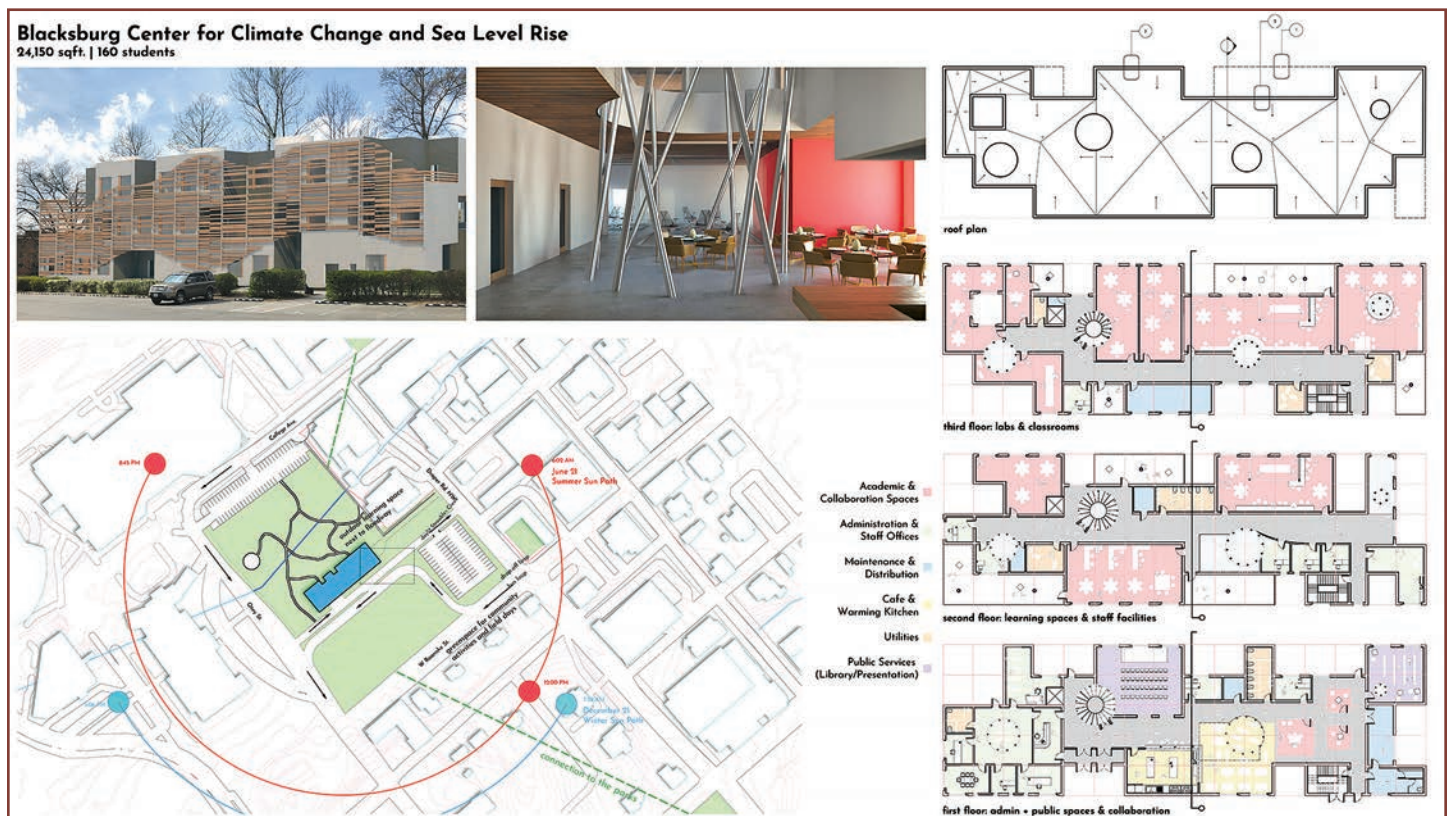


Figure 3. First-place entry from the 2020 competition. Note: 1 sqft. = 1 ft² = 0.0929 m².

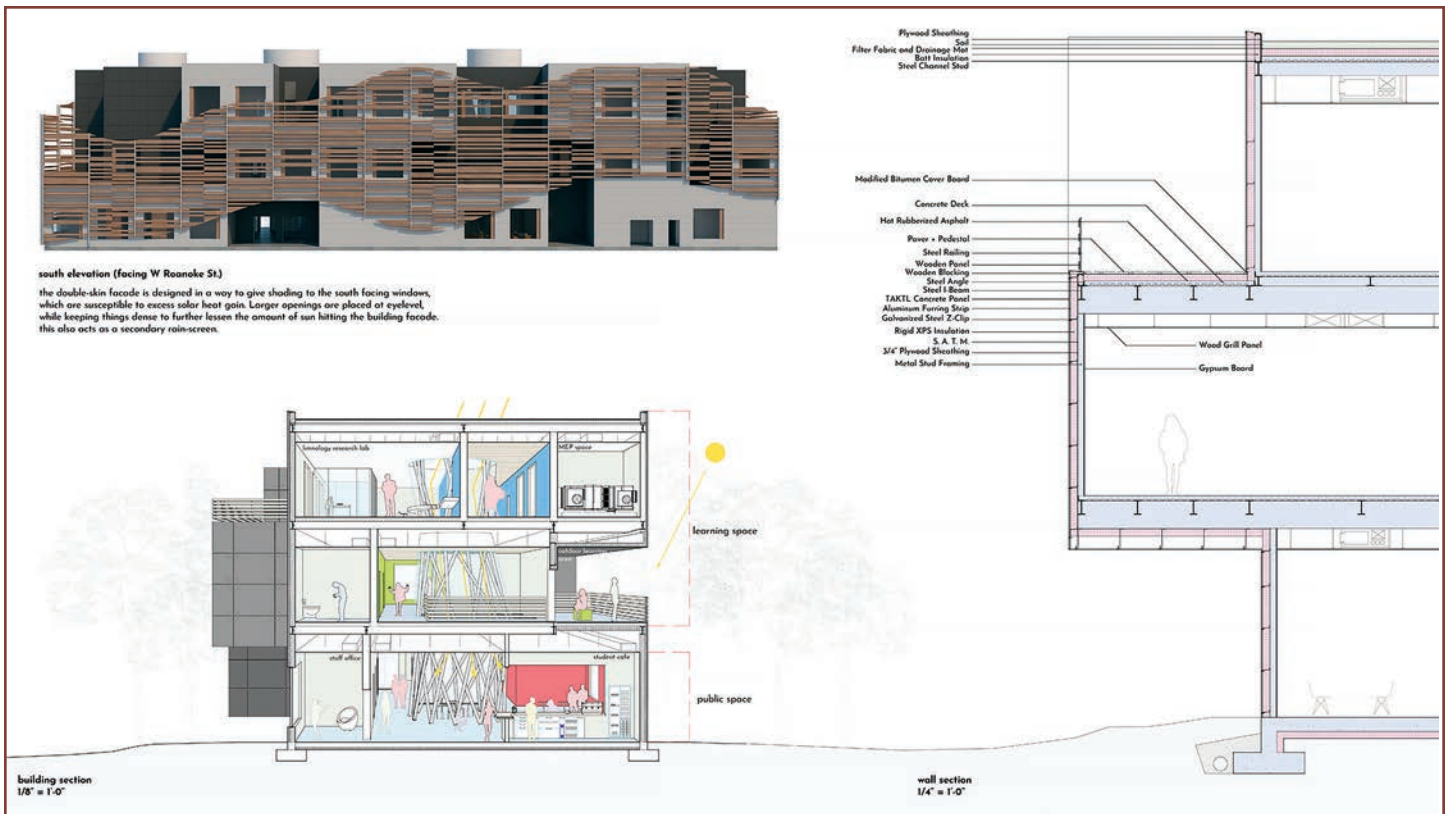


Figure 4. First-place entry from the 2020 competition. Note: MEP = mechanical, electrical, and plumbing; S. A. T. M. = self-adhered transition membrane; XPS = extruded polystyrene. 1" = 1 in. = 25.4 mm; 1' = 1 ft = 0.305 m.

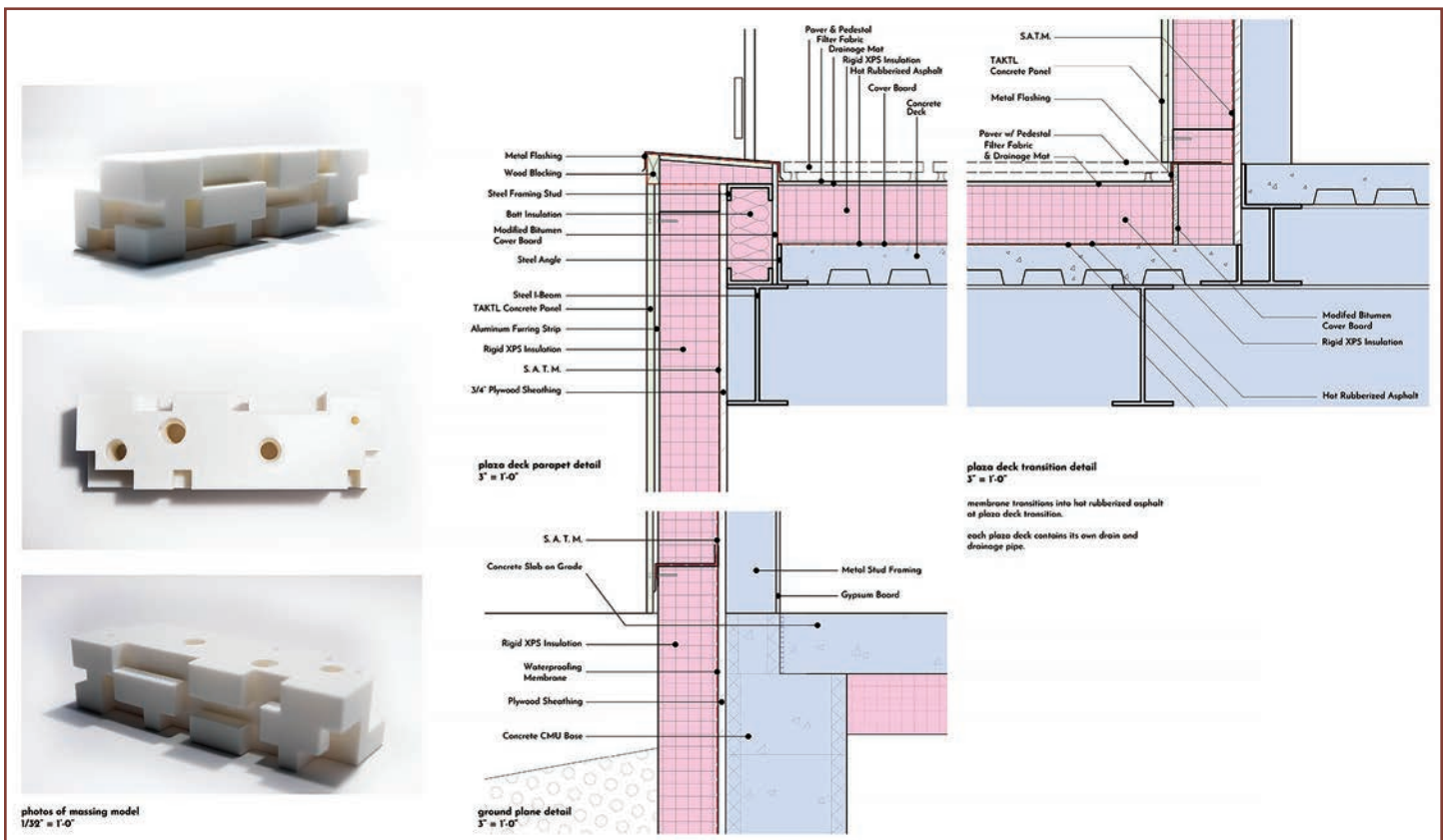


Figure 5. First-place entry from the 2020 competition. Note: CMU = concrete masonry unit; S. A. T. M. = self-adhered transition membrane; XPS = extruded polystyrene. 1" = 1 in. = 25.4 mm; 1' = 1 ft = 0.305 m.

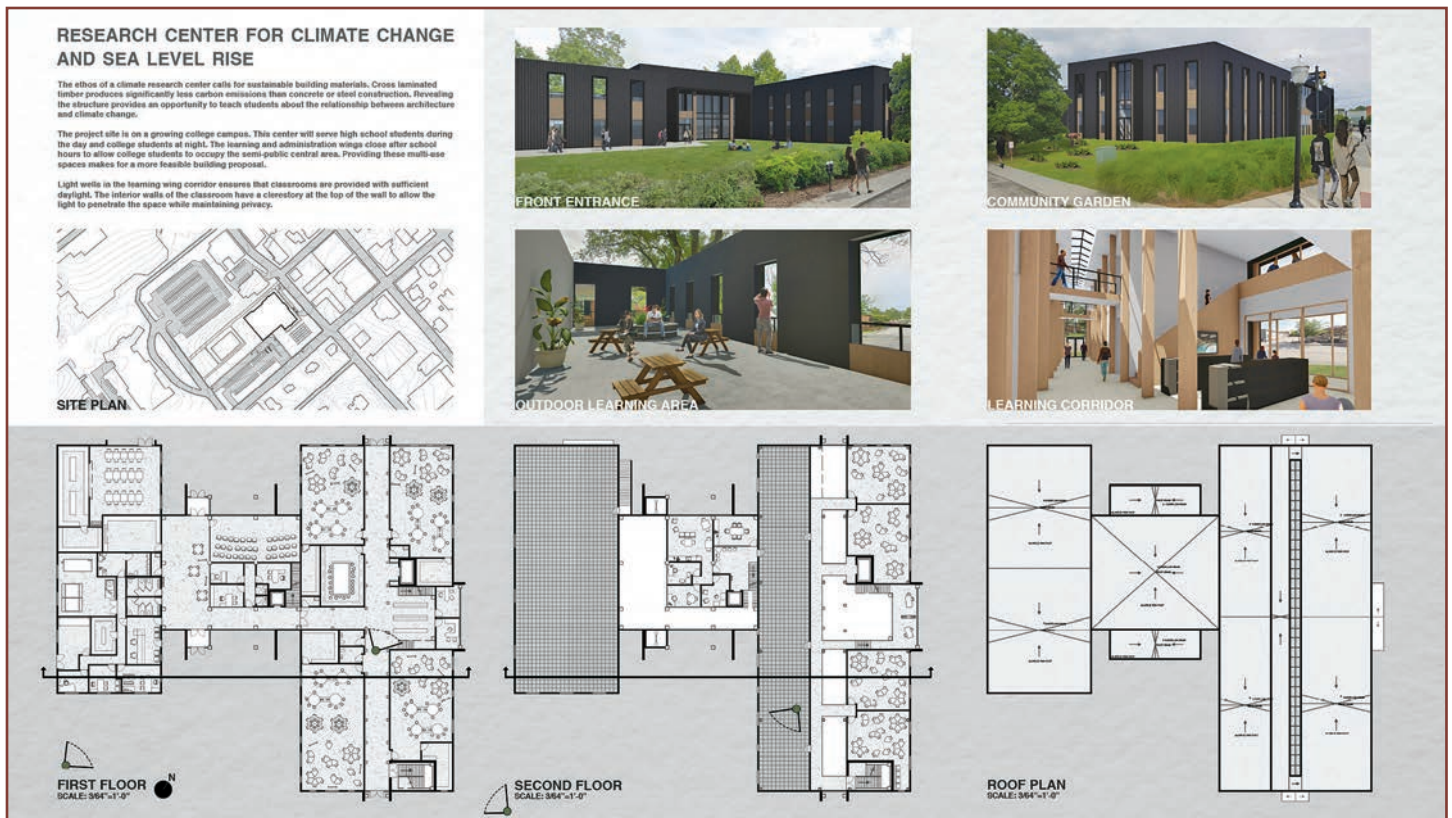


Figure 6. Second-place entry from the 2020 competition. Note: 1" = 1 in. = 25.4 mm; 1' = 1 ft = 0.305 m.



Figure 7. Second-place entry from the 2020 competition. Note: CLT = cross-laminated timber. 1" = 1 in. = 25.4 mm; 1' = 1 ft = 0.305 m.

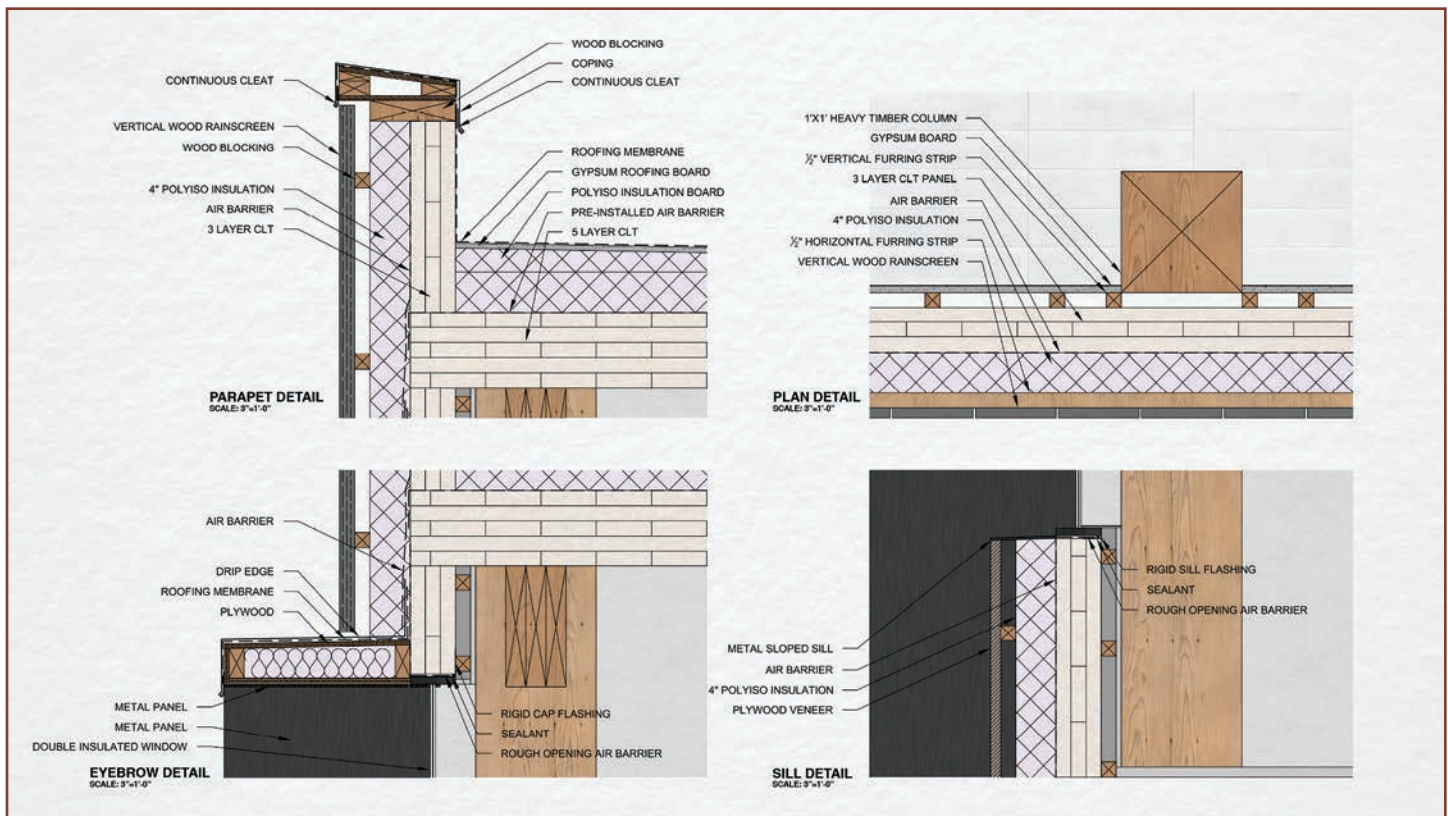


Figure 8. Second-place entry from the 2020 competition. Note: CLT = cross-laminated timber; Polyiso = polyisocyanurate. 1" = 1 in. = 25.4 mm; 1' = 1 ft = 0.305 m.

2020, with the final jury occurring on May 4, 2020. In the first set of mentoring sessions, students met with one or two mentors with several of their classmates and me in attendance. I was there mainly to run interference with the video-conference platform and to make sure the students and the mentors were able to understand one another. I relay details about the mentoring sessions with the competition winners in the sections that follow.

Mentoring Session #1: Isaiah Ho with Derek Cundiff, Elizabeth Grant, and Derek Ziese

In his first interaction with the mentors (Fig. 9), Isaiah briefly described the layout of his building, mentioning the light wells that extend between floors and the balconies that are inset into the building volume. He mentioned the use of ultra-high-performance concrete panels as a cladding material, and he presented a site plan, renderings, floor plans, structural framing plans, and a building section to the mentors. His first questions revolved around determining whether the angled steel tubes surrounding the light wells should or should not be integrated with the rest of the steel structure supporting the floor decks of his building. The mentors and I, his professor, all agreed that the structure should frame around the rough openings of his

light wells, freeing up the steel tubes to be more slender and elegant. It was generally agreed that, while architects don't typically size and specify structural members for a commercial project of this scale, architects do need to understand the relative size and depth of these members to allow enough space for them in the design. The spans Isaiah was proposing did not exceed 24 ft, and he had allowed for 4 ft of space between the underside of floor and roof decks and ceilings. All agreed he did not need the extra buttressing of the steel tubes, and leaving them free of the structure was a reasonable approach that would result in the most parsimonious structure as well as the best architectural outcome.

The discussion then turned to the interface between the interior and exterior at one of the balconies at the second-story floor level (Fig. 10). Isaiah had a good grasp of the fact that insulation should wrap around the structure of the enclosed portion

of the building, but wasn't sure how to accomplish the necessary roof drainage, nor how to tie the balcony assemblies into the walls of the second and third stories. The mentors walked Isaiah through the need to provide curbs both at the junction of the balcony with the second-story floor and at the edge of the balcony, and to include a drain in the floor assembly of the balcony. They suggested an inverted roof membrane assembly (IRMA) system with a hot rubberized asphalt waterproofing layer beneath insulation and pavers on pedestals, and referred him to manufacturers' websites for details. They also noted that his wall assembly with high-performance concrete panels would likely

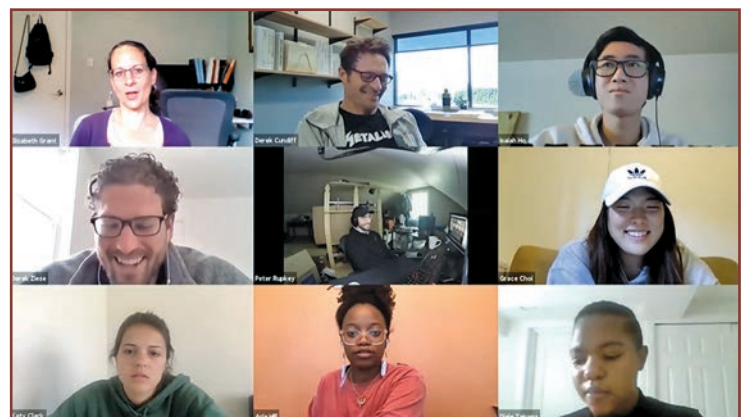


Figure 9. Isaiah Ho's first mentoring session.

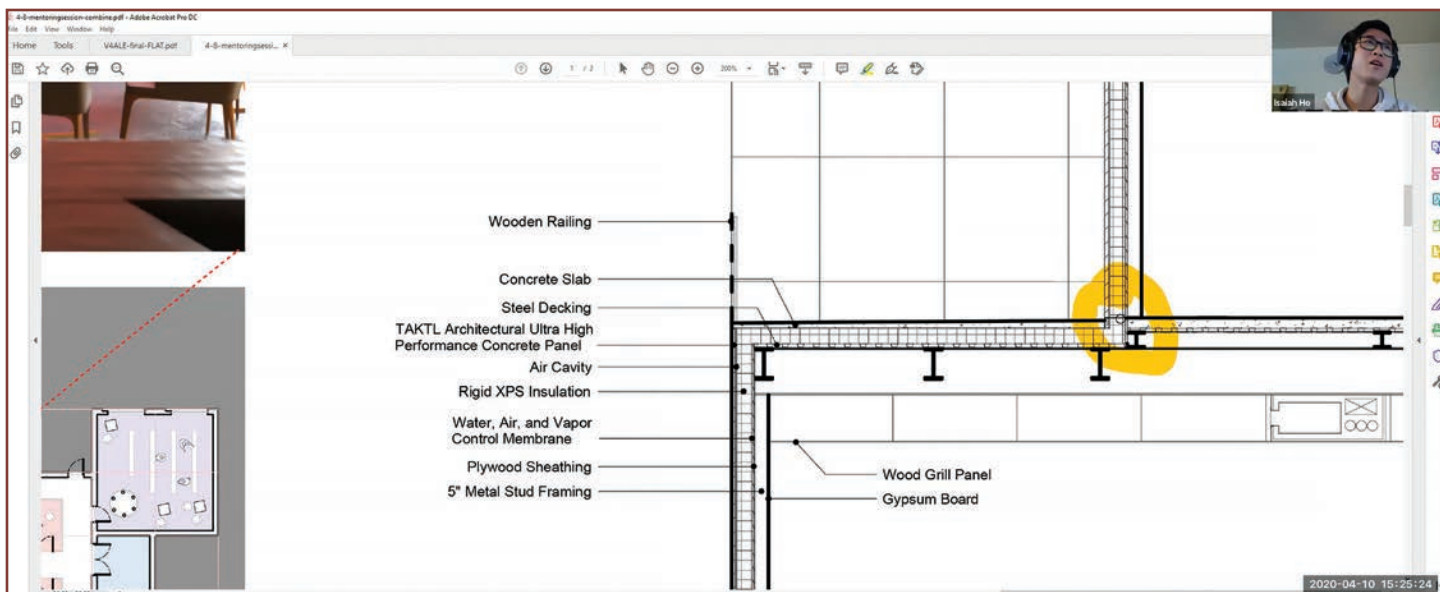


Figure 10. Isaiah Ho's interior-to-exterior connection at a balcony. Note: XPS = extruded polystyrene.

be a rainscreen with a backup wall, and that the water and air control layers of this wall needed to be detailed as well, especially as they interfaced with the hot rubberized asphalt system suggested. They left him with the notion that, while his section as drawn reflected a good theoretical understanding of building control layers, the section needed to be adjusted and detailed to reflect the actual size limitations of materials and the need for tie-ins at two- and three-dimensional corners, which appeared in abundance in his design.

Mentoring Session #2: Isaiah Ho with Derek Ziese

The second set of mentoring sessions were set up as one-on-one conversations with

an individual mentor. I dipped in and out of rooms to check on the progress, troubleshoot, and listen in, but tried mostly to stay out of the conversations since the students and the mentors had already developed a rapport.

In Isaiah's second mentoring session, he had a video conference with Derek Ziese about the further development of his details. They first discussed the waterproofing detail at the balconies and how the hot rubberized asphalt would tie in with sheet metal flashing and an air barrier at the second- and third-story facades. Derek indicated that Isaiah should show all the layers of the IRMA system, either on the section or in a separate callout.

Isaiah and Derek then proceeded to discuss the roof plan (Fig. 11), where a number of

different options were considered—a ballasted IRMA roof, a green roof, and a single-ply membrane roof. After Isaiah mentioned that he intended to put a solar photovoltaic array on the roof, the two decided that a hot rubberized asphalt IRMA roof assembly over a composite deck to match the system used on the balconies below, but with gravel ballast instead of pavers, was a good approach. The complexity of the roof with its multiple protruding light wells also lent itself well to this type of roof system. Derek suggested that Isaiah slightly amend the roof plan to better align the roof drains, remove some unnecessary drains, and remove crickets and saddles he had drawn that were more appropriate for a single-ply roof with tapered insulation beneath.

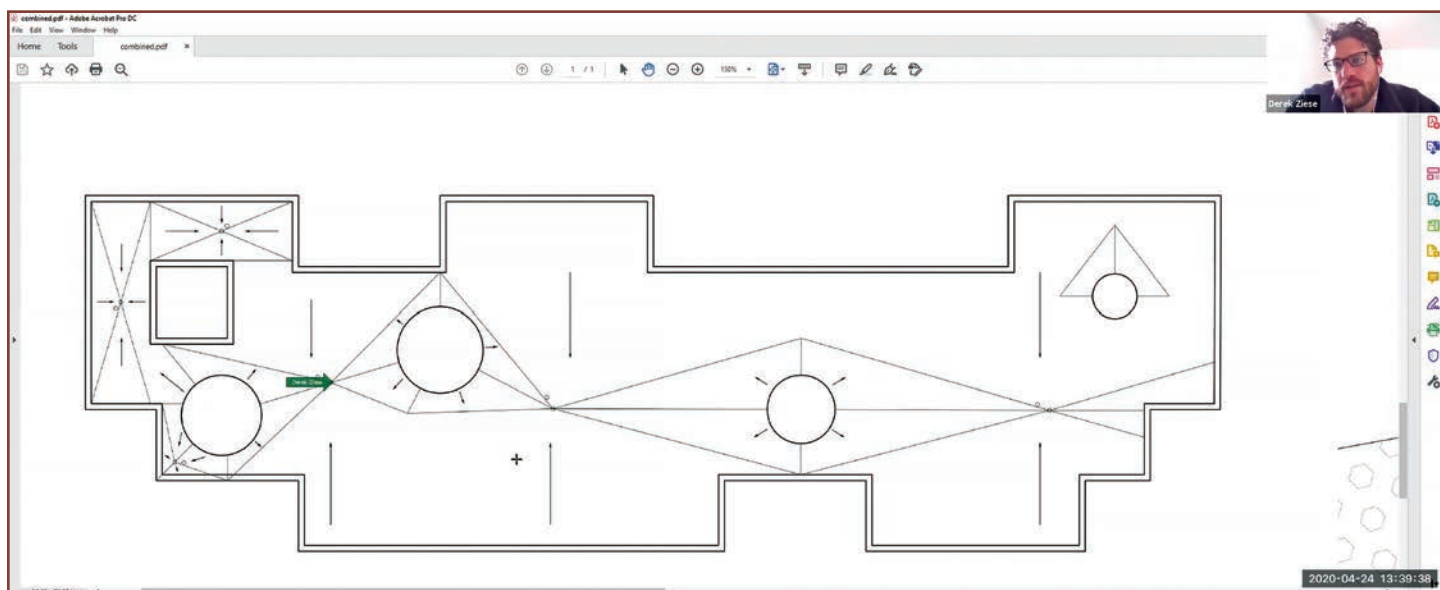


Figure 11. Isaiah Ho's roof plan.

Isaiah raised a question that I had raised, largely rhetorically, in an earlier mentoring session: where is the appropriate place to show roof elements—on an overall roof plan or on the level where they appear? Derek suggested that the roof terraces with their drains be shown on the level where they appear—that is, on the second- and third-floor plans rather than the roof plan for better clarity and ease of placing detail tags.

Finally, the two turned their attention to the detail at the base of the wall. Derek marked up Isaiah's drawing to help him understand the distinction between a slab-on-grade, a stem wall, and a footing. Once again, a single line of waterproofing drawn as a theoretical indicator along the wall and around the foundation was redrawn as an air-barrier layer overlapping waterproofing, with through-wall flashing capturing any moisture entering the cavity behind the cladding. The video-conference markup tools proved crude but useful in explaining the appropriate extent and shingling of these elements.

Mentoring Session #1: Erika Jacobs with Derek Cundiff, Elizabeth Grant, and Sam Zalok

Erika met with mentors Derek Cundiff and Sam Zalok in a video conference with four of her peers and me, her professor. She began

with questions about the exterior-grade metal panel shading elements she was proposing around each stack of windows on her school's façade, and showed a detail of the head of the window coupled with the parapet condition above (Fig. 12). Sam Zalok pointed out that her air/water barrier was a continuous dashed line with her roof membrane, and that while that was a good theoretical suggestion for this schematic phase, in reality these would be two different materials. He also indicated that this barrier should be placed inboard of the exterior wall insulation, the "warm-in-winter" side.

Sam then explained how in typical cases, the air/water barrier would be turned into the rough openings of the window, and the windows would be sealed to that air/water barrier. He was concerned that this discussion was getting too granular and I said, "No, not at all!"

Continuing the discussion of the window head detail, Sam indicated the need for through-wall flashing to remove any water that gets through the rainscreen to the air/water barrier on the backup wall above the window. He explained that the air/water barrier should lap over the flashing. I suggested that Erika choose this head detail as one of her required 3 ft = 1 ft 0 in. building details.

Derek Cundiff brought up the issue of the horizontal projection of the portal frame over the window, and both he and Sam agreed

it should be treated as a small roof—which I immediately started calling "a little baby roof"—by sloping it away from the building. The assembly would consist of sheathing, a self-adhering membrane that extends down the front lip of the frame, and metal sheathing on top of that, with a drip edge at the end. The air- and water-resistive barrier of the wall above would shingle over this flashing. Before moving on, I reminded Erika that she needed to add blocking at the top of her parapet wall.

We then looked at her foundation plan, one of a series of schematic structural drawings I had asked the students to do to ensure that they had some notion of how their buildings would stand up. Erika had a question about the foundation condition at the 1 ft by 1 ft heavy timber columns at the perimeter of her building. Derek explained the need for a more substantial column footing to distribute the point load of the column over a larger bearing surface, which Sam mentioned would be determined based on the bearing capacity of the soil. This would be more substantial than the small pier footings Erika had drawn as bump-outs of the spread footings supporting her walls. I raised the question of whether those columns were necessary in any event, because traditional cross-laminated timber (CLT) can serve as a load-bearing wall on a two-story structure. Put simply, I asked Erika

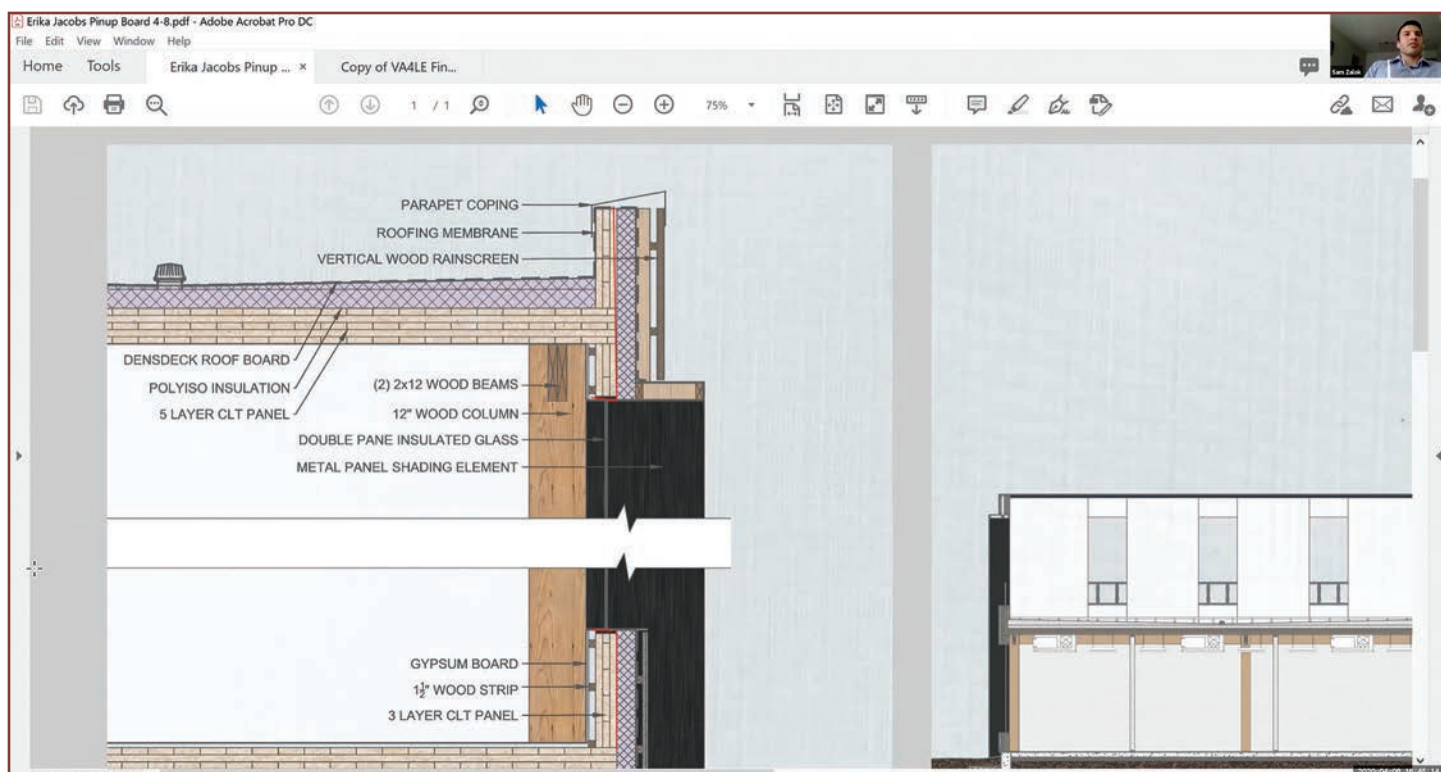


Figure 12. Erika Jacobs' parapet and window detail. Note: CLT = cross-laminated timber; Polyiso = polyisocyanurate. 1" = 1 in. = 25.4 mm.

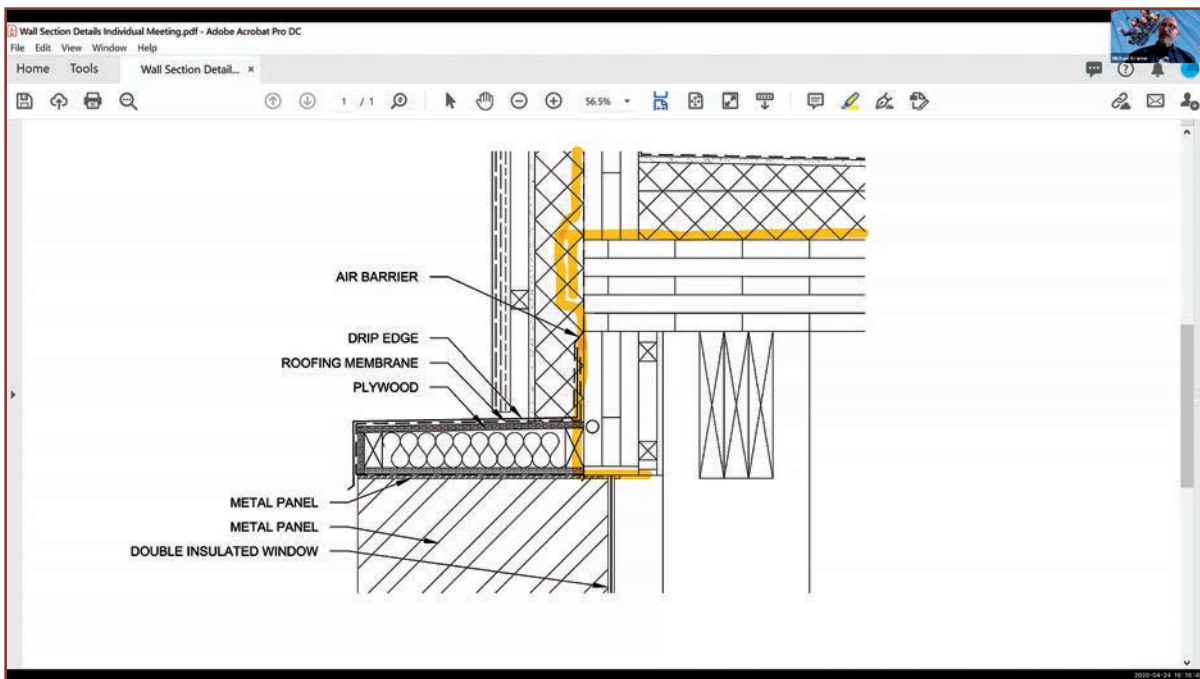


Figure 13. Erika Jacobs' window head detail.

to determine if the three-ply CLT she was showing was being used as cladding, resisting only lateral loads, because if it were increased to five-ply, it could be used as a bearing wall instead, eliminating the need for the columns at the building perimeter.

This led to a discussion of how to detail the connection of heavy-timber columns as they meet their spread footings in the interior of a building. Derek used the video-conference tools to sketch a section of a concrete column footing, topped by a concrete pier with a baseplate anchored to the pier to receive the heavy timber column. The slab would then be poured around the column. He indicated that everything from the top of the slab down should be reinforced concrete.

Erika expressed the difficulty she had been having trying to combine heavy timber with CLT, but the group agreed that she had tackled this with aplomb. Both Derek and Sam applauded Erika on her well-developed wall section for this mentoring session.

Mentoring Session #2: Erika Jacobs with Michael Kramer

Erika met with Michael Kramer, a "bonus" IIBEC Mid-Atlantic and Virginia Chapters' Student Design Competition mentor from the Puget Sound Chapter I recruited after meeting him in Seattle at a chapter meeting in February 2020, right before the COVID-19 hammer fell. Michael had given a talk titled "Rainscreens, Breathability, and High R-Value Walls" to the 16 members of the third-year design lab group

two weeks prior, and I asked him to meet with students who had a particular interest in wood construction in institutional buildings.

Erika again brought up the uncertainty of combining heavy timber with CLT, and that her main concern was ensuring the building was enclosed and that the air and moisture control layers were shown correctly. She introduced Michael to the metal panel shading elements surrounding windows stacked vertically on her facades. He suggested that she view the portals as "trim" or "add-ons" and run the control layers behind them.

The two then used the commenting tools in Adobe Acrobat to work through the shingled layers at the window head detail (Fig. 13). Michael reiterated Sam's suggestion to prestrip the window opening, and elaborated on the need to leave a half-inch gap between the window and the rough opening to allow for backer rod and sealant to join the air and moisture barrier to the window. He advised using a similar approach at the jamb. He also reiterated the first mentoring group's suggestion to treat the near-horizontal portion of the portal frame as a "little baby roof," though not in those words. The portal frame would be installed on top of the prestrip, and then the top of the frame would be sloped to the exterior, covered with a high-temperature-resistant self-adhered membrane wrapping over the top of the frame and down its face. He then suggested a cleat be installed on the front face of the portal frame, with the self-adhered membrane lapping over it to form a drip edge, and finally a through-

wall flashing would cover the assembly, with its own drip edge attaching to the cleat.

Looking at the parapet detail, Michael suggested that Erika use a factory-applied air and vapor barrier at the top surface of the CLT roof deck to protect it during construction and to provide continuity with the air and moisture barrier in the wall. He suggested a vapor-permeable self-adhered sheet at the wall for the air/moisture barrier. He

referenced the "perfect wall,"¹ with which Erika was familiar, and said that the vapor-impermeable layer it demands could work here, too, but that because all the insulation was outside the structure, the vapor-permeable sheet would be a better choice because it would provide additional resiliency in allowing the CLT to dry outward as well as inward in the event it were wetted during construction.

Moving to the windowsill detail, Michael advocated for the use of 8- to 11-pound-per-cubic-foot-density mineral wool board in lieu of the polyisocyanurate (or XPS) board covered with gypsum board that Erika had drawn. Using mineral wool would eliminate the need for the gypsum board because of its inherent fire-resistant properties, and it could dry more readily if it got wet during construction. Then he suggested she could install the wood rainscreen furring directly over the insulation and screw through to the CLT wall beyond with long screws, a technique he had shown in his lecture two weeks prior. He again explained how to run the moisture barrier (prestrip) into the rough opening, and the need to lower the CLT by ¼ in. to 1/2 in. to provide a space for water to collect and drain to the exterior. He drew the suggested layers beneath the window frame: a back dam angle, an air/moisture barrier adhered to it, with backer rod and sealant connecting the back dam angle to the back of the window frame; then, additionally, a "sill drip flashing" tucked under the window frame to catch water around the frame and carry it to the exterior.

He then suggested that the air/moisture barrier should also be installed under the jamb and head of the window frame and that Erika should provide a small gap behind the metal panel cladding at the portal frames, treating them as mini versions of the rainscreens at the walls. He explained that a minimum $\frac{3}{8}$ in. gap is necessary to break capillary action. He suggested Erika refer to the *Illustrated Guide R22+ Effective Walls in Residential Construction in British Columbia*⁵ and also the *Guide for Designing Energy-Efficient Building Enclosures*.⁶

Final Jury

In the final jury, the 16 students in the design laboratory presented their work for 10 minutes each, then left the video conference while the mentors deliberated. I did not vote, but listened in to the conversation to hear the mentors' evaluation of the work. I shared the jurors' comments with the students in general terms in subsequent video conferences. **Figure 14** shows the group reassembled to hear the outcome of the competition. While students did not make all of the changes suggested in the mentoring sessions in their final entries, and some errors and inconsistencies remain, as can be seen in Fig. 3 through 8, the work developed considerably across the short time frame of the competition, thanks in large part to the interventions of the mentors.

FINDINGS

Building the Airplane While Flying: Conducting Mentoring Sessions Via Video Conference

The mentors, students, and I were learning how to use video-conference markup tools largely on the fly during the mentoring sessions, but were able to make a series of clumsy but effective drawings on the screen. In some cases, students and mentors used the highlighter in Adobe Acrobat as the closest available "pen." If this experiment of conducting mentoring sessions and jury reviews during quarantines or times of physical distancing is necessarily repeated, my hope is to either have a better personal command of the video-conference markup tools or find a better alternative, and to offer a short tutorial on these tools to any mentor who would like one.

Occasionally during the mentoring sessions, the students got a deer-caught-in-the-headlights look because they were not familiar with all of the terms the mentors were using. In these cases, it was helpful to have me (their professor) present to ascertain when this was happening and translate both during the ses-

sions and in separate meetings afterward. I also wrote key words and links in the chat in real time to help them follow the conversation and look up references later.

To allow enough time for the one-on-one sessions to occur on April 24, 2020, I, with the help of my teaching assistant Alsaleh Sugati, hosted two concurrent video conferences. This was a bit of a three-ring circus, but allowed for more mentoring sessions to be held during the scheduled class period. Recording these video conferences was helpful not only for the students whose work was being discussed, so they could rewind and pause to catch key details, but also for other students with similar questions who could watch the videos as well. As the professor, I did note that multiple students rewatched some of the video recordings.

Students' Lack of Prior Exposure to the Building Enclosure

Erika expressed a frustration in her first mentoring session common to many third-year architecture students putting together a detailed wall section for the first time: "It's kind of been a confusing time figuring out how all this works."

To Sam Zalok's expressed concern in Erika's first mentoring session that a discussion of how to prestrip and flash a window was too much in the weeds for this student group, I respond that most students have minimal understanding of how buildings go together and that these discussions are invaluable. Even strong students like Erika with some experience in architectural detailing from summer internships do not always remember the "perfect wall" rules, nor have much exposure to how head and jamb details are handled in the progressive construction types they want to use in their designs. Notably, Erika was one of the students who was granted a Student

Convention Sponsorship to the IIBEC convention this year, but was unable to attend the virtual event. She would have benefited greatly from seeing air- and water-resistive barrier and flashing details at window openings at the trade show. This mentoring session was the next best thing.

The Value of Individual Mentorship

Individual interaction is key to the success of this competition and student learning in general. I have long suspected this, but the video-conference interactions required by the pandemic revealed this truth in high relief. For these interpersonal interactions to be meaningful, students must become familiar enough and comfortable enough with their professors and mentors to ask what may seem to be basic or seemingly self-evident questions. Despite the fact that the same key points arose in nearly every project in this competition—namely, parapet, balcony, window, and foundation details—the students' questions about these no doubt felt very specific to each student asking about them.

The students, quite understandably at this beginning stage of their architectural education, lack the full capacity to extrapolate from a typical condition to their own projects. Having been an architecture student myself, I remember feeling that each building I was designing was a complete original, and the first such building ever to have been designed. One might call this "Howard Roark syndrome," from *The Fountainhead*, by Ayn Rand. This perception is partially inculcated by an education in the first years of architecture school that asks each student to throw out their prior understanding of the building environment so that their mind becomes a *tabula rasa* on which foundational knowledge can be built. While this approach has some advantages, it

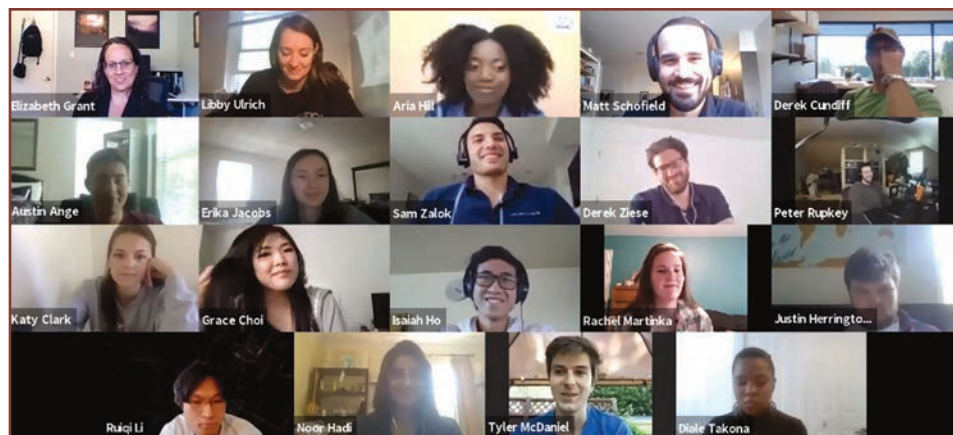


Figure 14. Final student design competition jury video conference.

leaves students wondering how buildings are put together in the real world, while simultaneously expecting themselves to design everything that goes into their buildings from scratch. The reason students draw what look to more seasoned eyes as impossible building assemblies is that they have no frame of reference and desperately need guidance in this regard.

This naiveté is to be expected in the third year of architecture school, the first year they are expected to really engage building enclosures and the year during which they are still being taught the foundations of structures and building assemblies in lecture classes. They will continue to build this facility over their fourth year and during their subsequent architectural internships, but in the third year, they require faculty or other mentors to “walk” with them through their building sections. There is no substitute for this hands-on intervention to get students past their paralyzing frustration and self-doubt and enable them to learn for themselves.

CONCLUSION

It indeed takes a village to mentor architecture students. Many architecture faculty have not practiced architecture in a traditional way, or, if they have, it was often years ago, as academia is often a full-time job that typically allows only for episodic consulting work. Even as a scholar actively doing research on specific building enclosures, I personally have felt humbled by the interactions with the mentors during these competitions. I, like many of my peers, am often digging into memories of work I did some 25 years ago as a young architect to help guide my students. Fortunately, I espouse Karl Popper’s famous quote, and I am not too proud to call in reinforcements in the form of my IIBEC colleagues:

The more we learn about the world, and the deeper our learning, the more conscious, specific, and articulate will be our knowledge of what we do not know; our knowledge of our ignorance—the fact that our knowledge can only be finite, while our ignorance must necessarily be infinite.⁷

Especially given the new constraints and challenges of COVID-19, faculty do not have enough hours available, and often lack the specific expertise, to help students get past their blind spots to envision how their buildings go together. IIBEC mentors can help immensely

with this shortfall through vehicles like these competitions.

Near the start of the pandemic, I had an email exchange with Mike Violette, one of the original cofounders of this student design competition, who indicated that there was interest in replicating a version of this competition at other universities. I would encourage any IIBEC chapter that is interested in conducting a similar activity to contact me and my colleagues at the IIBEC Virginia and Mid-Atlantic Chapters.

One of the keys to reaching the next generation of building enclosure consultants is reaching their professors, as explained in a letter one of my students wrote to the RCI/IIBEC Foundation Board as thanks for her Student Convention Sponsorship:

I really believe it is important to understand how a building is put together in order to be more creative in the way it is designed. Specifically, through a class I had with Dr. Elizabeth Grant (an IIBEC member herself) I realized that I was very interested in the building envelope and how buildings can be responsive to their environments in order to be better. It was through her that I become aware of the IIBEC Foundation Scholarship, and it was largely due to my attendance at the event last year that I chose her as my thesis professor for my final year of schooling. I am looking forward to learning more and incorporating what I learn into my thesis.

The IIBEC Mid-Atlantic and Virginia Chapters’ Student Design Competition encourages student interest in the profession of consulting and gives architecture students with a budding interest in the building enclosure a place to shine. I will be happy to share how the relationship between Virginia Tech’s School of Architecture + Design and IIBEC was established, how it has been sustained over the years, and the interest it has generated amongst the students.

Thanks in part to the exposure to IIBEC these design competitions give to architecture students, both inside my design laboratory and in the broader college community, over 30 Virginia Tech students have attended RCI and IIBEC conventions, and two have received Robert W. Lyons Scholarships, since 2012. I would like nothing better than to help this type of success be repeated at other schools in the United States, Canada, and beyond. 

ACKNOWLEDGMENTS

I would like to thank the boards of directors of the two chapters for their enthusiastic financial and moral support of this project. Special thanks go to the jurors and other mentors who have served on the mentoring teams for the competitions over the years (Table 1). As always, the real heroes of this story are the students, who fully embraced the challenge posed by these competitions. The students involved in the spring 2020 competition in particular are noted for their willingness and ability to “pivot” with grace when they were required to do this competition fully online at extremely short notice.

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Air Barrier Performance in Building Enclosures: Compliance, Continuity, and Complexity

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ABSTRACT

Energy codes require continuous air barriers to reduce the overall energy consumption of buildings. Air barriers also offer benefits beyond potential energy savings and contribute to long-term enclosure durability by reducing the risk of condensation from air leakage. This paper discusses relevant energy code requirements, design-based applications, and construction best practices for air barriers, and provides a roadmap with examples for continuous air barrier strategies to perform in building design, construction, and operations.

Recognizing that materials often serve dual functions to contribute to the continuous air barrier is key to success, such as roof system vapor retarders that are part of the air control strategy, as well as roof membranes designed as part of the air barrier tie-in to the wall below. The paper will review key enclosure interfaces including the roof-to-wall connections, parapets, and transitions between enclosure assemblies. Construction quality assurance and performance testing for owner acceptance are important steps to ensure the design intent is delivered onsite.

With regard to air barriers, this paper discusses the impacts of whole building performance, design requirements, material and assembly requirements, and installation verification requirements during construction. This paper will provide expert-level insight into the current energy code development process and experience from field observations.

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Air Barrier Performance in Building Enclosures: Compliance, Continuity, and Complexity

Continuous air barriers are required by energy code to help reduce the overall energy consumption of a building. The aims of this paper on air barriers are to raise the awareness of minimum code compliance, explain the underlying principles, and explore real-world challenges. Specifically, this paper addresses the following key concepts:

- Continuous air barriers are required by the energy code for new construction and renovations in most U.S. climate zones.
- Whole building airtightness is the primary measure to qualify the impact of airtightness improvements and better-than-code applications of air barriers.
- Air leakage is not the same as occupant ventilation, but managing air leakage can improve ventilation design, energy efficiency, occupant comfort, and air quality.
- Maintaining continuity of the air barrier during construction across the entire enclosure can be complicated by control layer design clarity, building construction types, and trade sequencing.

AIR BARRIERS IN ENERGY CODES

Section 1301.1.1 of the *International Building Code* (IBC)¹ generally requires that a building be “designed and constructed in accordance with the *International Energy Conservation Code* (IECC).² IECC commercial provisions apply to “all buildings except for residential buildings 3 stories or less in height.”² The IECC is structured in a way that provides the option of either complying with the prescriptive requirements within it or by complying with the American National Standards Institute (ANSI), American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), and Illuminating Engineering Society (IES) energy standard, ANSI/ASHRAE/IES 90.1.³ **Figure 1** summarizes the relationship between the energy code compliance options.

Regardless of the compliance path the

IECC Compliance		
Prescriptive Compliance		Performance Compliance
IECC	ASHRAE 90.1	ASHRAE 90.1, Appendix G
Use the itemized requirements, tables, and exceptions.	Use the itemized requirements, tables, and exceptions.	Model the design vs. baseline building

Figure 1. Energy code prescriptive and performance compliance paths.^{1,2}

project team selects, it is important to remember that the methods of compliance cannot be mixed for different building systems. For example, the HVAC cannot be designed to comply with IECC prescriptive requirements and the enclosure designed to meet the prescriptive requirements of ASHRAE 90.1; both building systems must comply with the same pathway.

Both the IECC or ASHRAE 90.1 have requirements for the building to include a continuous air barrier. These requirements apply to most buildings, except those that are classified as “semi-heated” in climate zone 0–6 and those that are single wythe concrete masonry buildings in climate zone 2B.²

Too often, the question is asked, “Is this material an air barrier?” ASHRAE 90.1³ defines a continuous air barrier as a “combination of interconnected materials, assemblies, and sealed joints and components which together minimize air leakage into or out of the building envelope.” That is a good definition and accurately describes what is needed to have a completed building enclosure that minimizes air leakage (IECC Section C402.5; ASHRAE 90.1 Section 5.4.3.1). Actual air leakage for a building is

measured by pressurizing the enclosure and measuring the airflow to determine the air leakage through all six sides of the enclosure being tested. The better question to ask is, “Is this material designed as part of the continuous air barrier assembly, *and* can it resist air leakage?”

To help accomplish the goal of whole building performance, the energy codes also specify aspects of air barrier design (IECC Section C103.2; ASHRAE 90.1 Section 5.4.3.1.1) and installation (IECC Section C402.5.1.1;

Regardless of the compliance path the project team selects, it is important to remember that the methods of compliance cannot be mixed for different building systems.

Air Barrier Design (Standard 90.1, Section 5.4.3.1.1)	Air Barrier Installation (Standard 90.1, Section 5.4.3.1.2)
• Components, Joints and Penetrations details • Extending over all surfaces, including the roof • Resist pressures from wind, mechanical, stack effect	• Junctions between walls and roofs or ceilings • Penetrations at roofs, walls, and floors • Joints, seams, and connections between planes • In accordance with the manufacturer's instructions

Figure 2. Air barrier design and installation summary per ASHRAE 90.1.²

ASHRAE 90.1 Section 5.4.3.1.2) for continuity across joints, penetrations, and assemblies. **Figure 2** summarizes the design and installation requirements from ASHRAE 90.1.³

In general, the energy codes require continuity of the air control layer. For example, ASHRAE 90.1 (Section 5.4.3.1.2 a through c) specifically requires the following aspects of air-barrier design to be “clearly identified” on the construction documents:

- Components designed to provide the continuous air barrier, and the component’s position within each of the building envelope assemblies
- Detailing of joints, interconnections, and penetrations for the continuous air barrier components
- Indication that the air barrier extends over the entire building enclosure and is identified as continuous

Detailing the air barriers to be continuous in the design and quality installation in the field are critical for energy code compliance.

WHOLE BUILDING PERFORMANCE

The ultimate goal of including air barriers is to improve whole building energy efficiency performance. Airtightness testing (according to ASTM E779⁴ or ASTM E3158⁵), does not attempt to “overpressurize” the building; rather, it uniformly pressurizes the enclosure to identify and remediate inconsistencies in the overall construction. The comprehensive whole building airtightness testing of the built enclosure can have broad performance impacts on achieving the intended energy efficiency from the design to the field, mitigating ongoing condensation moisture accumulation due to air leakage, and enabling the HVAC design to deliver a comfortable space to the occupants.⁶

The current whole building airtightness code baseline is 0.40 cfm/ft² at 75 Pa.³ In a recent study based on actual whole building airtightness testing, Emmerich, Ng, and Doi⁷ tested 290 existing buildings built without an air-barrier system and then retested them after an air sealing effort was performed on the buildings. The results were applied to two U.S. Department of Energy standard building prototypes to compare the impact of the results. Based on this analysis, they concluded that “the average measured reduction in air leakage after retrofit was 34% with a range of –11% to 88%.” We calculated potential heating energy savings ranging from 6.0% to 17.4% for a one-third reduction in air leakage and from 10.8% to 31.8% for a two-thirds reduction in air leakage” (see **Fig. 3**). While the referenced study focused on heating energy savings, additional energy savings would occur during cooling cycles.

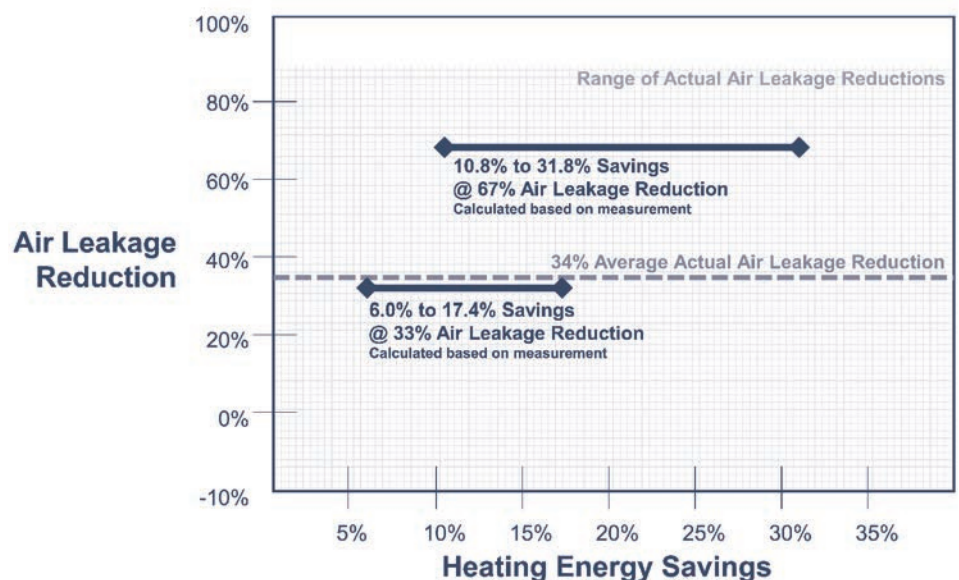


Figure 3. Air leakage reductions and energy savings from 290 building data set compiled by the National Institute of Standards and Technology.⁷

This is a significant energy savings from an improvement in only airtightness of the building enclosure in the study by Emmerich, Ng, and Doi are consistent with findings from a study by Der Ananian and coauthors⁶ based on actual tightness testing and HVAC operation of an existing office building, where the measured result, 0.26 cfm/ft² at 75 Pa, were better than the current code requirement. In the study by Der Ananian and colleagues, the air-leakage improvement performed better than the minimum code, met the Passive House Institute U.S. (PHIUS)⁸ 2015 threshold (0.08 cfm/ft² at 75 Pa), and “reduced the predicted HVAC energy usage by 4.6% annually.”⁶ Again this shows that improving airtightness can result in significant energy and cost savings and also provide additional energy benefit by greatly exceeding the code for airtightness. Of course, energy cost savings are not guaranteed, and the amount of savings may vary based on climate zone, utility rates, radiative properties of roofing products, insulation levels, HVAC equipment efficiency, and other factors.

AIR LEAKAGE IS NOT VENTILATION

Air leakage is uncontrolled airflow through the building enclosure caused by pressure differences across the building enclosure due to factors such as wind, differences between inside and outside temperatures, and imbalance between supply and exhaust air systems. Air leakage can move inward (infiltration) or outward (exfiltration) through the building enclosure, and it occurs as a result of installation inconsistencies or inadvertent gaps in a building enclosure.

Ventilation, alternatively, is the intentional process of supplying or removing air by either “natural” or “mechanical” means, primarily for the benefit of the occupants. Natural ventilation is intentional airflow through an operable element of the enclosure, like an open window, whereas mechanical ventilation is provided by powered equipment, fans, or louvers, and is generally part of the designed operation and controls of a building.³

It is important to understand that air leakage through the building enclosure is *not* a primary ventilation strategy. This point is especially critical as the world is currently struggling to find ways to improve indoor airflow and ventilation to combat the spread of airborne contagious diseases.⁹

To put air leakage in context, it is helpful to quickly review what air leakage is *not*. It is

- *not* a designed feature in the building enclosure;
- *not* uniformly distributed across the enclosure;
- *not* reliably located in an occupant “breathing zone” within a specific space;
- *not* considered an effective configuration for air distribution;¹⁰
- *not* an “intake” or “exhaust” strategy that can be considered in balance or equal to a mechanical system;^{10,11}
- *not* a mechanical economizer, providing supplemental heating or cooling in mild weather;
- *not* an acceptable means to mitigate outdoor air moisture and pollutants from entering into the building;¹⁰ and
- *not* designed by a mechanical engineer to ensure occupant comfort, who relies on the energy code requirements to minimize air leakage when sizing equipment.⁶)

Some of the listed items speak for themselves, but a few require clarification as they relate to codes and standards. Specifically, the 2021 *International Mechanical Code* (IMC)¹⁰ clearly requires that the mechanical system provides ventilation air as part of a designed system (IMC 403.1). Both the IMC and ANSI/ASHRAE/IES Standard 62.1-2019, *Ventilation for Acceptable Indoor Air Quality*,¹¹ recognize the need for balanced ventilation, where the supplied outdoor air and exhausted interior air are roughly equal. Of note, Section 5.16.1 of ASHRAE 62.1-2019 provides clarity about minimizing building enclosure air leakage to enable the designed ventilation system to not

only maintain balance but also control outdoor air moisture and pollutants. Improving enclosure airtightness can require a more carefully considered ventilation system design. At the same time, a more airtight enclosure can make designing mechanical ventilation through a central system or decentralized units, such as heat recovery ventilators, easier to balance and make them less impacted by wind and building height.⁴

Aside from being a poor ventilation strategy, uncontrolled air leakage can have a significant negative impact on the heating and cooling systems in a building. Rather than functioning as an “economizer” to save energy in mild weather or climates, relying on air leakage lacks the fundamental duct and damper arrangement and automatic control system that an economizer HVAC setting opportunistically capitalizes on. Air leakage is uncontrolled if the weather is either pleasant (economizer on) or beyond the occupants’ comfort range (economizer off). As buildings are built more airtight, proper mechanical ventilation becomes more important for occupant health and comfort, energy efficiency, and moisture control. Der Ananian and coauthors⁶ have noted that air leakage can result in:

- “...poor mechanical system performance, requiring additional energy to properly condition a building as intended. As a result, building owners incur additional operating costs and potentially require supplemental systems to improve occupant comfort, or in some cases, require mechanical system replacement.”
- “...environmental allergens or pollutants and other airborne particulates to contaminate interior air.”
- “...ice formation or ice dams at the roof eaves and... can cause condensation on interior surfaces and biological or mold growth within the building enclosure.”

Separating the concepts of air leakage and ventilation is critical to improve the performance of both building systems. Conceptually, air leakage is unintentional and

uncontrolled and is improved with a continuous air barrier, whereas ventilation is deliberate and designed and relies on intentional air movement through controlled systems, natural or mechanical. A comprehensive air barrier enables the designer to take control of the amount of air that is exchanged between the outside of the building and the inside of the building for the benefit of the occupants. As noted in “Illustrated Guide: Achieving Airtight Buildings,”¹² the combination of an airtight building enclosure and a properly designed mechanical ventilation system “can offer a high-performance solution that improves durability, reduces heat loss, and improves air quality.”

To recap from the affirmative perspective, minimizing air leakage, or tightening the enclosure:

- allows for improved ventilation design strategies to be effectively implemented;
- helps improve energy efficiency of the building;
- increases occupant comfort indoors; and
- limits entrance of uncontrolled exterior contaminants;

AIR BARRIERS ARE ONLY ONE OF FOUR CONTROL LAYERS

When beginning to think about enclosure design, it is helpful to start with an ideal scenario. The configuration of the ideal wall system includes the following: the cladding on the outside, continuous insulation keeping the rest of the control layers tempered in the middle, and structure to the inside. This “ideal” configuration can also be applied horizontally to the roof assembly (Fig. 4). For an example of a transition, the roof and wall meet

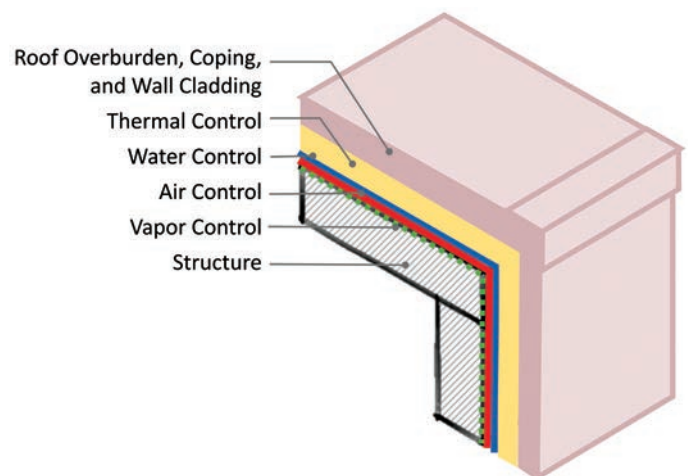


Figure 4. “Ideal” roof and wall transition.

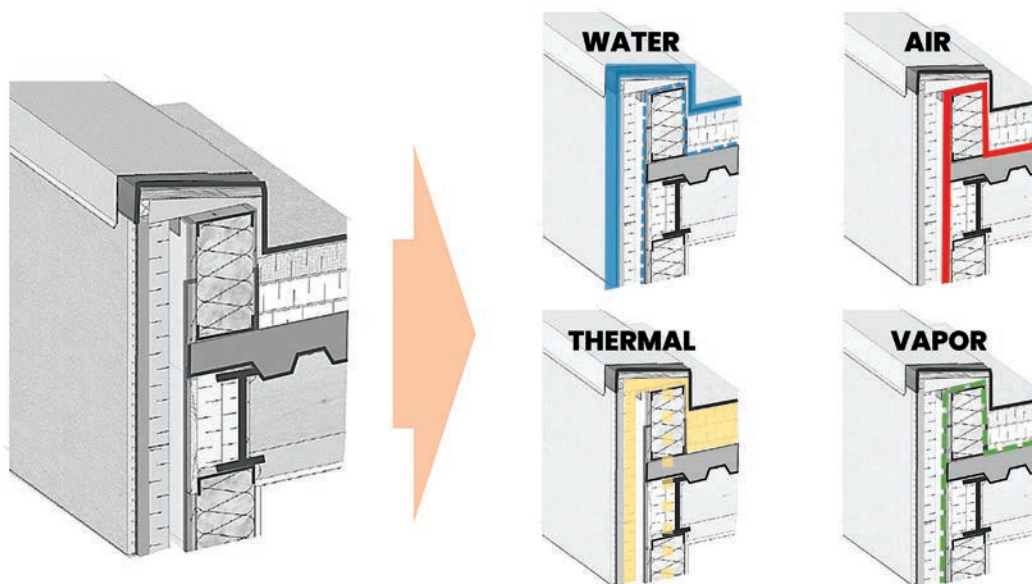


Figure 5. Example of breaking down a parapet detail by the four control layers.

as an “ideal” flush edge with very simple transitions. As a system moves away from these ideal configurations, including parapets or other project constraints, transition details become more challenging and trade-offs have to be made. However, understanding the basics, even under ideal scenarios, provides for better solutions of those complex transitions.

For more-complex scenarios, like parapets, there are simple design tools to connect the control layers as they transition from the wall to the roof. The pen test—tracing each of the control layers for continuity across the building enclosure—is a helpful tool during the design process. During construction, the pen test is helpful to communicate to the field the intent of the critical components and functions of the building enclosure.

Discussion of control layers as they apply to a roof or wall alone is fairly manageable. However, the process becomes much more complicated when the roof meets the wall at the parapet condition.¹³ The pen test is relatively easy in theory, but it can get complicated as we zoom in and consider the control layers at each condition, penetration, and transition, as shown in **Fig. 5**.

The following are important points to maintain continuity of the four key control layers:

- Water control is managed by the roof membrane and the cladding. Wall systems also commonly include redundancy with a water-resistive barrier (WRB), which is often found behind or below the exterior insulation.
- Air control can be managed at the deck

level of the roof, which can more readily be married into the wall air barrier. The roof membrane can also be used as an air barrier as long as the detailing and transitions are done carefully.

- Thermal control continuity is maintained by connecting the roof and wall insulation, which can be challenging. It is important to be mindful of cavity insulation and the potential design risks of condensation at the thermal bridges.
- Vapor control can also be in the same plane as the air control layer, based on location needs, construction methodologies, and occupant use of the building.

It is important to review continuity across the roof and wall systems, specifically the four key control layers: water, air, thermal, and vapor. These four key control layers should generally be continuous across all six sides of building enclosures.

COORDINATING COMPLEXITY

Although it can sometimes be difficult to achieve effective control layer continuity across building systems, especially at significant transitions like a

parapet where the roof system meets the wall system, achieving such control is certainly not impossible. This section presents a practical example of applying the control layer continuity principles to construction trade sequencing as well as some common challenges.

This example focuses on air barriers, which are often installed by multiple trades and in many steps over time. When confronted with a similar design as the example provided here, a general contractor may request alterations to the design to shorten the schedule or reduce costs. However, this value engineering process—which aims to reduce cost, time, or both—may also compromise continuity of the control layers (water, air, thermal, and vapor) and

reduce the intended long-term performance of the building enclosure.

Complexity is common for parapets. Critical detail locations are often difficult to illustrate on two-dimensional drawings alone, so exploded diagrams, sequence information, or both may be required to communicate the design intent. For the purposes of this discussion, the figures illustrating the materials applied to the parapet assembly sequence are color coded in their application step by their primary control layer function, with water control elements shown in blue, air control

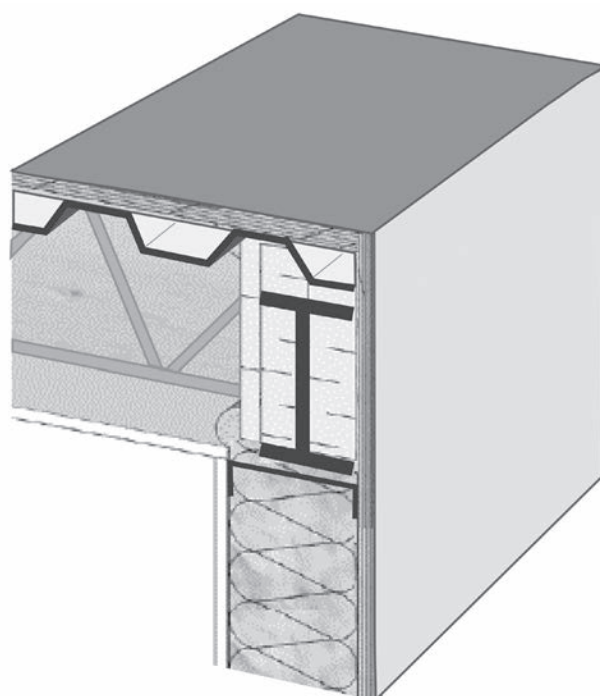


Figure 6. Initial condition.

elements in red, and thermal control elements in yellow; vapor control elements are not shown separately.

To help identify separate materials within a control layer, lighter and darker versions of the color are used to distinguish elements within the same step. Also, dashed or “hidden” lines are used to depict materials edges that may be overlapped or behind another layer in the sequence within the same step.

In the initial condition shown in **Fig. 6**, the wall and roof deck are assembled up to the sheathing. The roof structure is a corrugated steel deck with a substrate board placed on top to provide a continuous surface for air barrier adhesion and support. The exterior wall is steel framed with cavity insulation and exterior sheathing applied.

In preparation for the parapet wall construction, a strip of air-barrier material is applied to the roof and wall edge with sufficient material for future integration with the remainder of the continuous air barrier. This condition is shown in **Fig. 7**. It is important to note the material on the wall side is not yet adhered to allow for correct lapping in the future to manage water in “shingle fashion” as required by the IBC.¹ This can be accomplished by leaving a portion of the release liner in place for adhered materials.

The parapet wall is then assembled on top of the roof deck in a platform-framed configuration, as shown in **Fig. 8**. If lateral bracing for the parapet were required, additional detailing and coordination would be needed.

After the initial air barrier strip and parapet wall are in place, the remainder of the continuous air barrier can be applied to both the roof and wall systems. If the air control layer is also intended to act as the WRB in the wall and parapet system (as shown in **Fig. 9**), the application should start from the lowest point and work upward; this allows the subsequent layers to be lapped in shingle fashion. After the air barrier is applied to the walls (light red), the preapplied strip of material can be lapped

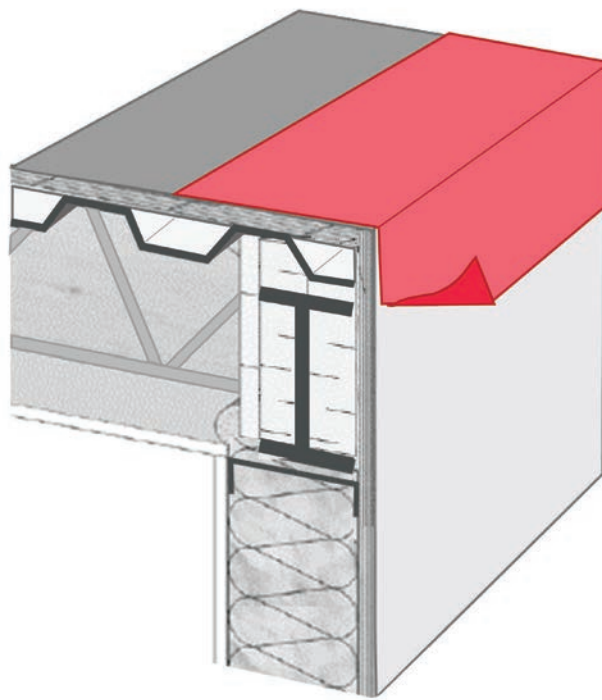


Figure 7. Pretreated corner.

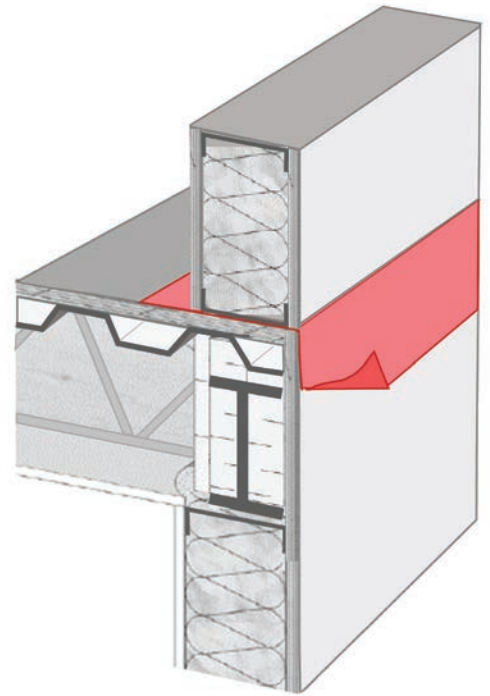


Figure 8. Parapet wall assembled.

and secured over it (dark red in the center of the wall). The air barrier can then be applied to the roof deck (light red), up the backside and over the top of the parapet wall, and then terminate downward on the outside of the wall, lapping over in shingle fashion (dark red at the top of the wall). Lapped edges hidden behind the layers of air barrier materials are shown with dashed lines in Fig. 6.

Locating the air barrier on top of the deck and under the parapet helps prevent moisture that is released by a new or wet concrete deck, and can help control air movement up into a taller, open-cavity parapet. For shorter parapets, or where the deck is not a source of moisture, locating the air barrier over the parapet may be appropriate. Although not shown in the example, balloon framing can allow direct airflow up into the parapet (via convective currents and stack effect); providing an appropriate air seal between the roof deck and exterior wall can be critical for long-term performance.

The roof insulation and high-density coverboard can now be installed to the roof deck. Mechanically fastened or adhered roof systems may be used, but the use of mechanical fasteners through the entire roof insulation can adversely affect thermal perfor-

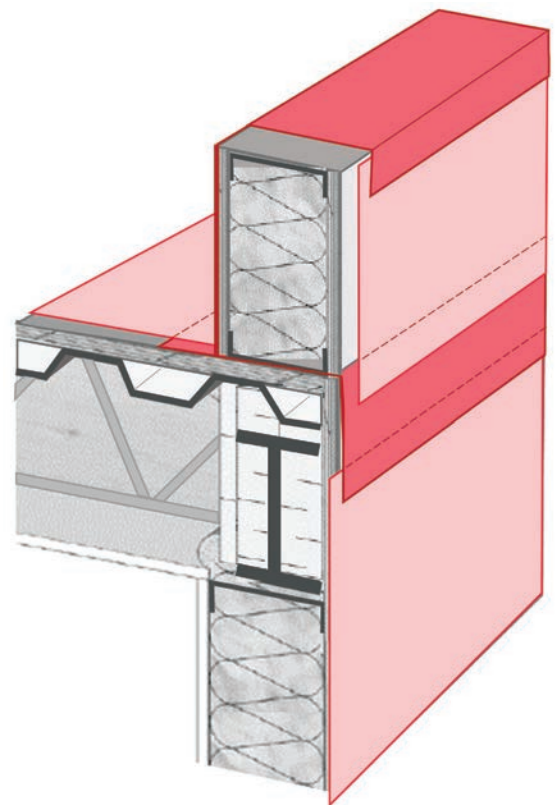


Figure 9. Air barrier integrated (staggered at section cut for sequence clarity).

mance of the building.¹⁴ Continuous insulation is also applied to the backside of the parapet wall to maintain continuity. Another option could be to install spray foam insulation inside the parapet at the deck level to “connect” the

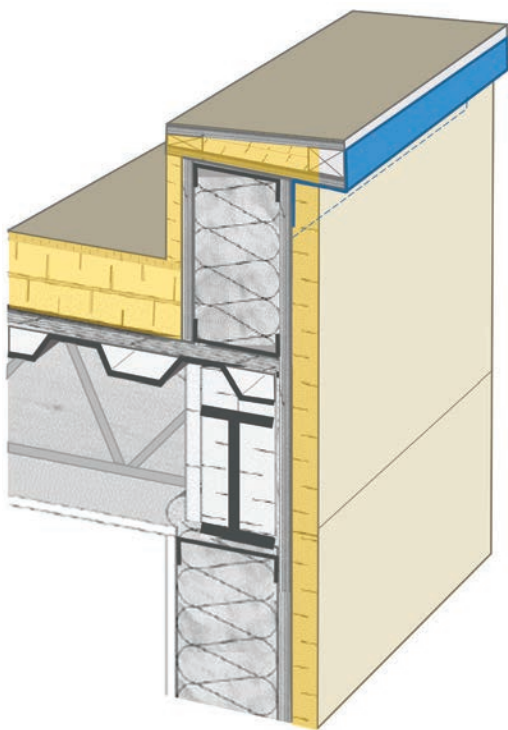


Figure 10. Continuous insulation installed.

roof insulation to the wall insulation, minimizing thermal discontinuities.

The parapet blocking for the coping cap can now be installed. In this case, it also includes a layer of tapered insulation to provide slope back to the roof area and extend the continuous insulation to the top side of the parapet. Wood blocking is included as required to accomplish fastening to meet uplift requirements of the ANSI/Single-Ply Roofing Industry (SPRI) ES-1 standard.¹⁵ After the parapet blocking is in place, a piece of counterflashing (shown in blue in Fig. 10) is required to lap over the WRB prior to the installation of the walls' continuous exterior insulation; flashing will later lap over the coping cap, but without this piece being preinstalled, there would be a discontinuity in the water control layer. The bottom edge of the flashing, under the wall exterior insulation, is shown as a dashed line in Fig. 10.

The roof membrane is applied to the roof area. An expansion joint may also be added at the joint between the roof and the parapet wall to allow for any expected movement between the systems. The mem-

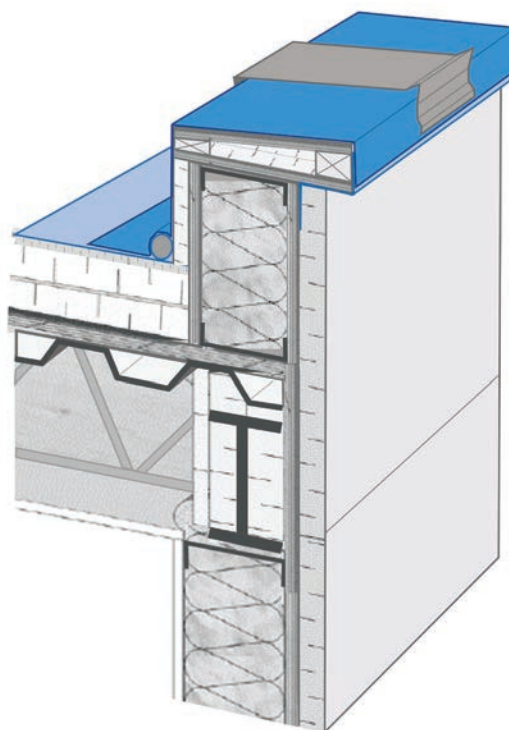


Figure 11. Roofing and terminations installed.

brane is then lapped, and seams are completed at the horizontal roof edge, extended up the backside of the parapet wall, and terminated over the previously installed counterflashing on the face of the coping blocking, as illustrated in Fig. 11. Terminating and lapping downward on the outside of the parapet wall

maintains the continuity of the water control layer and provides a shingle-lap onto the secondary water control layer on the wall. The membrane over the coping blocking will also act as a secondary protection below the future coping cap. The coping cap attachment cleats and concealed seam flashing are installed to the top edge of the parapet wall, bedding and treating the fasteners in sealant where they penetrate the membrane.

The exterior cladding is then installed to the outside of the parapet and exterior walls (light blue, as shown in Fig. 12). The coping cap is installed at the top of the wall, over the cleats and blocking (dark blue in Fig. 12). The coping cap and cleats should be attached as tested for their rating capacity by ANSI/SPRI ES-1,¹⁵ lapped over the cladding with drip edges on both sides, and maintain an

overall slope inward toward the roof system to shed water. Appropriate joinery methods should be used for the coping seams to ensure a watertight installation.

The parapet assembly is now complete, as shown in Fig. 13. During the service life of

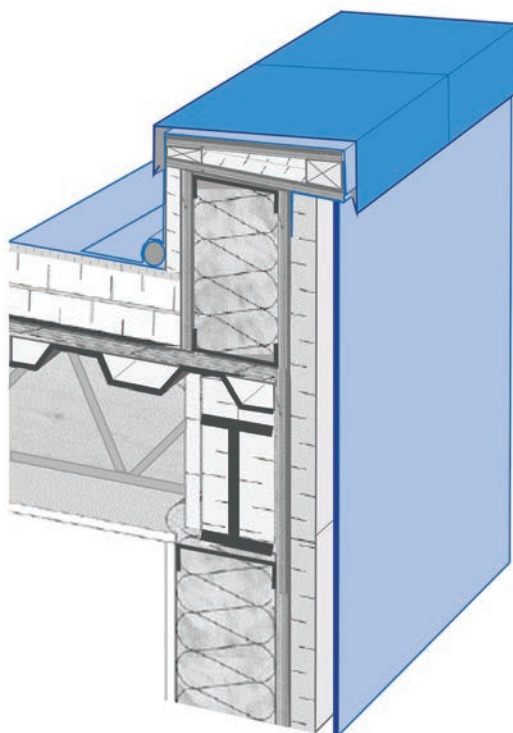


Figure 12. Coping and cladding installed.

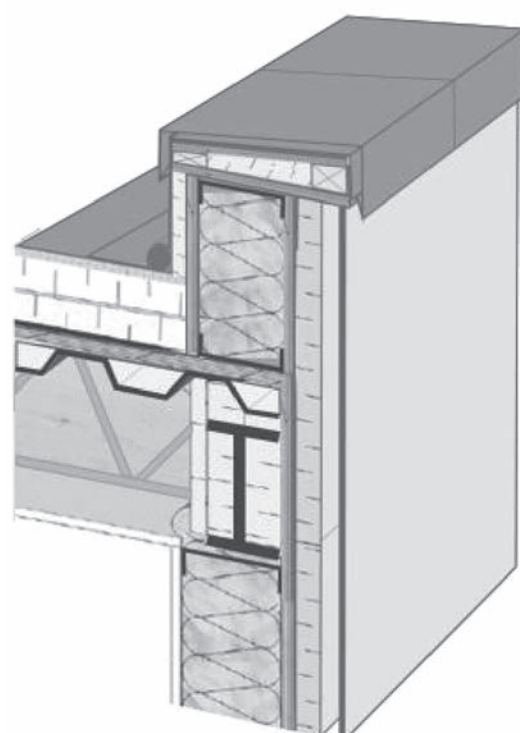


Figure 13. Final parapet assembly.

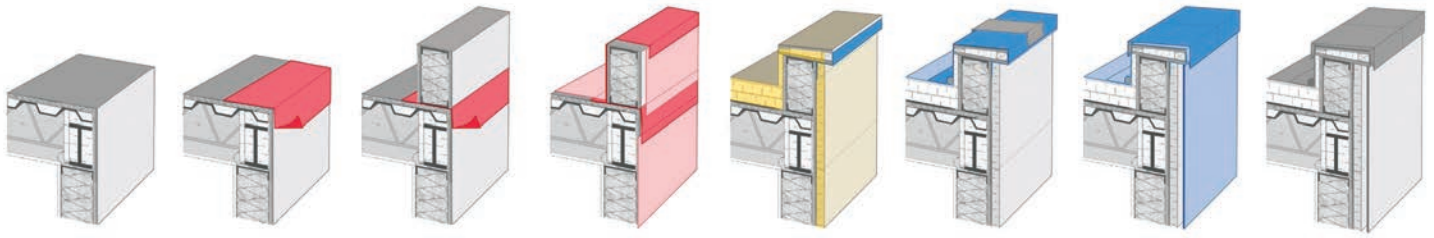


Figure 14. Parapet coordination sequence.

the building, regular inspections and maintenance are needed to retain the performance of the parapet's many roof, coping, and wall components. If the roof system is recovered or replaced in the future, as-built documentation should be used to understand how to continue to manage the wall and roof system control layers. Similarly, the initial design and construction should take into account future reroofing requirements.

Current design choices have been examined in the field. Research has shown that while a drywall ceiling can be designed and detailed to be adequately airtight, implementation can be confusing given the complexities of proper, long-term boundary layer construction. For example, Estrada reported "although it is simple to design an airtight drywall ceiling approach with a vented attic in a midrise building, it is difficult to implement an airtight drywall in practice and stay within the code's mandated target of 0.4 CFM/SF [cfm/ft²] @ 1.57 [lb/ft² (75 Pa)]."

Estrada noted that while implementation can be lacking, the complexity of the design is a strong influence to the overall successful implementation:

Once air barrier detailing is established, much of the burden is on the implementation of that air barrier design and on quality control of the installation. To put it another way, air barrier systems are not designed to meet specific numerical targets—you either have an air barrier design or you don't. Hypothetically, the same air barrier design that complies with a 0.4 CFM/SF [cfm/ft²] @ 1.57 [lb/ft²] (75 Pa) target should be able to comply with a 0.1 CFM/SF [cfm/ft²] @ 1.57 [lb/ft²] (75 Pa) target if the quality control in the field and sequencing of trades are managed carefully. When considering air barrier design, some approaches are more difficult to implement. The author's experience suggests that the more difficult a task

is to perform, the more likely it is to be performed incorrectly.

Many project teams tend to focus on material choices when it comes to ensuring proper air barrier performance. However, overall design of the building or structure may play a larger role. As Estrada¹⁶ explained, "The data seem to indicate that choosing between a vented attic and an unvented attic in design may have a more significant impact on the air barrier performance than the choice among distinct types of air barrier membranes at the wall." If buildings can be designed with ease of detailing in mind, wouldn't the logical outcome be greater long-term performance? For example, the use of can lights in a ceiling, while aesthetically pleasing to many, creates complex requirements to install an air barrier at the ceiling level that is continuous around all sides of the housing for the can light.

Placement of insulation in a roof system—above the deck, below the deck, or a combination of both above and below—can affect the placement of the air barrier and the ability for execution in the field. In most cases (with a few exceptions such as cold storage buildings), air barriers are most commonly located on the interior side of the insulation layer. Given that, when insulation is located above the deck, an air barrier can also be located above the deck. In contrast, when insulation is located below the deck, the air barrier—to be inboard of the insulation—is often at the ceiling level, which requires a more complex air-barrier installation.

CONCLUSION

Designing to maintain continuity of the four key control layers is important to ensure long-term performance. To implement the designer's intent in the field, detailing and identification of the control layer or layers in the drawings and specifications are critical, and code compliance is required. This can require the design to be fairly specific, providing more guidance than just "or equal" or "by others." Specifying materials with known compatibility is important. And if the sequenc-

ing of components and members in the field will impact the intended continuity or performance of the control layer in the design, that should be addressed during the design stage. Designers may wish to specify on-site mock-ups (Fig. 14) because they can be useful tools for determining construction sequencing.

Control layer challenges should be considered for every project. "Standard" details cannot capture project complexities such as high-to-low parapet transitions, terminations into a rising wall, and curtainwall flybys. These conditions all require unique detailing that must include continuous, well-conceived, and clearly communicated transitions. A building enclosure consultant can help the project team anticipate continuity and constructability issues. It is important to remember that control layer discontinuities can lead to failures in the field. For instance, air leakage can lead to concealed condensation, which can be mistaken for roof leaks.

The practice of preventing air leaking in buildings is becoming more commonplace. The industry is discussing design intent versus execution in the field, and there is still more to know about best practices. Are designs too complex for execution in the field? Do we have the products and the labor pool needed for success? Is the labor pool properly trained to execute in the field? Are construction timelines and schedules appropriate for the expected outcomes? Although there are many time-saving methods and tools, performing the precision work that is often required for air barrier installation requires time. 

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Twenty-Thousand Gallons versus Nine Ducks—Effective Communication in the Field, in Reports, and as an Expert Witness

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ABSTRACT

Effective communication—both written and verbal—is essential in our industry. Our written reports are often a large product of our services, and many times, they are the only deliverable our clients see from us. Reports must be clear, articulate, and accurate regarding the facts reported. Standards, such as the IIBEC *Manual of Practice* and ASTM D7186, provide guidelines for accurate reporting. We will review formatting, creative and liberal use of adverbs, providing facts, and maintaining third-party impartiality.

While on project sites, contractors, architects, engineers, and owners use different vernaculars and methods of communication to effectively relate to one another. We will discuss real-life situations where communication in the field is tailored to the parties engaged in the conversation, while consistent information is still relayed to all parties.

IIBEC members acting as expert witnesses need to clearly communicate as they discuss litigious items with attorneys, clients, juries, and judges. Depositions and testimony can be stressful as opposing members attempt to discredit and undermine experts' findings, and each side advocates for their clients. Experts must remain impartial, confident in their findings, and composed, regardless of the accusations.

SPEAKER



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Aaron Nelson, RBEC, RRC, RWC, REWC, RRO, is the president of Roofing Technical Services (RTS). He started in the roofing industry just after graduating from high school by working as a sheet metal fabricator/installer. After joining the office of a commercial roofing contractor in Seattle, Nelson worked as an estimator/project manager for 10 years. In 2004, he moved to the consulting side of roofing and started working on projects across the United States. Nelson and the team at RTS provide consulting and quality assurance observations for clients on projects throughout the nation, working with various code and climate conditions that make each project unique.

Twenty-Thousand Gallons versus Nine Ducks—Effective Communication in the Field, in Reports, and as an Expert Witness

Effective verbal and written communication as we work with clients, contractors, architects, and litigators requires us to understand the perspective of our audience. Failure to clearly present the facts, either verbally or in written form, and ensure that the recipient is able to understand the information behind what is presented can result in issues being easily avoided.

Consider the story of the two-duck versus the nine-duck pond: In a meeting with an architect and a contractor, an owner inquired about the size of a pond being built for him. The architect indicated that the pond would hold 20,000 gallons of water with waterfalls cascading into and out of the pond, utilizing a circulation method that would be concealed from view. The owner asked simply if the pond were a two-duck or a nine-duck pond. The contractor answered by discussing the method of construction using track hoes to dig the pond. The removed soil would be used to create a berm around the pond. As the discussions continued regarding size and shape and method of creating the pond, the owner again asked if the pond were a two-duck or a nine-duck pond. Again, the architect and contractor attempted to explain about volume and depth and flow. When the owner asked for the third time if the pond were a two-duck or a nine-duck pond, his representative informed him that it was a nine-duck pond. The owner was pleased, and the meeting moved forward. A simple inquiry from the owner became confusing because each professional answered from their own perspective and within their respective areas of expertise. The architect answered correctly with “design intent,” focusing on the form and function of the project, and the contractor replied correctly with “means and methods,” addressing the constructability procedures. While their answers were correct, neither considered the owner’s perspective, “end use,” in their responses so they failed to provide the information the owner wanted.

As we communicate with our clients, and work with contractors and architects, we often need to be experts in communication to ensure that we are clearly stating the facts, and that we are providing the end user with the desired information in an understandable manner.

Often a project will begin with a field visit. The project may be something small, such as a single-family residence where we may be interacting with a homeowner, or it may be a large building where we work with design and construction teams. Field visits often include interactions with others, and the communication will provide additional insight into the project. If we learn how the design intent was constructed in the field, by those who completed the tasks, we will have greater understanding of the project, and more information that can be documented. Project information will often be documented through field reports such as quality assurance (QA) or condition assessment reports. These reports capture information from the visits that provides snapshots in time of the project, and they may document items that seem insignificant at the time of construction. Projects occasionally have unresolved issues leading to litigation. Litigation may include hiring of attorneys for both sides, field visits, mediation, depositions, and expert witness testimony at trial. Each of these general categories: “in the field,” “in reports,” and “as an expert witness,” requires specific communication methods so that the end user has the information they need.

IN THE FIELD

While standing on a project site, we may find ourselves gathered with owners, architects, and contractors, discussing a particular detail, such as a base flashing at a mechanical curb.

Whereas the owner may want to hear that the roofing assembly extends from the roof to the top of the curb, the architect may want to know how much additional thickness the assembly adds to the overall dimension of the curb to ensure that the mechanical equipment will rest atop the curb correctly. The contractor, however, may want to understand how the base sheet is to be installed, if a cant at the base of the curb is to be provided, how high the field membrane should extend above the cant, how far the interply sheet should extend beyond the toe of the cant, and so on. The particular nuances of the installation of the assembly, while important to the owner and architect, may not need to be discussed at that exact moment. While the owner and architect are looking at the big picture, the contractor is looking at the distinctions of the specific installation methods.

If we learn how the design intent was constructed in the field, by those who completed the tasks, we will have greater understanding of the project, and more information that can be documented.

To ensure mutual understanding between the parties communicating, it is important to understand particular vernacular and installation methods for the regional location in which you are working. For example, asphalt roof cement is often used in asphalt-based roofing systems. Depending on the location, the product may be referred to as asphalt roof cement, plastic cement, mastic, or bull. Knowing the particular lingo of the region is important so that you can be sure that the correct products are used in accordance with the contract documents.

In addition, you should understand regional installation methods applicable to your project. These methods are sometimes overlooked during the bidding, contract execution, submittal or pre-bid-meeting portions of the project progression, but they are significant when installers are executing the work. For example, while performing a punch-list inspection of a project, a sheet-metal coping detail was examined with the coping installers. The architect's plans were examined, along with the approved submittals and the installed copings. It was clear that the fabrication style and installation method varied from the contract documents. The installers explained that this was the way that they always fabricated and installed copings in the region, and that they believed the regional installation method generally followed the "guidelines" of the contract documents. However, the copings installed using the regional method did not meet the contract requirements and the architect did not accept the work. Had the contractor discussed the difference between the contract documents and the planned means and methods, the issues could have been resolved prior to fabrication. Regional differences greatly impact a contractor's knowledge and skill levels, and may impact their performance. For example, a contractor working in northern Canada would likely have greater familiarity and expertise installing vapor barriers than a contractor working in southern Florida. Regional nuance and vernacular without clarity and understanding by all parties could be costly!

In addition to understanding the correct information to convey to each respective party, understanding the contractual responsibilities and proper channels (chain-of-command) for communication is equally important. In some cases, the owner of a project engage consultants as well as a contractor (this may be a general contractor who hires subcontractors) and an architect/engineer. On projects where

the consultant is not the architect or engineer of record, the owner may lean on the consultant to provide insight for proper contract administration; however, there is generally no legal standing for the consultant to direct any work, including stopping or starting crews, or making changes to contract documents. Therefore, when there are issues on the project site, consultants should refer to the contract documents for clarity, as these documents dictate the contractor's requirements. Pointing out any variance between the actual installation and the contract document in a professional manner will provide an opportunity to make necessary corrections. When such reminders are not effective in the field, it may be necessary to move from the site to the contractor's office, where conversations can include the contractor's project manager or owner.

Occasionally, these reminders are not heeded by the contractor in the field or in the office. In that event, the next step would be discussions with the project owner to advise them of the situation. The project owner has the contractual authority to provide direction to the contractor. Understanding this legal "line of authority" is important to ensure that, as consultants, we don't cross legal lines thereby potentially confusing the project and opening ourselves to litigation. For example, a contractor submitted a change order request based on changes made by the consultant in the field. Discussions ensued, ultimately resulting in a denial of the request because the consultant did not have authority to make changes to the work. This situation created animosity within the project team due to poor communication between the consultant and the installers, with costly results such as completion of work in excess of the contract documents. In contrast, there are times when the consultant may be contracted with the architect or engineer of record on a project. This contractual arrangement may allow for the consultant to have direction over the work if they have contractual responsibility for contract administration. Therefore, it's vital that we know and understand the contractual roles that we have in the completion of a project.

Similarly, it is important to recognize the authority of those you are working with and be respectful of that authority. If a roofing mechanic is making a mistake on the roof, we should alert the roofing foreperson, and allow them to make the correction with their roofing mechanic. This shows both the roofing mechanic and the foreperson that we are cognizant of the "chain of command" and

reinforces the proper delegation of responsibility among the contractor's work crew and the overall project from the roofing mechanic to the foreperson, to the project manager, to the contractor, to the owner.

Although communication between the consultant and the field crew is certainly subject to the legal lines previously discussed, that does not mean interaction is frowned upon. The foreperson may need help understanding specific details or language in the contract documents. In such cases, we can provide valuable clarity without directing the work. Furthermore, as installation methods may differ from the consultant's experience, a dialogue between the installer and the consultant can be helpful regarding why a particular method is being used. This type of field communication will not only increase the consultant's knowledge but can also allay suspicions that the installation may differ from contract documents. The free flow of information between the contractor and consultant helps ensure that there are not misunderstandings in the field that could be harmful to the outcome of the project.

My first exposure to the importance of effective field communication occurred early in my career. On a roofing project, the roofing foreman asked me about how I wanted a drain sump formed. I told him how I wanted it completed, and he responded with an odd look and an uncomfortable indication of understanding. I went to look at another part of the roof while work began on the sump. The foreman came to me again and questioned my response regarding the sump and we discussed it further. I realized that my previous description was wrong. I apologized and informed him that I had misspoken and provided an incorrect description. He was relieved and informed me that he knew it was incorrect and had waited to begin work until he could speak with me again. The confidence on the part of the foreman to return for clarification of something that he knew was wrong provided me assurance that the foreman wanted to install the assembly correctly. From this interaction, I learned that it is important to realize that our industry has many experts. The foreman in this example is an expert in the installation of that roofing assembly. His knowledge and expertise were essential in the completion of a successful project. By communicating effectively with each other, we were able to overcome differences in ideas and come to a successful resolution.

Site visits with a mentor can be learning

opportunities. I recall one of my first preconstruction meetings held onsite, wherein a manufacturer's representative and the site superintendent were shouting at each other and pointing fingers at each other aggressively for 10 to 15 minutes. I truly believed that a brawl was going to break out in a room of 20 or so people. I recall turning to one of my coworkers who had accompanied me to the meeting and asking if all preconstruction meetings were like this. That experienced coworker was able to explain to me the situation of that project and reassure me that, thankfully, not all site meetings are that intense. A mentor sharing an on-site visit can expand the learning of less experienced co-workers by elaborating on construction means and methods.

IN OUR REPORTS

Our industry produces a variety of reports for our clients. For the purposes of this paper, the discussion of written reports will be condition assessments and QA reports. These reports provide both factual information and opinions. It is important to maintain impartiality during the factual aspects of these reports. Opinions, recommendations, or other subjective items must have a basis of support and not be based on "like" or "don't like."

For general purposes, it is important to note that the readers of these reports may not have an intimate knowledge of roofing systems and materials. Therefore, common nomenclature is appropriate for providing a general overview of the subject matter without the use of detailed technical information. This approach allows the reader to understand the general concepts without needing to delve into the specifics of the assembly.

For example, let us compare two sentences:

- The roof is a four-ply built-up roof assembly with a mineral-surfaced cap sheet.
- "The roof is a BUR with three layers of Ply IV and a layer of Cap, all set in Type III,."

While both sentences are correct, the first sentence describes the assembly in general terms, whereas the second sentence uses specific nomenclature (material manufacturers will have even more specific nomenclature) that may require the reader to perform research to understand what the sentence is describing. When the specific assembly products are known, it is beneficial to outline the generic assembly, followed by a description of the materials. This allows the reader to

understand the generic assembly and have the information needed if delving into the specifics becomes necessary.

Condition Assessment

A condition assessment report is generally used to document the current condition of the structure for periodic system evaluations, when components are nearing the end of their service life, or when there are moisture intrusion issues. ASTM E2018-15, *Standard Guide for Property Condition Assessments: Baseline Property Condition Assessment Process*¹ includes information on the completion of the assessment and the report. The standard does not present a specific format to follow for the report, indicating that this should be decided between the end user and the consultant. We recommend that these assessments should contain the following items at a minimum:

Description

This portion of the report describes the building and has information regarding the various systems in place (roofing, wall, waterproofing). Historical information regarding the dates of installation, warranties in place, previous changes to original construction, as-built drawings and specifications, maintenance records, and other general information about the building should be included. It is important to differentiate between information obtained by actual knowledge and that reported by others or by documents provided for review. The sources of material information should be included in the report. Determining the composition of the building may involve topical observation, intrusive investigation, or both. If intrusive investigation is not performed, it may not be possible to verify the exact assembly. Applying a professional understanding of assemblies will allow the author to include items that "may be" or "are likely to be" included. For example, while examining a rainscreen system on a vertical wall, we may mention a weather-resistive barrier that is likely in the assembly but is not readily visible for verification. Verification of essential components may require cores or other intrusive investigation and should not be assumed.

Current Condition

This portion of the report provides the overall condition of the assembly and an estimate of expected remaining service life. This is an opportunity to identify specific conditions that may be in need of attention. The need to address each condition may be

immediate or preventive against continued degradation. Conditions of concern should be noted from most to least severe, to provide the client an order of priority for repairs or modifications. This is a simple method to evaluate the conditions and how they may impact the service life of the assembly. When discussing the conditions of concern, it is beneficial to use basic, subjective characterizations (such as "good, fair, or poor") or a grading system (such as A-Excellent, B-Good, C-Adequate, D-Marginal and F-Failure), along with descriptions of the characterizations/grades. It is important to provide a description and explanation for each condition of concern. This gives the reader an understanding of why a condition is characterized as it is, and what the potential impacts of doing nothing, or resolving the concern, could be, allowing the reader to make an educated decision regarding how to address the condition. Although many of the descriptions of the conditions of concern may be subjective, they should be based on the writer's expertise, not their personal biases regarding products or installation methods. For example, the creation of a "pig ear" in an inside corner of a single-ply roof may not be a writer's preferred method; however, if that installation method complies with the construction documents, it may be acceptable. Preferences of a writer should not be included without sound rationale to support them; otherwise, the preferences are subjective opinion and not in harmony with the impartiality that we strive for in our reporting. In addition, understanding the applicable building codes that were in effect at the time of installation is important for verification of correct installation methods. It's important not to apply current building code requirements to older installations that may have been completed according to prior code requirements. Consider a 25-year-old shingle installation on a residence, without a drip edge at the eave. It would be inappropriate in this instance to indicate a code violation due to the omitted flashing, as the code in effect at the time of installation likely did not require the flashing.

Recommendations

This portion of the report will provide recommendations for the system. A global recommendation for the assembly is best presented as the first item. This should be followed by recommendations to address the current conditions in the same order they were previously ranked, from most to least severe. Each area of concern noted should have a recommendation

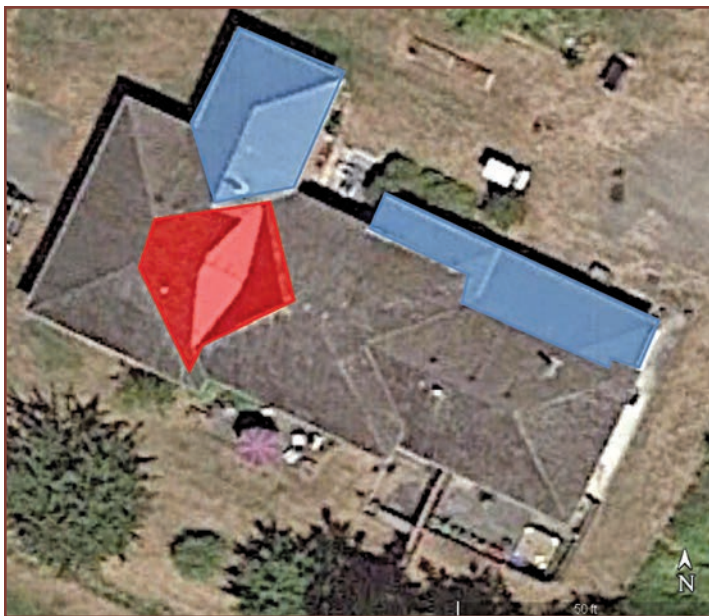


Figure 1. *Satellite view of residence.*

provided, even if the recommendation is not to do anything. This creates an easy reference from concern to recommendation. To facilitate the global recommendation, the line-item concerns and related recommendations should be first reviewed, and the level and extent of the work involved evaluated. During this evaluation, a newer application may have a small number of inexpensive recommendations that can increase the anticipated service life, whereas an older application may have many costly individual recommendations that may warrant removal and replacement as a better option. Therefore, the global recommendation for full removal and replacement may be warranted from the review of the related line items. Furthermore, understanding the owner's expectations for the building may influence the ultimate decision. For example, if a building that is slated to be demolished in the near future has an expired roof system, repairs identified in the assessment may be a more suitable and cost-effective approach than replacement. Costs associated with remediation for each condition of concern can be presented in the Recommendations section. These costs are often estimated by the author of the report. Another method is to obtain cost information from contractors qualified to perform the work either in the form of a budgetary range or a formal proposal. If the cost information is based on contractor's budgetary range or proposal, it is often helpful to provide that documentation to the client as an appendix to the report.

Photographs

Photographs are an essential part of most reports. The old adage that "a picture is worth

a thousand words" reminds us that we can include an appropriate number of photos representing various conditions in lieu of voluminous text. A typical report may include an elevation photograph of the building entry either as a cover page or on the first page of the assessment so that the client can clearly understand the building and its elements. Photographs are typically provided as supporting figures to the written assessment and are therefore located following the text. Photographs should have captions describing what the photos highlight; there might be a caption for a single photograph, or a caption could describe conditions shown in a group of related photographs. Captions should include a number notation that can be used as reference in the related report text or in discussions of the report. Overview photos can aid the reader in quickly understanding the basic essentials being discussed. Including photographs in the same order outlined in the Description portion of the report will provide consistency to the reader. It is important to note all photographs taken during the assessment do not need to be included in the report. Photographs included in the report should supplement the text, but they should not overwhelm the reader with excessive images of the same condition. For example, if the windows of an apartment complex are of similar construction and generally properly installed, there is likely no need to include photographs of each window. Boxes, circles, and arrows can be added to photos to highlight important elements. For example, while examining a residence that was not aligned with ordinate directions, I found the use of colored boxes extremely helpful to designate the various roof areas and materials (see **Fig. 1**). In the text of the report, I was able to state that the asphalt shingles were identified in red, the standing-seam metal panels identified in blue, and the remaining areas were cedar shakes. This helped the reader understand which steep-slope materials were being used, and in what locations. The use of a photograph and colored boxes made the writ-

ten description of the locations of the materials (referring to "red" and "blue") easy for both the author and reader to follow.

We recommend that consultants use a consistent methodology for every condition assessment survey and report. For example, when assessing a roof, a common reporting practice is to first discuss the building on which the roof system is installed, followed by a description of the roof system, including as much information as is known. A description of perimeter (or base flashing) conditions, slope, and drainage provisions follows. Large curbs with mechanical equipment, other curbs, and then penetrations would be a natural progression. By addressing items in logical sequence, from the largest item to the smallest (in terms of size), the author provides the reader with a flow that helps them understand the roof system. Consistently applying a particular method of organization makes it easier to gather information for each site visit and the draft the report because the process becomes repetitive. Additionally, if a consultant assesses multiple buildings for a client, each of the consultant's reports will be uniform. If there are multiple buildings on the same property, only one report including information for all buildings should be created.

QA Reports

QA reports are used while construction on a project is underway to provide a snapshot of the project's progress. These reports—which can be daily (meaning that the observer is on site each day work is progressing) or periodic (meaning that there are days of work progressing between site visits)—provide an essential service to our clients by providing a timeline of the events that are occurring on their project. For example, while preparing project documents for a roof replacement, review was made of original QA reports, which showed changes to the specified, bid, and submitted system. Further digging revealed approvals of the changes; however, the review of the QA reports provided critical information for the development of project documents.

It is important to note that ASTM D7186-14, *Standard Practice for Quality Assurance Observation of Roof Construction and Repair*² includes an "Observation and Recording Procedures" section. The standard prescribes guidelines for QA observation practices and recommendations for the accompanying report. Additionally, IIBEC has similar recommendations in the *Manual of Practice*.³ Gleaning from ASTM D7186, and the *Manual*



Figure 2. Example of satellite roof plan.

of Practice, we can identify key items to include in the QA report to establish a written and photographic record. Above all, QA reports should be clear, concise, objective and accurate in describing events.

Both ASTM D7186 and the IIBEC Manual of Practice include a sample form that can be reviewed and used as an appropriate QA report format. A minimum of six photographs is recommended for each report, and once the report is complete, it should be distributed in a timely manner, no later than prior to the beginning of work the next day. The rapid delivery of the reports aids in the communication of essential items to all the parties. This is particularly important when there are unresolved defects that may require the involvement of other parties in addition to the on-site crew.

One item that is briefly discussed in ASTM D7186 is the inclusion of a roof plan, which can show the reader the progress of the project at a given point in time. This plan can be as simple as a satellite image (see Fig. 2) with boxes imposed over the sections of work area and a key indicating what the colors represent. Degrees of opacity may be used to show the previous day's work, with a solid fill representing the reported day's work. This contrast in opacity allows the reader to see progress of the day, along with project's prog-

ress. Additionally, the use of different colors for various aspects of the scope of work is helpful to show multiple progress areas on one plan. The use of the same color schemes from project to project will make the reporting easier, and if the reader is a repeat client, they will be familiar with the report format.

Conciseness and Revision

Although ASTM D7186 is specific to roofing, similar reporting formats can be used for all aspects of building enclosure elements. In discussions with many clients, we have found that a fairly concise reporting format is appreciated and provides the best balance of necessary information for their daily review, and historical information for recording purposes. For many years, our format has generally followed the ASTM and IIBEC recommendations, with slight upgrades as technology allows. Clients have stated that they jump from the description of the day's events to the defects and resolutions section, to the photographs showing the day's work, and finally the plan showing the day's completed work.

Spending 10 years on the contracting side of the roofing industry prior to coming to the consulting side provided me with a large amount of knowledge and experience regarding the application of roofing; however, drafting reports was not included as a part of

my experience. When I wrote my first report for the consulting firm I worked for, my boss indicated that he would "bloody" up the report. Using a red pen, he deleted and inserted comments throughout the report—truly creating the "bloody" result he had promised. Following that experience, I strived to improve. Each time that you write a field report, condition assessment report, or a paper submitted for publication, you may expect the review process to be bloody. However, each time there is opportunity for powerful improvement with practice.

There are opportunities to submit exceptional reports through IIBEC's Document Competition, and to review these reports at the yearly conventions and through Interface. Reviewing reports prepared by others provides an opportunity to look for areas of improvement for our own reports, elevating our industry. Peer review of our reports provides an opportunity for a fresh set of eyes to review language, spelling, grammar, and sentence structure that we often miss when drafting reports ourselves. While reviewing our own work, our brains have the ability to fill in information that may be omitted from the written format and having a peer review of our reports helps find the gaps in thoughts and understanding.

Often in our office, we will "cross-examine" each other while reviewing reports if we

identify statements that might not be defensible. For example, in a report about a building that was completed long ago, the author stated that they could tell that the installer was a skilled sheet-metal worker. The author didn't know the installer, nor did they know the skills that the installer possessed, but they made an assumption about the installer based on the condition of the flashing. This statement should have been changed to describe the quality of the flashing, and not qualifications of the installer, thus reflecting the facts and not assumptions. By reporting facts without interjection of opinion, we can make reports that are not questioned.

EXPERT TESTIMONY

Rule 702 of the Federal Rules of Evidence⁴ states, "A witness who is qualified as an expert by knowledge, skill, experience, training, or education may testify in the form of an opinion or otherwise if: (a) the expert's scientific, technical, or other specialized knowledge will help the trier of fact to understand the evidence or to determine a fact in issue; (b) the testimony is based on sufficient facts or data; (c) the testimony is the product of reliable principles and methods; and (d) the expert has reliably applied the principles and methods to the facts of the case."

From the moment that an expert is engaged in a litigation case, they must be aware of all their communication. Written notes, emails, draft reports, phone conversation notes, and other written items may be subject to discovery and could be used to determine the expert's credibility. It should be noted that litigation is pursued when parties previous attempts to settle a disagreement fail, typically due to misconstrued or misunderstood facts. Therefore, the expert's objective is to examine the facts in evidence of the case and provide an opinion based on those facts, regardless of where those facts may lead. Although we are often retained by one of the litigants, our role is to be a neutral third party who analyzes and presents the facts. The expert role is different from the consulting role, where we are our client's representative. This distinction is important. While reading the deposition of an opposing expert, I noted that the expert indicated they are to be an "advocate for their

client." This indicated that their role was to represent their client's interests, not to serve as an independent and unbiased third-party expert.

A deposition is the process wherein attorneys examine persons involved in the case, to learn and provide clarity about that expert's trial testimony. This written transcript may be used at trial to challenge statements the expert makes while on the stand. When you are an expert witness, it is essential that you thoroughly review ahead of the deposition your understanding of the facts in evidence, all documentation that you have produced, and reports issued by others relating to the case so that you are prepared for questioning.

Answering questions clearly and answering the specific question that was asked are critical in legal proceedings. During questioning, it is essential that you clearly answer the

full question and understand the questions that are asked. If a question is unclear, or if multiple questions are being asked at one time, you must ask for clarification so that you can properly and accurately answer the questions. During an RCI Convention class, Carl Cash indi-

cated that he would take a three-second pause after each question during questioning. This tactic ensured that he did not attempt to answer a question that had not been fully asked, and it provided time for him to think of the accurate response for each question.

Once a deposition is complete, the recorder will send copies of the deposition to the various parties to review and verify that the recording of the deposition is accurate. One of the items that I review is the listing of words used, generally in the back of the deposition, to see how many times unclear words, such as "un-huh" or "uh-uh," were used during the deposition. In the context of the deposition transcript, these "pause words" are distracting and result in difficulty understanding the testimony. In contrast, a three-second pause is not reflected in the transcript and using clear, concise verbiage offers the readers a clear understanding of your answers. Head nods

or shakes, shoulder shrugs, and other similar nonverbal responses must be avoided during deposition and trial, as they may undermine the clarity of the verbal response.

I was involved in a litigation project where I performed a condition assessment of a roof with moisture intrusion issues. During the assessment, I spoke with the building owner and her contractor, who expressed their opinions prior to my assessment of the roofing system. Despite their opinions, I performed the assessment by topical examination and prepared a condition assessment report. The project eventually progressed to litigation.

During my deposition, I was asked to produce documentation regarding the interviews performed with the owner and contractor. When I indicated that there was no documentation because I simply listened to their comments and based my assessment on the topical examination, I was accused of spoliation of evidence. Spoliation of evidence is where there is intentional, reckless, or negligent withholding, hiding, altering, fabricating, or destroying of evidence relevant to a legal proceeding. That is clearly something that would violate the IIBEC Code of Ethics,⁵ which states that the member "shall exercise unprejudiced and unbiased judgement and conduct when performing all professional services."

Listening to all parties involved in litigation provides some measure of information; however, each side has differing opinions (as evidenced by the litigation proceedings). The information gleaned by listening to the parties may not contain any actual facts and likely is skewed by the parties and their anticipated results of the litigation. Obtaining information and relying on the facts of the case is the role of the expert witness. Such witnesses are not

obligated to record all interactions and conversations between parties, particularly if there are not any facts obtained during the conversations. However, the spoliation of evidence accusation made by the attorney against me is one of several techniques that may be used to try to discredit and unsettle

an expert during a deposition.

Mistakes are unfortunately a part of the communication process, and they are made often. The ability to admit fault when you make a mistake is a critical part of good communication. By admitting fault quickly and offering a resolution to the error, we show

Q. Could you give me an idea of what type of services (consulting firm name) provides?

A. Yes.

uh-huh
5:15 106:17
uh-uh
5:15

others how we respond to adverse situations. I recall a deposition wherein I made a statement and subsequently realized that it was incorrect. I corrected the statement as soon as I recalled the correct fact, and the attorney questioning me indicated that he had intended to bring up the misstatement later in the deposition as he realized that I had erred. If that had happened, the attorney might have used my error to discredit my testimony. By admitting that I made a mistake, and correcting it as soon as possible, I ensured that little, if any, damage was done.

In a deposition, the attorneys representing the litigants usually have an understanding of construction in general, as well as specific knowledge regarding the scope of your testimony. This may make the descriptions and explanations of various aspects of your testimony less exhaustive during deposition than during trial. The trier of fact, either a judge or jury, likely has little knowledge regarding your area of testimony.

This means that our communication must change so that our testimony is expressed in such a way that a layperson can understand it. While testifying at a recent trial, I was explaining that the required number of fasteners holding a standing-seam metal roof in place was not sufficient, based on the manufacturer's requirements. When asked what damage would be caused by this, I indicated that I did not know, but it was similar to an automobile tire that has four lug bolts, but only three nuts on the bolts. I didn't know if there was any damage, but I wouldn't want to drive very far that way. In taking something specific to our industry (the panels had 75% of the required fasteners), and using an item that is fairly relatable in general knowledge to illustrate my

point, I was able to help the trier of fact understand the unknown issues with insufficient fasteners in this application.

When preparing for deposition or testimony, it's often helpful to review a mentor's transcripts from other cases. This may provide insights regarding potential methods of questioning and questions that may be asked of you. An example of this would be a fairly standard question, "How much are you being paid for your testimony today?" If asked that question without preparation, one may refer to the standard fee chart and calculate the time involved and achieve a monetary answer. However, the question is framed to set you up as a "hired gun" and to provide an opportunity to discredit your integrity by implying that you are not providing independent testimony, but rather testimony that is bought and sold. A correct answer would be, "I'm not being paid for my testimony; I'm being paid for my time to testify." This response correctly establishes the facts that the testimony is not for sale, but the time to testify is.

CONCLUSION

Communication is a skill we develop throughout our lifetimes. As we strive to improve our communication skills, our mistakes will decrease in number and the output will improve, both written and orally. Although our respective ponds may hold any number of skill sets, there are nine "ducks of thought" that I'd like to stress regarding our communication:

- Duck 1. Correct mistakes rapidly.
- Duck 2. Repetition is the mother of all learning.
- Duck 3. Practice testifying, writing, communicating.

- Duck 4. Consultants do not direct the work.
- Duck 5. There are many experts that make up a project team.
- Duck 6. Peer review is power review.
- Duck 7. "Bloody" reports are opportunities for improvement.
- Duck 8. Answer the question that is asked clearly and factually.
- Duck 9. Make sure that your correct answer correctly answers the question. 

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The Leak Stops Here: Understanding the Methodology of Leak Detection for Roofing and Waterproofing Systems

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ABSTRACT

This intermediate-level presentation is intended for owners, designers, and contractors. Portions of the building enclosure's water barrier subjected to hydrostatic water pressure must be waterproofed to prevent water infiltration. For the purposes of this presentation, waterproofing can be in the form of a roofing or waterproofing membrane. Roofing and waterproofing membranes need to be evaluated for continuity prior to the completion of original construction. This matter is of special concern if the application will be covered with a cladding system or overburden that makes access to the application difficult throughout the life of the building.

This paper will take a deep dive into water testing and other available test methods, such as high-voltage and low-voltage electronic leak detection, infrared testing, and electrical impedance testing. Testing does not replace visual observations during construction—it only confirms the initial performance of the membrane. A checklist of critical items to observe prior to, during, and after an installation will be discussed along with the recommended testing methodology.

SPEAKERS



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John Posenecker joined Terracon in March 2015. A registered mechanical engineer, he is on the Building Enclosure Council (BEC) National Board and is a board member and Technical Committee cochair for the Air Barrier Association of America. His experience includes the design, construction, testing, and forensic investigation of building enclosure systems. Posenecker has participated in a wide variety of projects associated with enclosures, including containment systems for commercial nuclear power plants, noise control systems for commercial and institutional projects, and waterproofing systems for a wide variety of commercial high-rise and low-rise buildings.

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The Leak Stops Here: Understanding the Methodology of Leak Detection for Roofing and Waterproofing Systems

Portions of the building enclosure's water barrier that may be subjected to hydrostatic water pressure need to be waterproofed in order to prevent water infiltration. This paper focuses on both horizontal waterproofing membranes and low-slope roofing membranes. Because these are often covered with some type of overburden, the remediation of water leaks can be very expensive and disruptive. Roofing and waterproofing membranes need to be evaluated for continuity immediately following their installation and prior to the completion of the original construction project. This is especially important if the membrane will be protecting occupied spaces or difficult to access during the remainder of the building's life.

Historically, testing of horizontal waterproofing and low-slope roofing membranes has been attempted with flood testing. There are many limitations and difficulties with water testing. If leaks are observed during water testing, it is very challenging to find the actual breach in the membrane that is the source of the water. Also, small leaks may not release enough water during the relatively short duration of water tests to result in the observation of water beneath the supporting structure. This paper will take a deeper dive into flood testing and other available test methods, such as high-voltage and low-voltage electronic leak detection (ELD), infrared testing, and electrical impedance testing.

Testing and building enclosure consulting services should be contracted by the owner/developer directly to help ensure their services are performed in the best interest of the owner/developer and are independent of any contractual or employment obligation to the contractor(s), design team, or manufacturers associated with a project. While test results may validate the performance of waterproofing or roofing systems, testing alone should not be used to replace tough scrutiny of the design or quality assurance measures such as mock-ups, preconstruction and coordination meetings, and confirmatory field observations



Figure 1. Flood testing.

during construction. Some manufacturers may require testing for certain warranties and require that the testing be coordinated through the manufacturer. In this case, the testing should still be performed by a qualified third-party testing agency and specified as such in the contract documents.

There are several ASTM standard guides and practices for evaluating and locating leaks in waterproofing and roofing systems. There is no one method that will provide all the results needed. A strategic approach utilizing several testing methods in combination is typically required. The following provides some explanation of the most widely used tests and how they may be incorporated into a successful strategy for locating breaches in low-slope waterproofing and roofing membranes.

TESTING STANDARDS

Water Testing: ASTM D5957, Standard Guide for Flood Testing Horizontal Waterproofing Installations¹

This guide addresses flood testing of waterproofing membranes installed over habitable spaces on elevated horizontal surfaces having a slope no greater than 2% (¼ in. per foot). It is not intended

to be used for testing of building roofing systems. This guide is intended to be used for testing of fully adhered sheet membranes, fluid-applied membranes, or loose-laid sheet membranes. During flood tests, areas may be temporarily subdivided for convenience and drains within the test area may be temporarily blocked. Typically, water (1 in. minimum to 4 in. maximum) is held in the test area for 24 to 72 hours. The test should be constantly monitored so that no unintended changes to the water level are made and to identify any leakage. If leakage is identified before the test period has been completed, the observers should immediately suspend the test and drain the water so that any damage is minimized. A

Roofing and waterproofing membranes need to be evaluated for continuity immediately following their installation and prior to the completion of the original construction project.



Figure 2. Electronic leak detection—high voltage.

separate, adjacent, small test specimen should be used to compare water-level changes that may result from evaporation.

ELD Testing: ASTM D7877, *Standard Guide for Electronic Methods for Detecting and Locating Leaks in Waterproof Membranes*²

This guide addresses electrical conductance measurement methods that can be used to locate breaches in waterproofing and roofing membranes. It is limited to use on membranes that are considered to be electrical insulators and that are directly over substrates considered to be electrically conductive. Low voltage and high voltage are the two basic types of ELD testing. For this paper, consider low voltage as less than 50 volts and high voltage as greater than 10,000 volts. Several variations of low-voltage ELD testing are covered in this guide. Electric field vector mapping is the most common low-voltage testing technique used and will be the focus of this paper along with high-voltage testing. Low-voltage methods require a path of water across the membrane and through any overburden to any breach in the membrane.

Infrared Testing: ASTM C1153, *Standard Practice for Location of Wet Insulation in Roofing Systems Using Infrared Imaging*³

This practice applies to infrared imaging techniques used at night for the purpose of locating wet insulation beneath a roofing membrane and above a waterproofing membrane. Several weather-related parameters affect the ability of infrared imaging to locate thermal anomalies:

1. Inside to outside temperature difference. The larger the better.
2. The rate of change of temperature in the hours prior to viewing. The larger the better.

3. The amount of sunlight prior to viewing. The more the better.
4. The wind speeds. The lower the better.

Many times, these are not present and greatly reduce the effectiveness of infrared imaging. Materials covering the roof membrane also reduce the effectiveness of infrared imaging. The more heat-holding capacity and higher thermal insulating properties of these materials, the less effective the infrared imaging will be.

Electrical Impedance Testing: ASTM D7954, *Standard Practice for Moisture Surveying of Roofing and Waterproofing Systems Using Nondestructive Electrical Impedance Scanners*⁴

This practice applies to electrical impedance scanning techniques used for the purpose of locating moisture and evaluating the comparative moisture content beneath low-slope waterproofing and roofing membranes. The membranes to be surveyed must be electrically nonconductive and installed over electrically nonconductive thermal insulation. Membranes that include conductive materials such as EPDM or other conductive additives cannot be accurately scanned. Metal and other electrically conductive materials at or near the surface of the membrane may also skew the results of the impedance scanning.

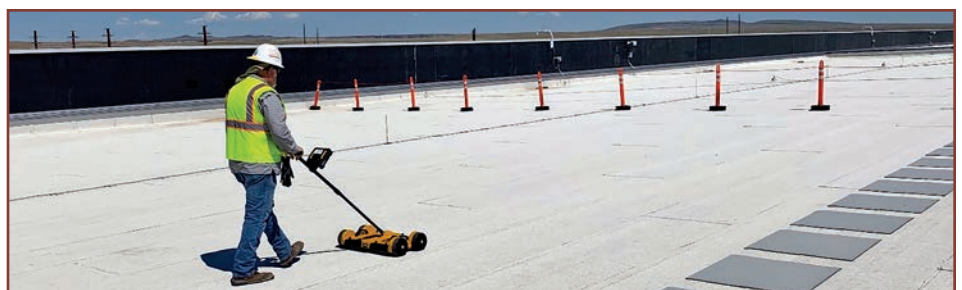


Figure 4. Electrical impedance testing.

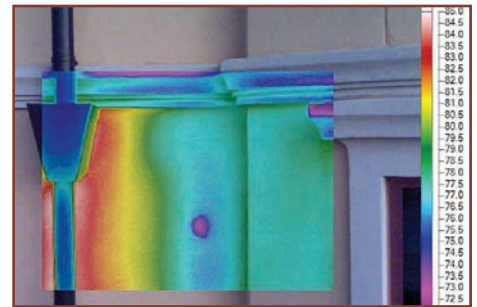


Figure 3. Infrared image.

ACCEPTANCE TESTING OF NEW MEMBRANES

Testing That Relies on Water

Many of the methods available for testing newly installed horizontal waterproofing membranes and low-slope roofing membranes rely on water. In the case of flood testing, water is introduced on top of the membrane with the intent of creating water infiltration past the membrane to expose leakage paths. In the case of infrared testing, evidence of water infiltration will only be detected if the substrate near the water leak is relatively wet and there is an adequate temperature differential for the moisture to be detected. In the case of electrical impedance testing, the same conditions must exist as for infrared testing, but the necessity to sense temperature differentials is not required.

Flood, infrared, and impedance tests rely on a saturated substrate beneath the waterproofing or roofing membranes to identify water leakage, indicating there is a breach in the membrane. If there is a breach in the membrane but there is not adequate water in the substrate, the test may not identify any problems.

In the case of flood testing, the size and location of breaches in the membrane may not pass enough water into the substrate for visual identification. The substrate's capacity to hold water may also prevent visual identification of leakage if the duration of the test is too short.

In the case of infrared and electrical impedance testing, there may be a breach in the waterproofing or roofing membrane, but either the membrane has not experienced a water event

resulting in water infiltration or the water from previous infiltration has dried. The result may be that the test provides results indicating there is no presence of water/moisture beneath the membrane and giving the false impression that there are no breaches in the membrane. This is the reason that infrared and electrical impedance testing are not the best choices for performance/acceptance testing of new waterproofing and roofing membranes. These tests are good diagnostic tests if there are known active leaks in the membrane. They may help focus other testing methods more suited to locating breaches in the membrane to areas that have water/moisture beneath the membrane.

Most low-voltage ELD testing requires the entire top of the membrane being tested to be kept wet for the duration of the test and requires a conductive substrate in direct contact with the membrane being tested. A low voltage potential is created across the membrane being tested by connecting one side of a direct-current voltage source to the structure/substrate beneath the membrane being tested. The other side of the voltage source is connected to two testing probes. Electrical current induced by the voltage potential will flow from the test probes through the water on top of the membrane and down to the structure below through the completed electrical circuit at breaches in the membrane. This type of testing can very accurately locate very small pinholes or thin spots in the membrane. There are, however, several other considerations before selecting this method of testing:

1. The area to be tested by low-voltage ELD requires that it be electrically isolated from the surrounding areas and the structure below so that other sources of low voltage do not interfere with the test. The result is that many times, items penetrating the membrane that are electrically conductive are isolated from the test. These items typically are rebar, sleeves, piping/conduit, and drain bowls. Unfortunately, penetrations in a membrane are the source of a large percentage of water leaks.
2. Because water is required on top of the membrane, it is difficult to maintain wetness on vertical surfaces. This results in vertical turn-ups, which are another source of a large percentage of water leaks, being isolated from the test.
3. Because water is required on top of the membrane, if there are breaches in

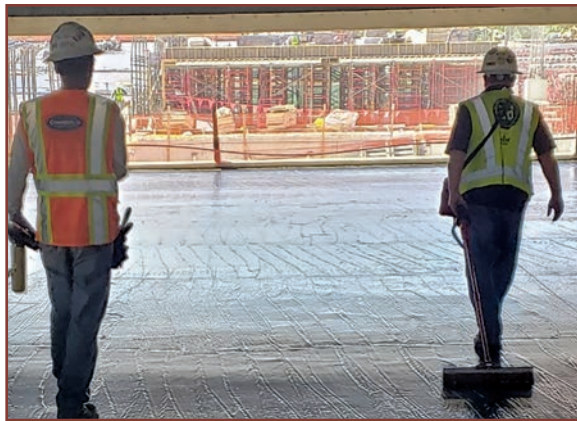


Figure 5. High-voltage electronic leak detection.

the membrane, water infiltration may occur, resulting in additional damage to the substrates.

4. Because water is required on top of the membrane and many membrane repair methods require the surfaces to be dry, repairs to identified breaches in the membrane must be conducted at a different time. This may result in additional unplanned mobilizations for testing.

While ELD is a very accurate means of finding breaches in waterproofing and roofing membranes, for the reasons discussed previously it is not viewed as the best option available for performance/acceptance testing when compared with high-voltage ELD testing.

Testing That Does Not Rely on Water

High-voltage ELD testing is very similar to low-voltage ELD except that water on the surface of the membrane is not required and there is no need to electrically isolate the area of membrane being tested. This eliminates the difficulties caused by the introduction of water and allows testing of 100% of the membrane, including portions around penetrations and vertical transitions, which are the source of a large majority of leaks. Our testing crews experienced in both high-voltage and low-voltage ELD testing prefer the high-voltage ELD. The benefits they cite for high-voltage testing as compared with low-voltage testing are as follows:

1. The setup and cleanup times are much less because



Figure 6. Low-voltage electronic leak detection.

there is no need for a continuous application of water and there is no need to install perimeter isolation wires.

2. One person can easily test alone, therefore increasing productivity.
3. Breaches in the membrane can be identified, repaired, and retested the same day.

There are two limitations to both types of ELD testing that must be considered. The substrate beneath the waterproofing or roofing membrane must be conductive so that the only resistance preventing a flow of electrical current is the membrane being tested. For instance, if there are layers of material (insulation or cover board) beneath the membrane that block the flow of electrical current, then the flow of electrical current will be prevented by the insulating materials. This will prevent the identification of breaches in the membrane.

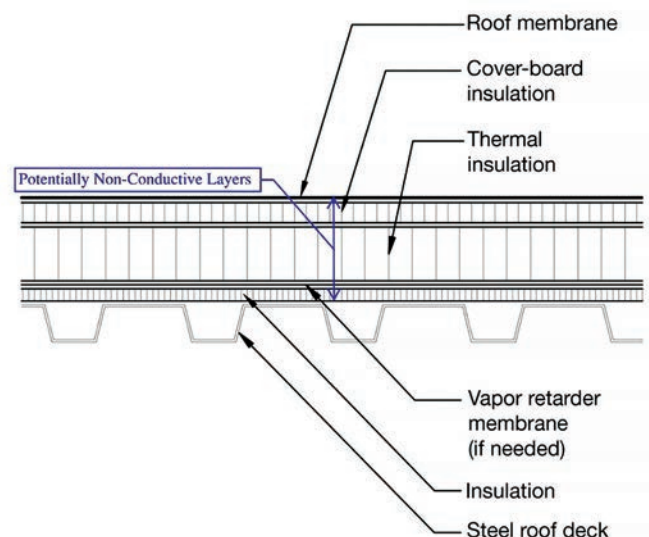


Figure 7. Typical low-slope roof section.



Figure 8. Low-slope roof with vegetative overburden.

The second limitation is that the membrane being tested must be nonconductive or, in other words, have a high resistance to the flow of electrical current. For example, membranes that include conductive materials such as EPDM or other conductive additives cannot be accurately tested.

TESTING OF IN-SERVICE MEMBRANES

ASTM D7053, *Standard Guide for Determining and Evaluating Causes of Water Leakage of Low-Sloped Roofs*,⁵ addresses methods for evaluating and identifying sources of water leakage in low-slope roofing systems that have active water leaks. Infrared and electrical impedance testing are both methods recognized by this guide that may be considered for use during the inspection phase to identify the suspect portions of the roofing system. Once the suspect portions of the roof system have been identified, diagnostic water testing to reproduce water leaks may be employed. ELD testing may now be useful if previously

nonconductive substrates become conductive in the presence of water. It should be noted that this guide is not intended for construction quality control performance/acceptance testing.

Because most waterproofing membranes do not tolerate exposure to ultraviolet light, they are covered with a variety of different materials. These materials, which we call overburden, are costly to remove when the membrane must be exposed in order to locate the source of leakage or repair the membrane. Without special provisions for monitoring water/moisture beneath the waterproofing or roofing system, low-voltage ELD is the only testing method available that may be capable of locating breaches in the membrane. Many times, removal of overburden is determined necessary to allow inspection and testing of the membrane.

CONCLUSION

For new waterproofing and roofing membranes that have a conductive substrate

beneath the membrane, high-voltage ELD testing is the most comprehensive, efficient, and accurate method of locating breaches in the membrane. Unfortunately, for waterproofing and roofing membranes that have a nonconductive substrate beneath the membrane, there are no testing methods to locate breaches in the membrane without recreating the leak with water. 

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Cladding and Building Enclosure Component Connections through Foam Plastic Continuous Insulation: Design and Prescriptive Code Compliance

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ABSTRACT

Cladding and building enclosure component connection details are important to the overall performance of a building enclosure, including resistance to loads and durability. However, they must also be coordinated with energy code insulation requirements, which are increasingly recognizing the benefits of continuous insulation and requiring its use. When coordinated with improved water- and vapor-control methodologies in the latest building codes, continuous insulation provides a means to improve energy efficiency (minimize thermal bridging) and provide a thermally stable and dry environment for the enclosed building components. However, cladding connections must extend through this layer of continuous insulation. This paper reviews the research and latest prescriptive code requirements for attaching claddings through a layer of exterior continuous insulation. It also presents a generalized design procedure that can allow various types of fastener connections through foam plastic insulating sheathing, including the attachment of cladding, furring, and even structural components such as roof and deck ledgers. These advancements provide building enclosure designers with a means to efficiently design, specify, and detail various cladding and component connection options in coordination with energy code and building code requirements to maximize the continuity of the thermal enclosure and overall integrity of the building enclosure.

SPEAKER



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Jay Crandell has over 30 years of experience in construction, engineering, and innovative building technology research for private- and public-sector clients. He has conducted benchmark studies of major natural disasters as well as research to address significant structural, energy, and building science challenges. His work has helped to propel many innovative technologies into the International Code Council's codes and consensus standards. He has published on various engineering, construction, and building science topics. For additional information visit www.aresconsulting.biz and www.appliedbuildingtech.com.

Cladding and Building Enclosure Component Connections through Foam Plastic Continuous Insulation: Design and Prescriptive Code Compliance

Continuous insulation provides a means to comply with modern energy conservation codes and can provide various other building code-required functions for building enclosures. Continuous insulation is defined as follows in the *International Energy Conservation Code* (IECC)¹ and ASHRAE Standard 90.1:²

Continuous insulation (c.i.): insulation that is uncompressed and continuous across all structural members without thermal bridges other than fasteners and service openings. It is installed on the interior or exterior or is integral to any opaque surface of the building enclosure.

This definition allows some limited thermal discontinuity to occur for fasteners attaching components such as the c.i. material, cladding, fenestration, and even structural ledgers placed on the surface of a c.i. to avoid major thermal discontinuities (such as, thermal bridging). Even so, the amount or size of these fasteners should be specified to minimize their cumulative effect as relatively small and repetitive point thermal bridges.³ But these fasteners must also be able to adequately transfer the weight of cladding, furring, fenestration, or structural loads from ledgers that are surface mounted and attached over a layer of c.i. These two competing design objectives should be optimized and the content of this paper provides guidance for that purpose.

BACKGROUND

The use of only fasteners to attach cladding and other exterior architectural or structural building components through a layer of c.i. is not without its challenges. First, the c.i. material must have sufficient compressive resistance or rigidity to resist fastener draw-down forces during installation and shear-transfer reaction forces that may cause compression during service. For example, if an exterior insulation

material is not sufficiently rigid (that is, has low resistance to compressive deformation), it will tend to compress due to these connection forces. In such cases, the code definition for *continuous insulation* will not be satisfied because the thermal performance of the insulation layer is altered (that is, not continuous in thickness or R-value).

A common example of this compression condition occurs when metal roofing and siding panels are installed over blanket insulation that is placed over purlins and girts in metal building construction. Consequently, other means of attachment or support of cladding and exterior building components through a layer of compressible exterior insulation may become necessary to avoid compression, such as the use of steel shear tabs, metal Z-furring projecting through the exterior insulation layer, or specialty thermal break support devices. Because these attachment methods use elements that are not fasteners as required by the definition of *continuous insulation* (and can be substantial thermal bridges), the exterior insulation and cladding support method would not comply with the energy code's definition of and prescriptive R-values for c.i., even though it solves the compression problem.

These practical difficulties do not mean that such applications do not have thermal value. They simply mean that the previously mentioned application conditions do not permit the exterior insulation to be considered as c.i. as defined and intended by energy codes and standards. They also mean that energy code compliance and thermal performance for such assemblies must be demonstrated by use of an assembly U-factor analysis (including the impact of thermal transmission through the cladding support devices penetrating the exterior insulation layer or compression that occurs at through-fastened exterior components). For example, Appendix A of ASHRAE 90.1² provides tabulated U-factors for masonry walls where masonry veneer ties are pen-

etrating a layer of exterior c.i., such as foam plastic insulating sheathing c.i. (FPIS c.i.). As addressed later in this paper, it also is possible to place a conventional metal brick tie onto the surface of FPIS c.i. where only the tie fastener penetrates the FPIS c.i., such that compliance with the c.i. definition is maintained without having to determine a U-factor for energy code compliance. There are also a number of proprietary brick ties designed for this application with an "offset" connection to the structure to allow for a thickness of FPIS c.i.

As a means to avoid the above practical and energy-code-compliance difficulties or inefficiencies, this paper focuses on designing fastener connections through c.i. of rigid foam plastics, particularly FPIS. These products include expanded polystyrene (EPS), extruded polystyrene (XPS), and polyisocyanurate (PIR). Important to this topic of this paper, FPIS is available in a wide range of compressive strengths (for example, 10 psi to 100 psi or more) and is capable of supporting significant structural loads of various types. For example, FPIS can be specified to support building foundation loads with design compressive loads of up to 3000 psf or more, even including a safety factor of 3 to 5 applied to the material's nominal compressive strength to control deformation and creep. The conservatism of the safety factor generally depends on load duration (for example, sustained dead versus transient live or snow loads) and duty cycle (for example, lift truck loads versus column loads on a structural concrete slab with underlying FPIS insulation for a refrigerated warehouse). Consequently, with proper design and specification, FPIS materials are capable of providing a rigid exterior c.i. layer through which cladding and building component attachments can be made to the underlying structure using only fasteners. Thus, compression deformation becomes negligible and fasteners can be used for exterior building component attachments so that the FPIS complies

with the code definition for *continuous insulation* and can satisfy the required R-values for c.i.

Code-compliant FPIS products are manufactured in accordance with ASTM C578⁴ and ASTM C1289.⁵ These standards provide a foundation for complying with various building code and energy code provisions governing the use of FPIS in residential and commercial building construction.^{1,2,6,7} In particular, these ASTM standards provide a basis for specifying types of FPIS materials on the basis of compressive resistance properties.

FPIS materials are water resistant and have relatively high R-values per inch ranging from about R-4 per inch to more than R-6 per inch. For this reason, FPIS products are often used as c.i. for building foundations, walls, floors, and roofs as a means to comply with modern energy conservation codes and standards. Because of the relatively high R-value per inch, they also minimize the thickness of c.i. required to meet energy code requirements and this also helps with designing and specifying cladding and building component attachments through FPIS (as will become evident later in this paper). In addition, FPIS products can provide several building enclosure functions beyond just c.i. when they are properly integrated with a building enclosure assembly, including water-resistive barrier, air barrier, and water-vapor control. These various applications and functions of FPIS, including other code-compliance considerations such as fire safety and wind resistance, have been addressed in greater detail in two prior IIBEC conference papers and presentations.^{8,9} For additional information on these matters, including technical guidance, design resources, research, and code-compliance listings, refer to <https://www.continuousinsulation.org>.

Two common wall assembly applications with c.i. are shown in **Fig. 1**. One is considered a “hybrid” wall with a combination of exterior FPIS c.i. and cavity insulation. The other uses exterior c.i. only and is known as the “perfect wall” because it maximizes the protection of the structure from thermal and moisture cycling by substantially decoupling it from the exterior environment. As mentioned, FPIS can serve multiple “control layer” functions when used in either of these assembly approaches. In both of these approaches, cladding, furring,

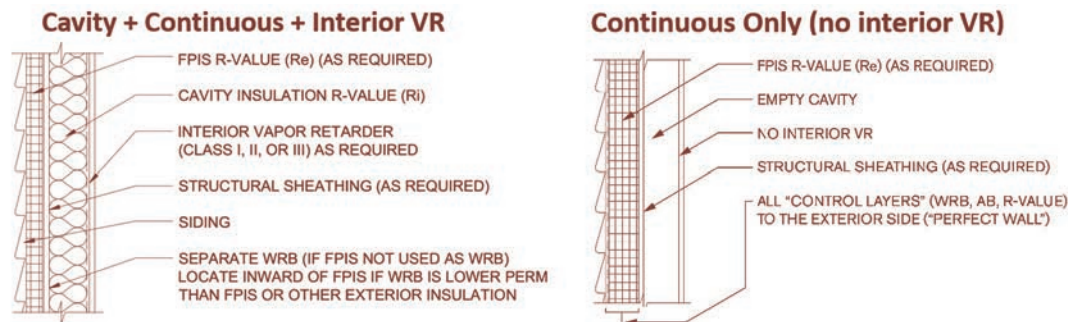


Figure 1. Example wall assemblies with continuous insulation.

Source: Reproduced by permission from Applied Building Technology Group (ABTG), “Model Moisture Control Guidelines for Light-Frame Walls: A Building Code Supplement for Builders, Designers, and Building Officials,” 2017, <http://www.appliedbuildingtech.com/rr/1701-01>; and J. H. Crandell, “Assessment of Hygrothermal Performance and Design Guidance for Modern Light-Frame Wall Assemblies,” in *Advances in Hygrothermal Performance of Building Envelopes: Materials, Systems and Simulations*, ed. P. Mukhopadhyaya and D. Fislser. West Conshohocken, PA: ASTM International, 2017, 362–394, <http://dx.doi.org/10.1520/STP159920160097>. Note: AB = air barrier; FPIS = foam plastic insulating sheathing; VR = vapor retarder; WRB = water-resistive barrier.

and other structural or architectural building components are ideally placed on the surface of the rigid foam sheathing insulation and attached through it with an appropriate fastener schedule to minimize thermal-bridging effects and maintain compliance with the energy code’s definition of *continuous insulation*.

For support of gravity loads, such as caused by the weight of cladding or structural live and dead loads on a roof or deck ledger, the fasteners through the FPIS layer to the primary structural system must provide sufficient shear capacity and stiffness. As a bonus, the use of stainless steel fasteners can add durability to exterior component connections through FPIS while also reducing heat transfer through the fasteners (stainless steel has about one-third the thermal conductivity of a regular carbon steel fastener).

CLADDING AND BUILDING COMPONENT CONNECTIONS THROUGH FPIS

Regardless of the number of functions that FPIS c.i. may be used to provide for a given building enclosure assembly, one thing is certain: exterior wall coverings and even structural building components must be fastened or supported through it to the underlying structure. The remainder of this paper focuses on how to properly attach such components through FPIS to the underlying structure while minimizing thermal bridging and maintaining conformity with the energy code’s definition of *continuous insulation*. The following two approaches to code compliance are addressed:

1. Prescriptive requirements for cladding and furring connections through FPIS

to wood, cold-formed steel framing, or wood structural panels (WSPs).

2. Engineering design procedures for various types of building component connections through FPIS to the structural frame or substrate.

The technical basis of the prescriptive solutions and design procedures that follow is described in Applied Building Technology Group research report no. 1503-02, “Attachment of Exterior Wall Coverings Through Foam Plastic Insulating Sheathing (FPIS) to Wood or Steel Wall Framing.”¹⁰ That report and the data and references described therein serve as the basis for prescriptive cladding attachment provisions found in the *International Building Code*⁶ (IBC) and the *International Residential Code*⁷ (IRC). Refer to 2021 IBC Sections 2603.12 and 2603.13 and 2021 IRC Sections R703.15 and R703.16. These prescriptive cladding and furring attachment requirements have been included in the IBC and IRC since the 2012 editions. In addition, Table R703.3.3 of the 2021 IRC provides for attachment of lightweight cladding through up to 2-in.-thick FPIS to minimum 5/16-in.-thick WSP sheathing; thus, it does not require fastening to studs for this limited condition. Alternatively, such connections directly to WSP installed over a layer of FPIS c.i. also are permissible, but placing WSP over FPIS c.i. must consider the impact to shear wall bracing capacity of the WSP (as done for some proprietary sheathing panels with FPIS c.i. laminated to the interior side rather than the exterior side of a structural panel).

Prescriptive Cladding and Furring Attachment Through FPIS

Several important general requirements for use of the codified prescriptive cladding and furring attachments through FPIS are addressed in this paper:

1. All of the codified prescriptive provisions are engineered to work with and require use of minimum 15 psi compressive resistance FPIS as specified in accordance with ASTM C578 or ASTM C1289. They address FPIS thicknesses up to 4 in., depending on the fastening schedule and cladding weight.
2. The provisions address support of cladding weight by a fastener transferring shear through a layer of FPIS to the structure. Therefore, these provisions are intended to supplement fastening requirements for each type of cladding found in the code or the specific cladding manufacturer's installation instructions (unless those instructions specifically address installation over FPIS). The more stringent fastening schedule should apply.
3. To maintain wind or seismic out-of-plane load resistance—that is, fastener design withdrawal strength—the fastener must have sufficient length to penetrate through the FPIS layer and maintain the required minimum embedment in wood framing or engagement of fastener threads in cold-formed steel framing.
4. Fasteners must be installed in a manner to adequately draw all intervening material layers together without over- or underdriving resulting in problems such as warping of materials or gaps between material layers. However, more recent research has shown that a drainage plane gap up to $\frac{3}{8}$ in. thick, provided by an intervening drainage mat rather than furring placed behind lath for stucco (one-coat and three-coat varieties inclusive), can be tolerated with use of the prescribed attachments and design procedure discussed later in this paper.¹¹ This is important to be able to address new stucco drainage requirements in the 2021 editions of the IRC and IBC for moist climates (much of the United States). Back ventilation or improved drainage behind other types of cladding is also a recommended practice, particularly for moist climates.

5. The fastener schedules and permissible FPIS thicknesses will vary according to the cladding weight supported (including all materials outboard of the FPIS layer). The cladding weight categories are as follows.

- 3 psf: vinyl siding, wood lap siding, most fiber cement siding
- 11 psf: three-coat stucco
- 18 psf: medium-weight adhered masonry veneer
- 25 psf: heavy adhered masonry veneer

These examples are not inclusive of all cladding types or weights. Refer to cladding manufacturer data for actual unit weight and, for absorptive claddings, a “wet” weight should be used.

6. Fasteners, framing materials, and FPIS materials must comply with the specifications and minimum properties referenced in the tables and table notes.
- For masonry or concrete structural sub-

strates, the IRC and IBC require an engineered design or use of fastener manufacturer data because commonly used concrete/masonry fasteners are proprietary. While the code provisions use commodity (standardized) fasteners for wood and steel framing, proprietary fasteners may also be used, but must be analyzed in accordance with the engineering procedure addressed below. Where the scope limitations of the design procedures are not satisfied, design lateral (shear) values for a given fastener or connection scenario should be determined in accordance with a suitable test methodology consistent with that used to develop the design procedure and IRC and IBC code provisions derived from that procedure; refer to ABTG research report no. 1503-02¹⁰ for a description of the test methodology and performance criteria, which were based on applying ASTM D1761 connection shear tests including also long-term shear tests to evaluate creep stability under constant load.

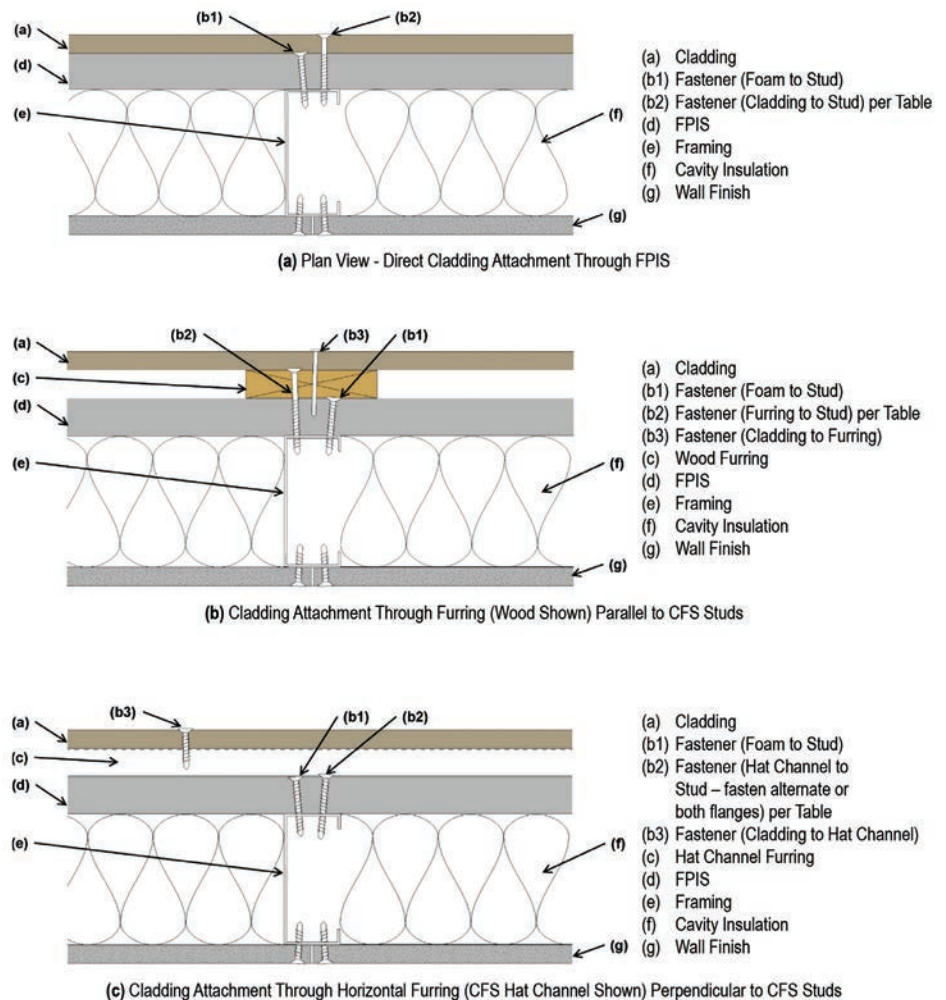


Figure 2. Illustration of cladding and furring attachments through FPIS to CFS framing. Note: CFS = cold-formed steel; FPIS = foam plastic insulating sheathing.

Cladding fastener through FPIS into:	Siding fastener type and minimum size	Siding fastener vertical spacing (in.)	Maximum thickness of FPIS (in.)							
			16 in. o.c. fastener horizontal spacing				24 in. o.c. fastener horizontal spacing			
			Max. cladding weight				Max. cladding weight			
			3 psf	11 psf	18 psf	25 psf	3 psf	11 psf	18 psf	25 psf
Steel framing (minimum penetration of steel thickness + 3 threads)	#8 screw (0.285 in. head) into 33 mil steel or thicker	6	3.00	2.95	2.20	1.45	3.00	2.35	1.25	DR
		8	3.00	2.55	1.60	0.60	3.00	1.80	DR	DR
		12	3.00	1.80	DR	DR	3.00	0.65	DR	DR
	#10 (0.333 in. head) screw into 33 mil steel	6	4.00	3.50	2.70	1.95	4.00	2.90	1.70	0.55
		8	4.00	3.10	2.05	1.00	4.00	2.25	0.70	DR
		12	4.00	2.25	0.70	DR	3.70	1.05	DR	DR
	#10 (0.333 in. head) screw into 43 mil steel or thicker	6	4.00	4.00	4.00	3.60	4.00	4.00	3.45	2.70
		8	4.00	4.00	3.70	3.00	4.00	3.85	2.80	1.80
		12	4.00	3.85	2.80	1.80	4.00	3.05	1.50	DR

Table 1. Siding minimum fastening requirements to cold-formed steel framing for direct cladding attachment over FPIS to support cladding system weight

Note: Tabulated values are based on minimum 33 ksi steel for 33 mil and 43 mil steel and 50 ksi steel for 54 mil steel or thicker. Screws shall comply with the requirements of ASTM C1513. FPIS shall have a minimum compressive strength of 15 psi in accordance with ASTM C578 or ASTM C1289. DR = design required; FPIS = foam plastic insulating sheathing; o.c. = on center. 1 in. = 25.4 mm; 1 psf = 0.0479 kPa; 1 psi = 6.895 kPa; 1 ksi = 6.895 MPa.

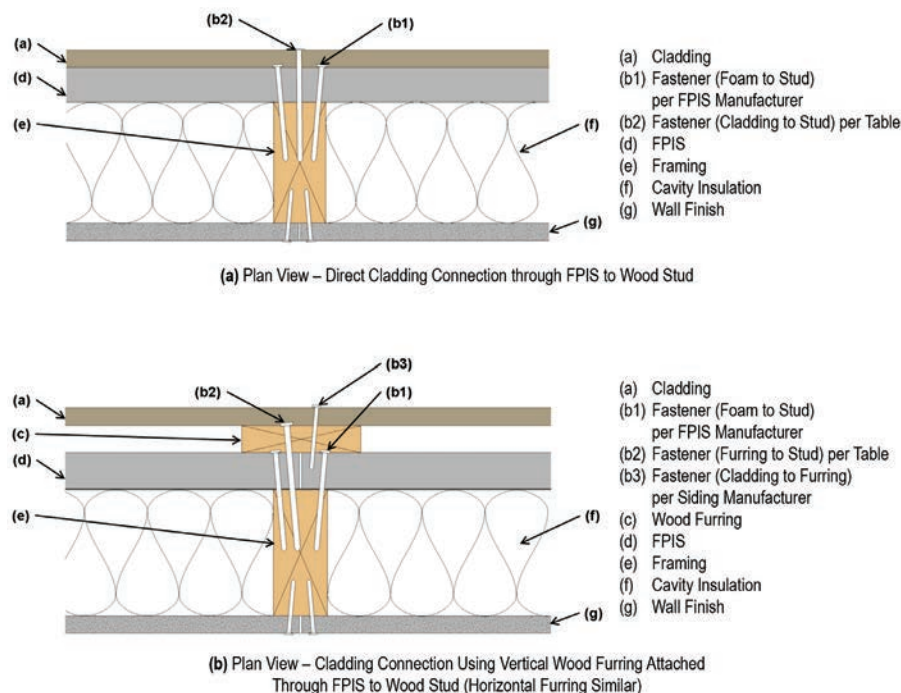


Figure 3. Illustration of cladding and furring attachments through FPIS to wood framing.
Note: FPIS = foam plastic insulating sheathing.

Prescriptive Cladding and Furring Attachment Through FPIS to Cold-Formed Steel Framing

Figure 2 illustrates cladding direct attachment over FPIS (no furring) and also furring attachment over FPIS. The requirements for direct cladding attachment and furring attachments over FPIS are shown in **Tables 1** and **2**, respectively.

It is important to note that the figures included in this paper focus only on detailing connections. The wall assembly details will require additional components or materials for code compliance, depending on design conditions.

Prescriptive Cladding and Furring Attachment Through FPIS to Wood Framing

Figure 3 illustrates cladding direct attachment over FPIS (no furring) and also furring attachment over FPIS. The requirements for direct cladding attachment and furring attachments over FPIS are shown in **Tables 3** and **4**, respectively.

Lightweight Cladding Prescriptive Connection Through FPIS to WSP Sheathing

In accordance with Section R703.3.3 of the IRC, direct connection of lightweight claddings

Furring material	Framing member	Fastener type and min. size	Minimum penetration into wall framing (in.)	Fastener spacing in furring (in.)	Maximum thickness of FPIS (in.)							
					16 in. o.c. furring				24 in. o.c. furring			
					Siding weight				Siding weight			
					3 psf	11 psf	18 psf	25 psf	3 psf	11 psf	18 psf	25 psf
Minimum 33 mil steel hat channel or minimum 1×3 wood furring	33 mil cold-formed steel stud	#8 screw (0.285 in. head)	Steel thickness +3 threads	12	3.00	1.80	DR	DR	3.00	0.65	DR	DR
				16	3.00	1.00	DR	DR	2.85	DR	DR	DR
				24	2.85	DR	DR	DR	2.20	DR	DR	DR
		#10 screw (0.333 in. head)	Steel thickness +3 threads	12	4.00	2.25	0.70	DR	3.70	1.05	DR	DR
				16	3.85	1.45	DR	DR	3.40	DR	DR	DR
				24	3.40	DR	DR	DR	2.70	DR	DR	DR
	43 mil or thicker cold-formed steel stud	#8 screw (0.285 in. head)	Steel thickness +3 threads	12	3.00	1.80	DR	DR	3.00	0.65	DR	DR
				16	3.00	1.00	DR	DR	2.85	DR	DR	DR
				24	2.85	DR	DR	DR	2.20	DR	DR	DR
		#10 screw (0.333 in. head)	Steel thickness +3 threads	12	4.00	3.85	2.80	1.80	4.00	3.05	1.50	DR
				16	4.00	3.30	1.95	0.60	4.00	2.25	DR	DR
				24	4.00	2.25	DR	DR	4.00	0.65	DR	DR

Table 2. Furring minimum fastening requirements to cold-formed steel framing for application over FPIS to support cladding system weight

Note: Table values are based on the following:

- Wood furring of Spruce-Pine-Fir or any softwood species with a specific gravity of 0.42 or greater per NDS.
- Minimum 33 mil steel hat channel furring of 33 ksi steel. Steel hat channel shall have a minimum $\frac{3}{8}$ in. depth, $\frac{1}{4}$ in. web width, and $\frac{1}{2}$ in. wide flanges with web or flanges bearing on FPIS surface.
- Cold-formed steel framing of indicated nominal steel thickness and minimum 33 ksi steel for 33 mil and 43 mil steel and 50 ksi steel for 54 mil steel or thicker. Screws shall comply with the requirements of ASTM C1513.

Furring shall be spaced a maximum of 24 in. o.c. in a vertical or horizontal orientation.

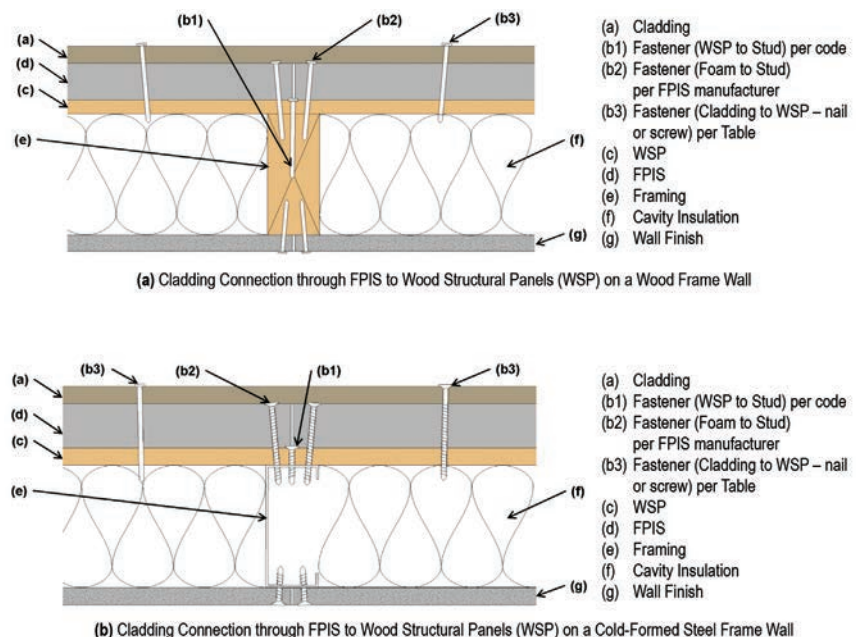
- In a vertical orientation, furring shall be located over wall studs and attached with the required fastener spacing.
- In a horizontal orientation, furring shall be fastened at each stud with a number of fasteners equivalent to that required by the fastener spacing. If the required fastener spacing is 12 in. o.c. and the studs are 24 in. o.c., then two fasteners would be required at each stud ($24/12 = 2$). In no case shall fasteners be spaced more than 24 in. apart.

FPIS shall have a minimum compressive strength of 15 psi, in accordance with ASTM C578 or ASTM C1289.

DR = design required; FPIS = foam plastic insulating sheathing; NDS = American Wood Council (2018); o.c. = on center. 1 in. = 25.4 mm; 1 psf = 0.0479 kPa; 1 psi = 6.895 kPa; 1 ksi = 6.895 MPa.

(maximum 3 lb/ft² unit weight) through FPIS (maximum 2 in. thick) to WSPs (minimum $\frac{3}{16}$ -in. thickness) can be done in accordance with Fig. 4 and Table 5. The cladding fastener must be of sufficient length to penetrate a minimum of $\frac{1}{4}$ in. beyond the back side of the WSP sheathing. Also, fastener minimum size and maximum spacing must comply with the cladding manufacturer's installation instructions, especially where the instructions require a more stringent fastening schedule. Where applicable, this is one of the simplest means of connecting cladding through foam sheathing where a steel- or wood-frame wall is sheathed with WSPs.

Figure 4. Illustration of lightweight cladding attachment through maximum 2-in.-thick FPIS to minimum $\frac{3}{16}$ -in.-thick wood structural panel sheathing.
Note: FPIS = foam plastic insulating sheathing.



Cladding fastener through FPIS into:	Siding fastener type and minimum size	Siding fastener vertical spacing (in.)	Maximum thickness of FPIS (in.)							
			16 in. o.c. fastener horizontal spacing				24 in. o.c. fastener horizontal spacing			
			Max. cladding weight				Max. cladding weight			
			3 psf	11 psf	18 psf	25 psf	3 psf	11 psf	18 psf	25 psf
Wood framing (minimum 1½ in. penetration)	Nail (0.113 in. shank; 0.226 in. head)	6	2.00	1.45	0.75	DR	2.00	0.85	DR	DR
		8	2.00	1.00	DR	DR	2.00	0.55	DR	DR
		12	2.00	0.55	DR	DR	1.85	DR	DR	DR
	Nail (0.120 in. shank; 0.281 in. head)	6	3.00	1.70	0.90	0.55	3.00	1.05	0.50	DR
		8	3.00	1.20	0.60	DR	3.00	0.70	DR	DR
		12	3.00	0.70	DR	DR	2.15	DR	DR	DR
	Nail (0.131 in. shank; 0.281 in. head)	6	4.00	2.15	1.20	0.75	4.00	1.35	0.70	DR
		8	4.00	1.55	0.80	DR	4.00	0.90	DR	DR
		12	4.00	0.90	DR	DR	2.70	0.50	DR	DR
	16d nail (0.162 in. shank; 0.344 in. head)	6	4.00	3.55	2.05	1.40	4.00	2.25	1.25	0.80
		8	4.00	2.55	1.45	0.95	4.00	1.60	0.85	0.50
		12	4.00	1.60	0.85	0.50	4.00	0.95	DR	DR

Table 3. Siding minimum fastening requirements to wood framing for direct cladding attachment over FPIS to support cladding system weight

Note: Table values are based on wood framing of Spruce-Pine-Fir or any wood species with a specific gravity of 0.42 or greater in accordance with NDS. *Required fastener minimum penetration shall be permitted to include thickness of wood structural panel sheathing materials.* Nail fasteners shall comply with ASTM F1667, except nail length shall be permitted to exceed ASTM F1667 standard lengths. Fasteners of equivalent or greater diameter and bending strength shall be permitted. FPIS shall have a minimum compressive strength of 15 psi in accordance with ASTM C578 or ASTM C1289.

DR = design required; FPIS = foam plastic insulating sheathing; NDS = American Wood Council (2018); o.c. = on center. 1 in. = 25.4 mm; 1 psf = 0.0479 kPa; 1 psi = 6.895 kPa.

Supplemental Prescriptive Furring Requirements for Wind Load Resistance

For furring materials and their attachment to a structure, prescriptive wind pressure resistance requirements are typically not available in the locally applicable building code and design values for typical 1×4 wood members used as furring are not available because they are only appearance graded. This concern affects wall assemblies using furring, with or without the presence of FPIS under the furring. Therefore, **Tables 6** and **7** are provided to supplement the prescriptive or designed furring connection requirements through FPIS as addressed in the previous tables for support of cladding weight. The more stringent fastening schedule for cladding weight support or wind load should apply.

The tabulated allowable wind pressure

resistance values in Tables 6 and 7 must be equal to or greater than the components and cladding allowable stress design (ASD) negative (suction) pressure wind load required by the locally applicable building code. Because these tables are only representative of an appropriate furring design for wind pressure resistance, the applicability for a specific use should be verified for suitability prior to use. The tabulated design values are based on analysis to determine which of the following limits the design: furring bending, fastener withdrawal, or fastener head pull-through.

Allowance for Brick Tie Attachments Through FPIS Continuous Insulation

Section R703.8.4 of the IRC permits typical brick ties, such as corrugated straps, to be

attached with only the fastener penetrating the FPIS c.i. layer where it is of sufficient length to maintain the embedment into framing or minimum ⅞-in.-thick WSP sheathing for withdrawal resistance. This applies to only the scope of the IRC where wall components and cladding ASD wind loads are 30 psf or less (refer to IRC Section R703.3.2, “Wind Limitations”). This connection strategy works only because anchored masonry veneers are separately supported and do not rely on the brick tie for support of the veneer weight. Therefore, resisting out-of-plane loads is of primary concern. For this reason, use of corrosion-resistant screws for tie attachment may be preferable, especially when attaching to minimum ⅞-in.-thick wood sheathing underneath. When fastened through FPIS,

Furring material	Framing member	Fastener type and min. size	Minimum penetration into wall framing (in.)	Fastener spacing in furring (in.)	Maximum thickness of FPIS (in.)							
					16 in. o.c. furring				24 in. o.c. furring			
					Siding weight				Siding weight			
					3 psf	11 psf	18 psf	25 psf	3 psf	11 psf	18 psf	25 psf
Min. 1×3 wood furring	Min. 2× wood stud	Nail (0.120 in. shank; 0.271 in. head)	1¼ in.	8	3.00	1.85	1.05	0.65	3.00	1.20	0.60	DR
				12	3.00	1.20	0.60	DR	3.00	0.70	DR	DR
				16	3.00	0.80	DR	DR	2.30	DR	DR	DR
		Nail (0.131 in. shank; 0.281 in. head)	1¼ in.	8	4.00	2.45	1.45	0.95	4.00	1.60	0.85	DR
				12	4.00	1.60	0.85	DR	4.00	0.95	DR	DR
				16	4.00	1.10	DR	DR	3.05	0.60	DR	DR
		16d nail (0.162 in. shank; 0.344 in. head)	1¼ in.	8	4.00	4.00	2.45	1.60	4.00	2.75	1.45	0.85
				12	4.00	2.75	1.45	0.85	4.00	1.65	0.75	DR
				16	4.00	1.90	0.95	DR	4.00	1.05	DR	DR
		#10 wood screw (0.363 in. head)	1 in.	12	4.00	2.30	1.20	0.70	4.00	1.40	0.60	DR
				16	4.00	1.65	0.75	DR	4.00	0.90	DR	DR
				24	4.00	0.90	DR	DR	2.85	DR	DR	DR
		¾ in. hex lag screw	1½ in.	12	4.00	2.65	1.50	0.90	4.00	1.65	0.80	DR
				16	4.00	1.95	0.95	0.50	4.00	1.10	DR	DR
				24	4.00	1.10	DR	DR	3.25	0.50	DR	DR

Table 4. Furring minimum fastening requirements to wood framing for application over FPIS to support cladding system weight

Note: Table values are based on wood framing and furring of Spruce-Pine-Fir or any wood species with a specific gravity of 0.42 or greater in accordance with NDS. Nail fasteners shall comply with ASTM F1667, except nail length shall be permitted to exceed ASTM F1667 standard lengths. Wood screws and lag screws shall comply with NDS Appendix L and ANSI/ASME B18.6.1. Other approved fasteners of equivalent or greater diameter and bending strength shall be permitted. Required fastener minimum penetration shall be permitted to include thickness of wood structural panel sheathing materials. A minimum 2× wood furring shall be used where the required siding fastener penetration into wood material exceeds ¾" and is not more than 11/2", unless approved deformed shank siding nails or siding screws are used to provide equivalent withdrawal strength, allowing the siding connection to be made to a 1× wood furring.

Furring shall be spaced a maximum of 24" o.c. in a vertical or horizontal orientation.

- In a vertical orientation, furring shall be located over wall studs and attached with the required fastener spacing.
- In a horizontal orientation, furring shall be fastened at each stud with a number of fasteners equivalent to that required by the fastener spacing. If the required nail spacing is 12" o.c. and the studs are 24" o.c., then two (2) nails would be required at each stud (24/12 = 2). In no case shall fasteners be spaced more than 24" (0.6 m) apart.

FPIS shall have a minimum compressive strength of 15 psi, in accordance with ASTM C578 or ASTM C1289.

DR = design required; FPIS = foam plastic insulating sheathing; NDS = American Wood Council (2018); o.c. = on center. 1 in. = 25.4 mm; 1 psf = 0.0479 kPa; 1 psi = 6.895 kPa.

Type and Size of Fastener	Horizontal Spacing of Fasteners along Siding
Roof sheathing ring shank nail (0.120 in. min. shank; 0.281 in. head)	12 in. o.c.
Post frame ring shank nail (0.148 in. min. shank; 5/16 in. head)	15 in. o.c.
No. 6 screw (0.138 in. min. shank; 0.262 in. head)	12 in. o.c.
No. 8 screw (0.164 in. min. shank; 0.312 in. head)	16 in. o.c.

Table 5. Lightweight cladding minimum fastening requirements for attachment through maximum 2-in.-thick FPIS to minimum 7/16-in.-thick wood structural panel

Note: Horizontal spacing of fasteners along siding is based on a siding width (distance between horizontal rows of fasteners) of 12 in. For other siding widths, multiply required horizontal spacing by 12/w, where w is the siding width in inches. Use of this table is limited to the wind load scope limits for cladding attachments in accordance with Section R703.3.2 of the *International Residential Code* (that is, maximum 30 psf negative design wind pressure). FPIS = foam plastic insulating sheathing; o.c. = on center. 1 in. = 25.4 mm; 1 psf = 0.0479 kPa.

Furring material	Framing member	Fastener type and minimum size	Minimum penetration into wall framing (in.)	Fastener spacing in furring (in.)	Allowable wind pressure resistance of furring attachment (psf)	
					16 in. o.c. furring	24 in. o.c. furring
Minimum 1×3 wood furring	Minimum 2× wood stud	Nail (0.120 in. shank; 0.271 in. head)	1¼ in.	8	42.6	28.4
				12	28.4	18.9
				16	21.3	14.2
		Nail (0.131 in. shank; 0.281 in. head)	1¼ in.	8	46.5	31.0
				12	31.0	20.7
				16	23.3	15.5
		0.162 in. diameter nail	1¼ in.	8	57.5	38.3
				12	38.3	25.6
				16	28.8	19.2
		#10 wood screw	1 in.	12	107.3	71.6
				16	79.0	52.7
				24	35.1	23.4
		¼ in. lag screw	1½ in.	12	140.4	93.6
				16	79.0	52.7
				24	35.1	23.4

Table 6. Furring minimum fastening requirements for application over FPIS to resist allowable stress wind pressure (wood frame structure)

Note: FPIS = foam plastic insulating sheathing; o.c. = on center. 1 in. = 25.4 mm; 1 psf = 0.0479 kPa.

use of stainless steel fasteners will not only maximize durability but also reduce the thermal conductivity impact of the tie fastener as mentioned previously.

Engineered Design of Cladding and Building Component Connections Through FPIS

Where applicable, the calculation procedures in this section should be used by a registered design professional to determine the lateral (shear) and withdrawal design values for fastener connections through FPIS to the underlying structure or substrate. The lateral design value calculation procedures provided below are applicable to FPIS having a maximum 4-in. thickness and a minimum 15 psi compressive strength in accordance with ASTM C578 or ASTM C1289. They also apply only to attachment of cladding, linear components or members such as furring or ledger, and panel products installed over FPIS. In addition, the general requirements for the prescriptive provisions listed previously also apply to use of these engineering procedures.

Design of Connections Through FPIS to Cold-Formed Steel Framing

The installation and design of screw-type connections shall comply with AISI S100,¹² Section J4 with the additional requirements indicated in (a) and (b) as follow for connections including a layer of FPIS sandwiched between the connected parts. Where screw fasteners are installed through FPIS, the fastener length shall be sufficient to provide a minimum of three threads of penetration through the cold-formed steel member receiving the fastener tip.

a. Tension allowable design values.

Nominal tension design values for screw connections shall be determined in accordance with AISI S100, Section J4.4, and divided by a safety factor of not less than 3.0 to derive an allowable design tension value.

b. Shear allowable design values.

Nominal shear strength design values for screws shall be determined in accordance with AISI S100, Section J4.3.1, and divided by a safety factor of not less than 3.0 to derive an allowable

shear design value. Where the connection includes a layer of FPIS sandwiched between the connected parts, the following additional requirements and limitations shall apply:

- For connections using #8 or #10 screws, AISI S100, Eq. J4.3.1-1 [$P_{ns} = 4.2 (t_2^3 d)^{1/2} F_{u2}$] shall be multiplied by one of the following gap effect reduction factors G_r as applicable:
 - For #10 screw in 54 mil (0.054 in. [1.370 mm]) and 50 ksi (345 MPa) steel:
 $G_r = 0.17 - 0.0048r$
 - For #10 screw in 43 mil (0.043 in. [1.09 mm]) and 33 ksi (228 MPa) steel:
 $G_r = 0.19 - 0.0066r$
 - For #8 or #10 screw in 33 mil (0.033 in. [0.838 mm]) and 33 ksi (228 MPa) steel:
 $G_r = 0.16 - 0.0064r$
- where
 G_r = gap effect reduction factor for use with AISI S100, Eq. J4.3.1-1

Furring material	Framing member	Fastener type and minimum size	Minimum penetration into wall framing (in.)	Fastener spacing in furring (in.)	Allowable wind pressure resistance of furring attachment (psf)	
					16 in. o.c. furring	24 in. o.c. furring
Minimum 33 mil steel hat channel or minimum 1×3 wood furring	33 mil cold-formed steel stud	#8 screw (0.285 in. head)	Steel thickness +3 threads	12	52.9	35.3
				16	39.7	26.5
				24	26.5	17.6
		#10 screw (0.333 in. head)	Steel thickness +3 threads	12	62.9	41.9
				16	47.1	31.4
				24	31.4	21.0
	43 mil or thicker cold-formed steel stud	#8 screw (0.285 in. head)	Steel thickness +3 threads	12	69.0	46.0
				16	51.8	34.5
				24	34.5	23.0
		#10 screw (0.333 in. head)	Steel thickness +3 threads	12	81.9	54.6
				16	61.5	41.0
				24	35.1	23.4

Table 7. Furring minimum fastening requirements for application over FPIS to resist allowable stress wind pressure (cold-formed steel frame structure)

Note: FPIS = foam plastic insulating sheathing, 1 in. = 25.4 mm; 1 psf = 0.0479 kPa.

$$r = d_{sep}/d$$

d_{sep} = separation between connected steel parts caused by thickness of FPIS, in. (mm)

d = nominal screw diameter
= 0.164 in. (4.17 mm) for #8 screws
= 0.190 in. (4.83 mm) for #10 screws

- ii. The value of r shall not exceed 21.
- iii. For $0 < r < 2$, calculated G_r in accordance with item i does not need to be less than $1 - r/2$.
- iv. A larger steel thickness and screw size than indicated in item i for the respective G_r equations shall be permitted, provided the P_{ns} value calculated in accordance with AISI S100, Eq. 4.3.1-1, uses the screw size and steel thickness as indicated in item i for the respective G_r equations.
- v. The material against the screw head shall be minimum 33 mil and 33 ksi steel, minimum 3/8-in.-thick wood or wood-based material with a specific gravity of not less than 0.42, or equivalent.

The gap reduction factors provide control of long-term deflection (creep) and limit short-term deflection to 0.015 in. based on evaluation

of test data to develop and confirm the design methodology.¹⁰ With application of the gap reduction factors to control joint deflection, the resulting safety factors are typically much greater than the minimum safety factor of 3 required by the AISI S100 standard for connections without FPIS or a gap in the joint. The minimum 15 psi compressive resistance and maximum 4-in. thickness for FPIS are associated with the test data upon which the gap reduction factor equations are based.¹⁰ Higher compressive resistance FPIS may provide improved performance, but the design provisions are based on this typical minimum value.

Design of Connections Through FPIS to Wood Framing

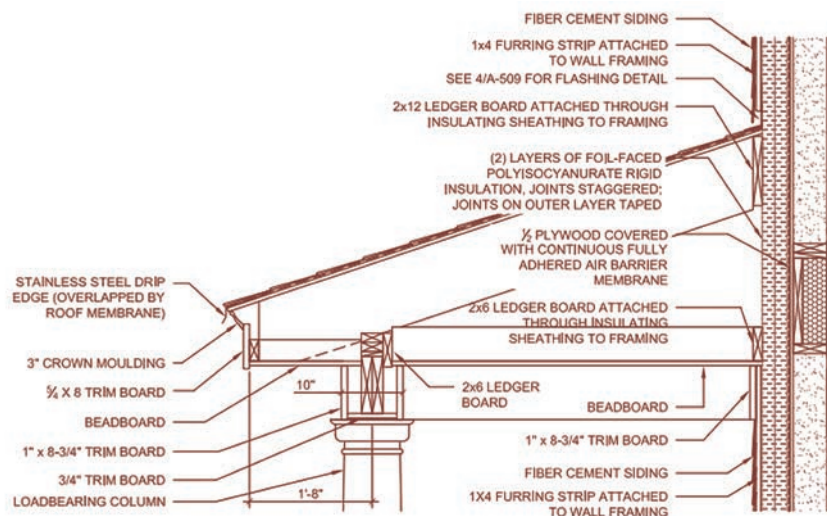
The installation and design of connections using dowel-type fasteners (that is, nails and screws) shall comply with the American Wood Council's *National Design Specification for Wood Construction*¹³ (NDS), including the additional requirements indicated in (a) and (b) as follow for connections including a layer of FPIS sandwiched between the connected parts.

- a. **Allowable withdrawal design values.** Withdrawal design values for dowel-type fasteners shall be determined in accor-

dance with NDS, Section 12.2. Where dowel-type fasteners are installed through FPIS, the specified fastener length shall be sufficient to provide the design penetration into wood framing.

- b. **Reference lateral design values.** Reference lateral (shear) design values for dowel-type fasteners shall be determined in accordance with NDS, Section 12.3, with the following modifications and limitations where the connection includes a layer of FPIS sandwiched between the connected parts:

Higher compressive resistance FPIS may provide improved performance, but the design provisions are based on this typical minimum value.



6 FRONT PORCH ROOF DETAIL

SCALE: 3/4" = 1'-0"

Figure 5. Porch roof ledger and soffit ledger connection detail through 4-in.-thick FPIS.*

Source: Building Science Corp., National Institute of Standards and Technology (NIST) project no. NI ST NZERF, CAD (computer-aided design) DWG file A-PLOT-DETL-NZERTE, 2009, <https://www.nist.gov/system/files/nzertf-architectural-plans3-june2011.pdf>.

* Using the previous design procedure for connections to wood framing through FPIS, two 3/8-in. lag screws (or similar-capacity proprietary self-drilling wood screws) were used for the roof ledger connections to each stud at 24 in. on center. Soffit ledger connections are less substantive (smaller or fewer fasteners) due to lower connection forces and this distinction minimizes thermal bridging and cost.

Note: FPIS = foam plastic insulating sheathing. 1" = 1 in. = 25.4 mm; 1' = 1 ft = 0.305 m.

- The reduction term R_d in accordance with NDS, Table 12.3.1B, shall not be less than 3.0.
- The yield limit equations in accordance with Table 1-1 of AWC Technical Report 12, "General Dowel Equations for Calculating Lateral Connection Values,"¹⁴ which include a gap parameter g equal to the thickness of FPIS sandwiched between connected parts, shall be used in lieu of the yield limit equations in NDS, Table 12.3.1A.
- The minimum fastener penetration in the main member (member receiving the fastener tip), including the thickness of WSPs attached to the main member, shall comply with NDS and shall not be less than 1 in. for screws or 1/4 in. for nails.
- The minimum specific gravity of wood materials being connected shall be 0.42.

The use of a minimum R_d value of 3.0 controls long-term deflection (creep) and limits

initial deflection to not more than 0.015 in. for dowel-type fasteners of 1/4-in. diameter or less, FPIS of minimum 15 psi compressive resistance and maximum 4-in. thickness, wood materials of 0.42 specific gravity or greater, and the fastener penetration in the main member as indicated previously.¹⁰ With application of the R_d value of 3.0 under these conditions of use, the resulting safety margins relative to ultimate lateral capacity are typically greater than 5.

Design Procedure Applications

The previously detailed engineering procedures provide for calculation of fastening solutions beyond the limited prescriptive solutions and fastener schedules for cladding and furring connections presented earlier. For example, they can be used to evaluate the following:

- Cladding and furring connections that use alternative fastener schedules and even proprietary types of fasteners, such as self-tapping wood lag screws, which may have better yield strength and stiffness than commodity fasteners, resulting in improved performance (that is, able to accommodate heavier loads or thicker FPIS)

- Load-bearing structural building component connections through FPIS, such as deck or roof ledgers, for code-compliant structural capacity and joint stiffness (Fig. 5)
- Various architectural building components attached to a structure through FPIS, such as window and door awning frames or shading device support systems
- Structural sheathing connections through a layer of FPIS (where FPIS is used as "undersheathing"—that is, structural sheathing placed over top of FPIS—not the more typical case of "oversheathing"—that is, FPIS placed over top of structural sheathing)
- Window and door frame anchorages through FPIS or through plastic or wood shims in a rough opening gap to enable calculation of shear capacity to support fenestration weight (or transverse wind loads) as a means to achieve or demonstrate compliance with fenestration industry standards for anchorage design, such as AAMA 2501.¹⁵ This design need, however, may only arise for anchorage and support conditions not prescriptively addressed in the fenestration manufacturer's installation instructions or where equivalent substitute anchors are considered as permitted by the code.

CONCLUSION

This paper has reviewed code-compliant prescriptive solutions and design procedures for attachment of cladding, furring, and various architectural and structural building components through FPIS c.i. The primary goals of these prescriptive requirements, design procedures, and details are to provide a means to maintain structural integrity while also promoting thermal continuity and efficient construction of a building enclosure when FPIS is specified as c.i. Some of the key takeaways from this paper include the following:

- The connection provisions addressed herein offer many options to provide structurally efficient, energy-efficient, practical, and durable means of constructing and designing code-compliant and high-performance building enclosures that use FPIS c.i.
- The prescriptive connection options and design approaches presented are necessary to meet the intent of U.S. model energy codes and standards (for

example, IECC and ASHRAE 90.1), particularly their shared definition for *continuous insulation*, thereby allowing compliance to be achieved by simply meeting required prescriptive insulation R-values for c.i.

- The presented connection provisions also meet the intent and requirements of U.S. model building codes (for example, IRC and IBC) for proper attachment of cladding and furring on walls with FPIS c.i.
- The same provisions can also be used to design structural connections through a layer of FPIS c.i., such as roof and deck ledgers.
- Finally, the use of connection provisions addressed in this paper help support compliance with improved water vapor control provisions in modern building codes, whereby FPIS c.i. can provide a uniform, stable, and dry environment within building enclosure assemblies. 

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Changes Coming to the 2021 IBC Requirements for Exterior Walls on Commercial Buildings

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ABSTRACT

This paper will highlight how U.S. codes and standards specifically control the use of combustible building products in commercial buildings to create assurances that energy efficiency improvements do not compromise fire safety. Examples of approved assemblies in a variety of exterior walls for different construction configurations will be provided. Presenters will also focus on how fire safety can be maintained throughout the design process and construction phases using code-compliant techniques such as engineering judgments for wall assemblies. Time will be allotted for an interactive discussion of current industry resources and topics of interest to the audience.

SPEAKERS



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Lorraine Ross has been involved for over 30 years in all aspects of the building products industry, including manufacturing, technical service, and regulatory issues such as building code development, compliance, and testing laboratory experience. As president of Intech Consulting Inc., she is actively involved in building and fire code development through the International Code Council, the National Fire Protection Association, and a variety of state code development activities, particularly regarding foam plastic insulation. She is a member of the Florida Building Commission Roofing Technical Advisory Committee and has delivered many presentations on building code topics at a variety of industry conferences.

Changes Coming to the 2021 IBC Requirements for Exterior Walls on Commercial Buildings

The year 2020 delivered many unexpected changes in our personal lives as well as the way we do business. However, in the world of building codes, the usual three-year update cycle for building, fire, and energy codes continued as usual, leading to the publication of the 2021 International Code Council (ICC) suite of codes, which include the *International Building Code (IBC)*¹ and the *International Energy Conservation Code (IECC)*.² Additionally, review of two major reference standards that affect commercial buildings resulting in updated versions were released in 2019:

- *ANSI/ASHRAE/IES Standard 90.1-2019: Energy Efficiency Standard for Buildings Except Low-Rise Residential Buildings*³
- *NFPA 285-2019: Standard Fire Test Method for Evaluation of Fire Propagation Characteristics of Exterior Wall Assemblies Containing Combustible Components*⁴

This paper highlights key code and standards revisions regarding the use of combustible building products in commercial buildings and reviews how code compliance techniques can be used to demonstrate fire safety for certain deviations from tested wall assemblies.

THE IMPORTANCE OF RESILIENCE

Although codes and reference standards are often viewed as “stand-alone” requirements, it is important to recognize the contribution of energy and building codes to improving the resilience of buildings in both the commercial and residential sectors. Some of the leaders in this effort include the American Institute of Architects, the U.S. Federal Emergency Management Agency, and ICC, among others. In the white paper “Resilience Contributions of the International Building Code [IBC],”⁵ ICC noted,

The National Academies (2012) have defined resilience as, “the ability

to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events.” The building industry, including organizations representing planning, design, construction, ownership, operation, regulation and insurance, have embraced the definition put forward by the National Academies. Nearly 50 building industry organizations signed on to an Industry Statement on Resilience recognizing the need for coordinated action through research, advocacy, education, planning and response.

The ICC white paper identifies specific parts of the IBC that address the problems of hurricanes, earthquakes, floods, wildfires, and other natural disaster events.

Like building codes, energy efficiency codes are also important in mitigating the impacts of a changing climate. The origins of energy efficiency codes and standards were rooted in energy supply issues and the rising costs of heating and cooling buildings. While these two drivers are certainly still important, energy efficiency requirements are increasingly important for addressing resiliency.

Of course, a resilient building alone cannot deliver full protection from natural disasters. Community resources must be leveraged to provide the level of resilience that must be reached to mitigate these risks. To that end, the ICC, along with the U.S. Resiliency Council and the Meridian Institute, facilitated the formation of the Alliance for National and Community Resilience, a coalition aiming to develop a “system of community benchmarks—the first system of its kind in the United States—that will allow local leaders to easily assess and improve their resilience across all functions of a community.”⁶

CODE UPDATES

ASHRAE 90.1-19 and 2021 IECC

Generally, minimum requirements for the energy efficiency of commercial buildings is established by the IECC, which recognizes the ASHRAE 90.1 standard as the most widely used compliance method. However, states may enforce specific codes, such as California’s Title 24 Building Energy Efficiency Standards.⁷ Further complicating matters, some green building rating systems, such as LEED, recognize ASHRAE 90.1 but not necessarily the IECC.

The latest revisions of ASHRAE 90.1 and IECC both include energy efficiency gains for commercial buildings. Some high-level changes for each are highlighted here.

The 2021 IECC energy efficiency gains are estimated to be in the range of 8% to 15%. The IECC revisions include the following:

- Disclosure of the energy compliance path (prescriptive, performance, etc.) on the construction documents
- Climate zones that are harmonized with ASHRAE 90.1
- For insulation materials, such as blown or draped products, without an observable R-value mark, an insulation certificate from the installer that documents the installed R-value of the material
- A permanent thermal envelope certificate, posted in specified locations, to document:

Like building codes, energy efficiency codes are also important in mitigating the impacts of a changing climate.

International Building Code (IBC)

Classification of Building Types

- **Types I and II:** The various building elements are made up of noncombustible materials.
- **Type III:** Exterior walls are made of noncombustible materials, and the interior building materials are of any material permitted by the IBC.
- **Type IV heavy timber:** Exterior walls are made of noncombustible materials, and the interior elements are made of solid or laminated wood without concealed spaces.
- **Type V:** Structural elements for both exterior and interior walls are of any materials permitted by the IBC—usually combustible construction.

Source: Chapter 6 of the *International Building Code*.¹

- R-value of insulation installed in or on ceilings, roofs, walls, foundations and slabs, basement walls, crawl space walls and floors, and ducts outside conditioned spaces;
- U-factors and solar heat gain coefficients (SHGC) of fenestration; and
- Results from any building enclosure air-leakage testing
- Energy improvements in building enclosure U-values and R-values that result in increases in continuous wall insulation

ASHRAE 90.1-2019 changed over 100 measures from the 2016 version.⁸ The U.S. Department of Energy is currently reviewing the updated standard to determine its energy efficiency improvements.

Some of the changes in ASHRAE 90.1-2019 include the following:

- For the first time, commissioning requirements in accordance with *ASHRAE/IES Standard 202: Commissioning Process for Buildings and Systems*⁹ are mandatory.
- Minimum criteria have been upgraded for SHGC and U-factor for fenestration for all climate zones.
- Air-leakage requirements are clarified.
- Changes in building enclosure U- and R-values, resulting in likely increases in continuous wall insulation/

- All compliance paths have specific rules related use of renewables and lighting.

2021 IBC

The IBC is a model building code for commercial construction, which is then adopted by states and jurisdictions. Compliance with local building code regulations, which may vary from the IBC model code, is imperative.

The increasing use of energy efficient continuous insulation and innovative wall assemblies places a greater emphasis on fire performance of exterior walls, which is evaluated using NFPA 285.

Generally, IBC requires NFPA 285 testing for combustible exterior wall assemblies, including combustible cladding, foam plastic insulation, or combustible water-resistive barriers (WRBs), installed on Types I, II, III, IV buildings of certain heights (see **sidebar** for information on IBC classification of building types). Type V wood construction does not require NFPA 285 testing.

The 2021 IBC requirements for the fire safety of exterior walls containing combustible claddings, WRBs, and foam plastic insulation are found in Chapter 14, “Exterior Walls,” and Chapter 26, “Plastic.” Chapter 14 includes the minimum requirements for exterior walls; exterior wall coverings; openings in the exterior wall; exterior windows and doors; and architectural trim. The provisions detail performance requirements regarding weather

protection, structural performance, moisture control, reaction to fire, and flood resistance. Other provisions in the chapter address materials of construction, installation of wall coverings, and use of combustible materials on the exterior side of exterior walls.

With respect to exterior walls, there are important revisions in the 2021 version of Chapter 14 regarding the use of moisture vapor retarders, particularly when used in combination with continuous insulation, spray foam insulation, and hybrid insulation systems. Other revisions clarify fire performance requirements and improve the consistency of fire testing of exterior walls containing combustible components. **Table 1** summarizes key changes in the 2021 IBC version of Chapter 14.

IBC Chapter 26 contains provisions for the use of foam plastic insulation in exterior walls, which were extensively described in a paper delivered at the 2019 RCI International Convention and Trade Show.¹⁰ The 2021 IBC does not make substantive changes to use in exterior walls (Section 2603.5), but these revisions have been made to other sections:

- A definition for spray-applied foam plastic is added.
- New Section 2603.1.1 requires spray-applied foam plastic to comply with both Section 2603 and ICC 1100.¹¹
- Section 2607.5 adds a height restriction of 75 ft above grade plane for light-transmitting plastic wall panels, where previously there was no height limitation.

NFPA 285-2019

As stated earlier, the IBC uses the NFPA 285 wall assembly fire test to evaluate the flammability characteristics of exterior, non-load-bearing wall assemblies/panels that contain combustible components, including combustible claddings, insulation, and many air- and water-resistive barriers. The multistory test assembly measures:

- Flame propagation over the exterior wall surface
- Vertical flame propagation within the combustible core or components
- Vertical flame propagation over the interior surface from one floor to the next
- Lateral flame propagation to adjacent compartments

NFPA 285 is a full wall assembly test conducted on a test specimen that is 18 ft high and 13 ft 4 in. wide, with a 78-in.-wide window

Section	Changes
1401: General	No changes
1402: Performance Requirements	Subsection 1402.5: • Title changed title from “Vertical and Lateral Flame Propagation” to “Water Resistive Barriers” • Clarifies that combustibility of components is determined in accordance with Section 703.5 • Clarifies Exception 2 fire testing for combustible WRBs, ASTM E1354 test conditions, and ASTM E84 (UL 723) test specimens
1403: Materials	Subsection 1403.2 (Water-Resistive Barrier): • Reorganized prescribed performance standards for WRBs into a list • Added ASTM E331 in accordance with Section 1402.2 as a prescribed performance standard New subsection 1403.14 (Attachments through Insulation): • Guides users to applicable sections under Section 2603 for situations when exterior wall covering attachments to the building structure are made through foam plastic sheathing
1404: Installation of Wall Coverings	Subsection 1404.3 (Vapor Retarders): • Editorial reorganization for ease of use • New and revised provisions regarding use of vapor retarders (Class I and II, and Class III) with continuous insulation, spray foam insulation, and hybrid insulation systems • New provisions regarding use of Class I and II vapor retarders (ASTM E96 Procedure A—desiccant method) that have vapor permeance >1.0 perm when tested using ASTM E96 Procedure B—Water Method • New and revised prescriptive guidance regarding permitted conditions (climate zone and wall configuration) and exceptions where Class I and II, and Class III vapor retarders are permitted in combination with continuous insulation
1405: Combustible Materials on the Exterior Side of Exterior Walls	No changes
1406: Metal Composite Materials	Subsection 1406.10 (Type I, II, III and IV Construction): • Simplified threshold for NFPA 285 testing to installations above 40 ft in height Subsection 1406.11 (Alternate Conditions): • Eliminated complex provisions regarding installations on buildings of Type I, II, III, and IV construction up to 50 ft in height and 75 ft in height
1407: Exterior Insulation and Finish Systems	No changes
1408: High-Pressure Decorative Exterior-Grade Laminates	Subsection 1408.11 (Alternate Conditions): • Revised to eliminate provisions regarding installations up to 50 ft in height
1409: Plastic Composite Decking	No changes

Abbreviation: WRB = water-resistive barrier.

Table 1. Notable revisions to Chapter 14 of the 2021 International Building Code¹

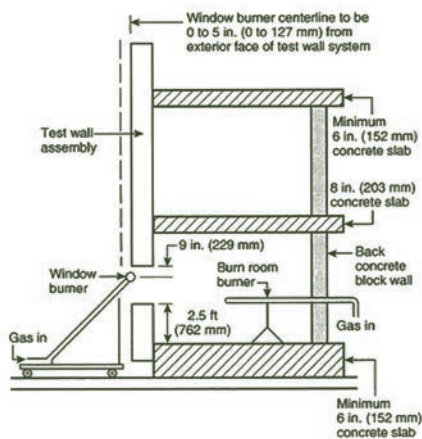


Figure 1. NFPA 285⁴ test assembly.

opening. The fire sources are two gas burners (one room burner located inside the first floor, and another window burner on the exterior side). Both of these burners are needed to simulate real conditions where a fire may originate from within the structure, all interior materials are burning (flashover), and the fire suppression system has failed (Fig. 1).

The wall assembly is mounted on the face of the apparatus (Fig. 2). Thermocouples are fitted on the exterior wall surface, in the wall cavity air space and stud cavity, and in the insulation.

After a testing period of 30 minutes, a successful test will show no flame propagation to the second story room and no thermocouple may exceed 1000°F. Flame spread cannot exceed 10 ft above the top of the window, nor more than 5 ft laterally from the centerline of the window (Fig. 3).

As with other standards-setting organizations, NFPA periodically updates its standards using a consensus-based process. For the 2019 edition of NFPA 285, substantial technical



Figure 2. Two-story test with interior and exterior burners.



changes were made to the test method. The critical technical changes include an expanded scope to encompass any construction type, revisions to include both load-bearing and non-load-bearing assemblies, and new sections added to Chapter 5 to address window header construction and the location of joints and seams in the test specimen assembly. Additional information is required for NFPA 285 test reports. Table 2 summarizes key changes in NFPA 285-2019.

COMPLIANCE PATHWAYS FOR EXTERIOR WALLS REQUIRING NFPA 285 TESTING

As described previously, combustible exterior wall assemblies must demonstrate compliance with the acceptance criteria of NFPA 285. To accomplish this, the exact wall assembly, with all components specified, is tested by an accredited laboratory. Taken at face value, the criteria seem to require that every wall assembly configuration undergo a separate test. However, considering the variables regarding foam plastic insulations, claddings, attachment methods, framing, and other factors, the

number of tests quickly becomes unmanageable. The situation is more challenging because only a limited number of accredited testing laboratories perform NFPA 285 tests.

Another compliance route is through the use of an engineering judgment (EJ). For exterior wall

assemblies complying with NFPA 285, an EJ is a report that provides a comparative analysis of the effects that one or more variations to a tested assembly will have on compliance with NFPA 285 acceptance criteria. These reports are prepared by qualified individuals and organizations, and must be based on full-scale test data. EJs may be general or specific to one construction project or project condition, and may include both qualitative and quantitative elements. EJs using an NFPA 285 full test report are within the scope and intent of IBC 104.11, "Alternative Materials, Design and Methods of Construction and Equipment." However, at the end of the process, the Authority Having Jurisdiction (AHJ) makes the final decision about whether such EJs are acceptable for use on a specific project.

In March 2018, efforts to improve the transparency and consistency of EJs led to the NFPA Committee on Fire Tests approving the formation of a task group to develop guidance for extending NFPA 285 test results. Under the task group, experts have collected experience and industry best practices in an annex to NFPA 285 for guidance when extending test results for assemblies meeting NFPA 285. The annex will provide guidance regarding items for which evaluation and EJ are more commonly requested or required today. These items include analyses regarding base walls, exterior sheathing, WRBs, air gaps, exterior insulations, drainage media, exterior claddings and attachment systems, and the window perimeter. Two key elements of the guidance will be that these wall assemblies are treated as systems that meet the requirements, and that analyses are based on assemblies meeting NFPA 285 acceptance criteria. The annex will likely also stipulate specific limitations to the scope of analysis. These stipulations will

How the NFPA 285 Tests Fire Safety:

- 1 No flame propagation to the second-floor room.
- 2 Critical thermocouple heat sensors shall not exceed 1,000° F during the 30 minute test.
- 3 Externally, flames shall not reach 10 feet above the window's top.
Externally, flames shall not reach 5 feet laterally from the window's centerline.



Figure 3. NFPA 285⁴ fire test parameters and pass criteria.

Chapter	Changes
Title; Chapter 1: Administration	Language from the Title, Scope, Application, and Purpose revised to include: • Both load-bearing and non-load-bearing wall assemblies • All <i>International Building Code</i> construction types
Chapter 3: Definitions	• “Limited-combustible (material)” definition added • “Noncombustible material” definition revised • “Test specimen” definition revised
Chapter 5: Test Specimens	New section 5.7.1 (General): • Clarifies that the test specimen assembly shall be representative of field installations and installed in accordance with the manufacturer’s instructions • Adds that the test specimen wall framing system may be of wood studs (previously, only steel studs were permitted) New section 5.7.2 (Joints and Seams): • Includes new requirements that the exterior veneer of the test specimen must contain – At least one vertical joint/seam – At least one horizontal joint/seam – Exceptions are provided for EIFS systems, standard Stucco systems $\geq \frac{3}{4}$ in. thick, and systems designed to not have horizontal joints or continuous vertical joints • The required joint/seam must be – For horizontal – Continuous across the specimen and located between 1 ft and 3 ft above the window opening – For vertical – Continuous up the full height above the window and located within 12 in. of the centerline over the window opening New section 5.7.3 (Window Headers): • Standardizes the material and configuration details for closure of the window opening—header, jambs, and sill • Allows for nonstandard closures of window opening, but it shall represent the as-constructed condition, and the details (drawings and descriptions) shall be included in the test report
Chapter 7: Calibration Procedure	Section 7.1.13: • Revised allowable limits on calibration temperature values to range of -10% to +20% (previously, limits were $\pm 10\%$)
Chapter 8: Fire Test Procedure	New section 8.1.8: • Adds a $\pm 10\%$ tolerance for gas flow rates when it is demonstrated that burners must follow different flow rates to comply with the required calibration temperatures and heat fluxes
Chapter 9: Data Collection and Observation	Section 9.1.2: • Removes the 10-minute observation period after burner shutoff Section 9.4: • Revised and reorganized for clarity
Chapter 11: Report	Section 11.1: • Adds requirement for the report to include drawings, descriptions, and other details regarding the window opening and the closure of that opening • Adds requirement to report date and results (temperature and heat flux) of the most recent calibration

Table 2. Notable revisions in NFPA 285-2019⁴

likely indicate that changes to the assembly under evaluation are normal and reasonable within the limits of standard construction, explain how to analyze multiple changes, and, importantly, acknowledge that it is not possible to analyze every configuration, every potential change, or every combination of changes to a tested configuration.

The annex is on track for submission under the current (fall 2021) NFPA revision cycle for inclusion in the 2022 edition of NFPA 285. We can expect more detailed information on NFPA 285 EJs as the NFPA Fire Test Committee completes its work on the EJ guidance document. 

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Saddle Flashing Detailing, Mock-Ups, and Construction Sequencing

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ABSTRACT

Moisture-related damage to building components resulting from water infiltration is a common occurrence at parapet terminations at high-rising walls due to discontinuities in the weather-resistive control layer at this critical interface condition. A combination of a lack of detailing and the lack, or improper installation, of the necessary materials to achieve a continuous weather-resistive control layer at parapet terminations against high-rising walls contributes to this issue. After reviewing industry-recognized saddle flashing details, which are limited for applications other than exterior insulation and finish systems and stucco, this paper presents multistep isometric details developed by the author to show the integration of the air-, vapor-, and weather-resistive barriers, roofing membrane, through-wall flashing, and sheet metal flashing for inclusion in one or more industry-recognized standard detail manuals. Additionally, the paper describes the author's recent collaboration with the International Masonry Institute to construct saddle flashing mock-up walls with the assistance of a manufacturer and contractors. These mock-ups will be used as an educational tool to help design professionals, construction managers, building enclosure consultants, manufacturers, contractors, and industry organizations succeed in the design and installation of saddle flashing.

SPEAKER



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Saddle Flashing Detailing, Mock-Ups, and Construction Sequencing

Moisture-related damage is common at parapet terminations of lower building portions against higher building walls (high-rising walls) that lack proper integration of the air and moisture control layers. In the author's experience, saddle flashing conditions are seldom detailed or specified within the design documents, the condition is often not installed correctly, and failure to properly address this condition during the design and construction phases can lead to water and air leakage issues in buildings.

Currently, there are very few industry-recognized saddle flashing details available to provide guidance on the integration of the air and moisture control layers. Among the limited resources for design professionals and contractors on this topic are the current Exterior Insulation and Finish Systems (EIFS) Industry Members Association (EIMA) *Guide to EIFS with Drainage Detailing*,¹ EIFS and stucco manufacturers' standard details, and a series of parapet-to-wall details in Chapter 15: "Details and Practice" of ASTM International's *Moisture Control in Buildings: The Key Factor in Mold Prevention*, second edition.²

This paper provides needed guidance to (a) design professionals and building enclosure consultants for the development of project-specific details for incorporation into their projects, (b) manufacturers for incorporation into their standard details, and (c) recognized construction-industry organizations to develop detail standards for reference by industry professionals and contractors. To address the limitations in available industry-recognized details depicting options to achieve a continuous water-resistive control layer at parapet terminations against high-rising walls, the author has developed multistep isometric details showing the integration of the air-, vapor-, and weather-resistive barriers, roofing membrane, through-wall flashing, and sheet metal flashing for further development and inclusion in one or more detail manuals published by, for example, the National Roofing Contractors Association (NRCA) or the International Masonry Institute (IMI). With the assistance of a manufacturer and multiple contractors, the author collaborated with the IMI to construct saddle flashing mock-up walls

representing a series of installation steps using the necessary flashing materials to achieve a continuous air and moisture control layer at a parapet termination against a high-rising wall. The mock-up walls will be used as an educational tool for design professionals, construction managers, building enclosure consultants, manufacturers, contractors, and industry organizations to succeed in the design and installation of saddle flashings.

THE PROBLEM

Interestingly, architects and designers enjoy developing complex, award-winning building designs that are often conveyed using three-dimensional modeling software, yet three-dimensional details (i.e., isometric and axonometric details) of critical flashing transitions are seldom incorporated into the design drawings. Why is it that firms often receive design awards for their most beautiful, inspiring, and eye-catching designs, but awards are seldom given for building enclosures that have demonstrated outstanding performance after being in service for several years?

Most award-winning building designs include numerous unique and complex interface conditions. Far too often, these unique and complex interface conditions lack a sufficient level of detail and have the propensity to lead to a host of latent building enclosure problems. These problems are disruptive and can lead to change orders, construction delays, water-related damage, and construction claims. While design professionals understand that most air and water intrusion problems occur at interface conditions of differing building enclosure components, these complex conditions are not often detailed and are instead left for the contractor or contractors to resolve during construction. This situation could possibly be a result of the lack of understanding of critical interface conditions,

limited available industry-recognized details, complex building designs with limited design fees, short design and construction schedules, the shifting of design responsibilities toward the contractor, or an overreliance on the contractor's knowledge and level of skill.

One condition that warrants more attention by design professionals, construction managers, building enclosure consultants, manufacturers, contractors, and recognized construction industry organizations is the integration of the terminal ends of parapets and roof edges into the adjacent wall construction of the upper floors and penthouses. The flashing configuration at this interface condition is referred to as saddle flashing and will be discussed in detail within this paper.

DESIGN FUNDAMENTALS

Building enclosures provide a separation between the interior and exterior environments, which allows the interior environment to be controlled and conditioned. Ideally, building enclosures provide continuous layers that control rainwater penetration, air leakage, vapor diffusion, and thermal conduction. Frequently, one or more of these boundaries

Why is it that firms often receive design awards for their most beautiful, inspiring, and eye-catching designs, but awards are seldom given for building enclosures that have demonstrated outstanding performance after being in service for several years?



Figure 1. Example of copper saddle flashing (dashed outline) installed on a building constructed in 1913.

migrating through the exterior cladding in a drainage wall from bridging to the backup wall. At this point, the water's only path of travel is down the inboard surface of the exterior cladding, where it can be managed by a system of flashings and weeps. If high winds accompany rain, water that reaches the air cavity may be blown to the backup wall in exterior walls with certain cladding systems (e.g., rainscreen cladding). The design should account for this when the building is in a high-wind area.

Barrier walls resist water infiltration to the interior by shedding water at the outboard surface of the exterior cladding.

can be achieved with a single material that is integrated with other building cladding components and assemblies to form a continuous barrier between the interior and exterior space. A continuous building air and moisture barrier can be achieved when the opaque wall air/moisture control layer is integrated with fenestration systems around rough openings in the wall, the roofing assembly at the top of the walls, below-grade waterproofing elements, and barrier cladding elements, with flashings and sealant. Discontinuities or holes in these boundaries, either within a material itself or at the interface with an adjacent material or cladding assembly, can result in air leakage and water penetration pathways that bridge interior and exterior conditions.

A general understanding of the differences in the principal exterior wall types and the four primary building enclosure control layers (air, moisture, vapor, and thermal) is essential for the proper detailing and construction of saddle flashings. Preventing the migration of water through an exterior wall system to the interior spaces can be achieved by one of three fundamental concepts: mass walls, drainage walls, and barrier walls.

Mass walls, which are generally associ-

ated with masonry construction, resist water infiltration to the interior by relying on the bulk of the exterior wall system absorbing the water that penetrates the exterior surface of the masonry. To be effective, mass walls typically require multiple wythes of masonry. If the amount of water introduced into the mass wall is greater than the wall's absorptive capacity, water infiltration to the interior may occur.

Drainage walls are designed to resist the migration of water to the interior by establishing a continuous clear cavity or air space between the inboard surface of the exterior cladding and the backup system. Drainage walls typically consist of an exterior cladding material, air space, and backup framing with a water management system consisting of a weather-resistive barrier, flashings, and backup wall. There is a wide variety of types of weather-resistive barriers, many of which can also function as air and vapor barriers when they are detailed and installed in a manner to provide air and vapor control within a given exterior wall assembly. However, the term "weather-resistive air barrier" will be used for the purposes of this paper when referring to the air and moisture control layers. The presence of a clear air space should prevent water from

Barrier walls do not incorporate water management systems, such as air and water barriers and flashings, within the walls to redirect incidental moisture that migrates into the wall back to the exterior. Barrier walls are heavily reliant on the watertight integrity of the exterior cladding system, seals, and coatings.

As noted previously, the four primary building enclosure control layers are the water, air, vapor, and thermal control layers. Best practices include designing and installing building enclosure control layers in a manner that maintains continuity of each layer around the entire building enclosure. Of the four primary control layers, the continuity of the air and moisture control layers at saddle flashing conditions is generally most critical due to the potential for air and water leakage to the building interior.

The approach to detailing and installation of saddle flashing, and the integration of the air and moisture control layers, varies depending on the selected enclosure systems, the building geometry at the parapet-to-wall condition, and the arrangement of the building materials at the interface condition. For mass walls and barrier walls, the detailing of saddle flashings differs considerably from drainage

walls, which incorporate weather-resistive air barriers, through-wall flashings, and weeps.

EARLY SADDLE FLASHING EXAMPLES

Surprisingly, saddle flashing is not a novel idea. The 1954 edition of the *Architectural Graphics Standards*,³ includes isometric, plan, and section details at a parapet-to-wall condition between a low building and a high building. These saddle flashing details illustrate a copper coping, head wall flashing, counter-flashing, and building expansion joint at a low parapet to high-rising wall condition between two buildings. Similar detailing is included in the same standard for a head wall condition at the terminal end of a copper built-in gutter that abuts a higher building wall. Other examples of saddle flashing that are now over 20 years old include details in a 1993 publication of the Sheet Metal and Air Conditioning Contractors' National Association (SMACNA) *Architectural Sheet Metal Manual*, fifth edition,⁴ and a 1997 publication of the *Stucco Resource Guide*, third edition, by the Northwest Wall and Ceiling Bureau.⁵

Occasionally, examples of saddle flashing can be found on older buildings, such as a 16-story building constructed in 1913 (Fig. 1). The saddle flashing occurs at the end of a copper coping of a lower roof that meets a wall of a higher building portion that is clad with copper siding.

CONTEMPORARY SADDLE FLASHING RESOURCES

A few contemporary examples of saddle flashing details are available, although industry-recognized saddle flashing details are generally limited to EIFS and stucco applications and tend to exclude other exterior cladding systems (e.g., brick masonry, metal wall panel). Three-dimensional saddle flashing details with exploded views for EIFS applications are included in the *EIMA Guide to EIFS with Drainage Detailing* (Fig. 2). Similar saddle flashing details for EIFS and stucco applications can be obtained from EIFS and stucco manufacturers' standard details. The EIFS manufacturer standard details include three-dimensional, step-by-step saddle flashing details. One EIFS manufacturer includes a saddle flashing detail that incorporates three sheet metal components: a saddle that straddles the parapet and two side flanges at the parapet-to-wall interface condition, all of which are detailed in a shingled manner that sheds water to the exterior. Another EIFS manufacturer

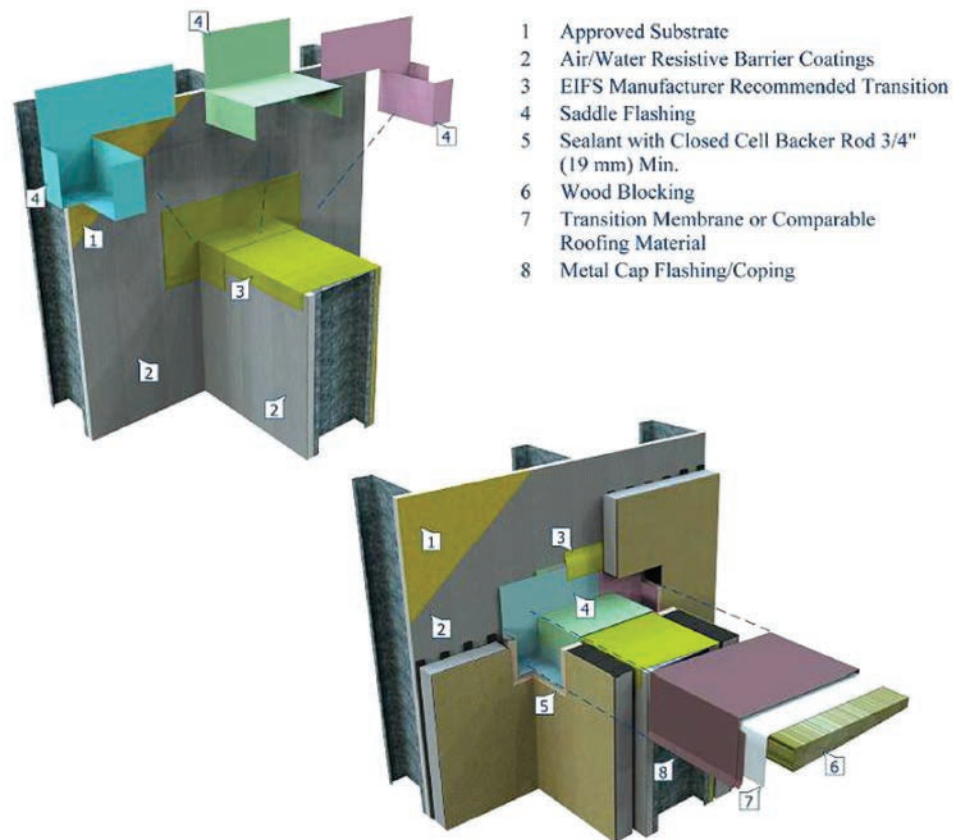


Figure 2. Saddle flashing details excerpt from the EIMA Guide to EIFS with Drainage Detailing.¹ Detail is included courtesy of the EIFS Industry Members Association.

includes a one-piece saddle with an integral upturned leg with continuous side flanges.

SMACNA's *Architectural Sheet Metal Manual*,⁶ seventh edition, includes a saddle flashing detail in figure 3-8D. The detail, which is also available in the fifth and sixth editions and has not changed substantially since the fifth edition, illustrates a sheet metal saddle that straddles the parapet wall and extends through the brick veneer with a sheet metal flange within the drainage cavity. Because details in SMACNA's *Architectural Sheet Metal Manual* are intended to provide guidance for the design and installation of custom-fabricated sheet metal, the details do not include the integration of the air and moisture control layers.

Chapter 15: "Details and Practice" of ASTM International's *Moisture Control in Buildings: The Key Factor in Mold Prevention*, second edition,² presents a series of step-by-step details (Details 5A through 5I) at a parapet to high-rising wall junction in a building with masonry veneer with an air cavity. These details show the progression of the installation of the weather-resistive air barrier, roofing membrane, masonry veneer, and shelf angle, and insulation and the integration of the

control layers at the intersecting walls. The details are developed in a manner such that the masonry on the high-rising wall extends vertically past the parapet and with the portion of masonry located above the lower roof held above the coping and roofing with a steel shelf angle.

A masonry control joint is detailed at the junction of the parapet to high-rising masonry veneer walls separating the multistory masonry veneer from the masonry veneer above the lower roof. At the lower roof, the masonry veneer and shelf angle project outboard and above the sheet metal coping. The series of details is successful in showing the integration and continuity of the weather-resistive air barrier and roofing membrane. However, the series of details does not incorporate a sheet metal saddle flashing at the terminal end of the coping. Because the details do not incorporate a sheet metal saddle flashing, additional design and consideration are needed to detail the end of the coping at the interface with the masonry veneer and shelf angle to prevent rainwater and melting snow from migrating into the air cavity of the masonry veneer wall.

Based on the author's research, resources from recognized construction industry



Figure 3. Deteriorated and wet wood blocking at a parapet-to-wall condition.

organizations—including *The NRCA Roofing Manual: Membrane Roof Systems*,⁷ *The Brick Industry Association (BIA) Technical Notes*,⁸ *IMI Masonry Detailing Series*,⁹ and *Copper and Common Sense*, 8th edition, by Revere Copper Products Inc.¹⁰—did not incorporate saddle flashing details within their design

manuals at the time that this paper was written.

INVESTIGATIVE FINDINGS

The author's first encounter with moisture-related distress to building components resulting from the lack of saddle flashing

occurred during a water infiltration investigation of an EIFS-clad residence in 2005. The two-story residence has a one-story terrace level with parapets

and copings that abut the second-floor exterior wall. No drawings were made available for review. A barrier EIFS cladding had been installed on both sides of the parapet and the adjacent second-floor wall. Removal of the parapet coping revealed that the wood blocking at the top of the parapet was covered with a self-adhered membrane underlayment. The EIFS cladding on the second floor extended down to the top of the wood blocking. The interface condition between the terminal edge of the self-adhered membrane underlayment and the adjacent EIFS was sealed with a fillet bead of sealant. The self-adhered membrane underlayment that covered the wood blocking at the parapet did not extend up behind the EIFS of the second-floor wall. Moisture levels in the wood blocking were high, and the wood blocking was significantly deteriorated at the parapet-to-wall interface (**Fig. 3**).

In 2009, the author investigated water infiltration at an academic building that was designed by a world-renowned architect. The building enclosure consisted of barrier EIFS, aluminum-framed curtainwalls, and single-ply roofing. The building configuration incorporated many roof levels at varying elevations and stepped parapet conditions. One of the many sources of water infiltration into the building occurred at the terminal ends of the parapets that interface with adjacent higher walls and at stepped parapet conditions. The detailing of the sheet metal coping at the parapet-to-wall interface condition was inconsistently installed, with most coping ends extending into EIFS cladding of the higher wall and sealed at the perimeter of the coping-to-EIFS interface with sealant. The architect-



Figure 4. Coping with the exterior insulation and finish systems lapped over the upturned leg of the coping. Side flanges (dashed outline) were omitted.



Figure 5. Parapet-to-wall condition with no integration of the single-ply roofing membrane with the exterior insulation and finish systems.

Figure 6. Some integration of the roofing membrane with the air/moisture barrier behind the exterior insulation and finish systems drainage system. However, no transition flashing was provided to integrate the roofing membrane termination to the air and moisture control layer (arrow).



tural detail called for concealed metal flashing with an integral upturned leg installed below the coping at stepped parapet conditions and parapet-to-wall conditions. The architectural details did not specify side flanges or other means to redirect water to the exterior. At some areas, the EIFS cladding lapped over the upturned leg of the coping (Fig. 4). No concealed sheet metal flashing was installed. A single-ply roofing membrane was extended up and over the parapet and lapped down over the wood blocking in general accordance with the design drawings. No attempts were made by the contractor to extend the single-ply roofing up onto the higher wall (Fig. 5). Diagnostic testing replicated water infiltration into the

building interior two stories below the coping condition. The wood blocking and exterior sheathing were water damaged.

In 2013, the author investigated problems associated with a newly completed EIFS drainage system at a large commercial building. During the investigation, several parapet-to-high rising wall conditions were found to be inconsistent with the EIFS manufacturer's standard details. No water infiltration had been reported, but a few inspection openings were made to confirm whether the conditions

were constructed in general accordance with the EIFS manufacturer's recommendations. The inspection openings revealed that some attempts were made to integrate the air/moisture barrier and the roofing membrane to provide water management in a manner that promotes drainage of incidental moisture to the exterior (Fig. 6).

Proper design and installation of saddle flashing requires careful consideration to properly integrate the air and moisture control layers while accounting for construction sequencing and coordination of various construction trades. Saddle flashing conditions can be made more challenging when introducing multiple cladding systems, fenestration systems, or building expansion joints (Fig. 7 and 8).



Figure 7. End of parapet-to-wall at a building corner with brick masonry, metal wall panels, roofing, and a roof-to-wall expansion joint.



Figure 8. End of parapet-to-wall interface condition with curtainwall, counterflashing, roofing, and building expansion joint.

CONTRACT DOCUMENTS

Detailing of parapet and coping conditions in architectural drawings is typically limited to two-dimensional wall sections and enlarged details. Seldom do architectural drawings include details for the terminal ends of parapets to the adjacent walls of low-to-high building conditions. However, on occasion, the author has seen three-dimensional details incorporated

within architectural drawing sets for complex interface details, with some of the details showing multiple steps. Providing multistep, three-dimensional details of critical interface conditions in architectural drawing sets helps achieve the desired goals for air and water penetration resistance, overall rainwater management, durability, and future maintenance requirements. Three-dimensional details are strongly recommended for complex interface conditions, such as fenestration head-to-jamb and jamb-to-sill conditions, kick-out (i.e., diverter) flashing at sloped roof-to-wall conditions, and saddle flashing conditions.

The introduction of comprehensive multistep, three-dimensional details by recognized construction industry organizations and manufacturers will help provide design professionals with useful resources to develop and incorporate project-specific details into their building designs and assist the construction trades with the integration of their materials at saddle flashing conditions.

Architectural technical specifications for sheet metal flashing and trim often reference standards in SMACNA's *Architectural Sheet Metal Manual*,⁶ without specifically mentioning saddle flashing details. It should be noted that this manual includes many details and

often has multiple ways of detailing a given condition. Although SMACNA includes a single detail for saddle flashing in the *Architectural Sheet Metal Manual*, the detail does not show the integration of the weather-resistant air barrier, membrane flashings, and through-wall flashings with the saddle flashing. If architectural drawings do not include project-specific saddle flashing details and the technical specifications do not explicitly address all the requirements for saddle flashing, including integration with the weather-resistant air barrier, the design intent may not be fully understood, and the installation of this critical interface condition may not be installed effectively to mitigate the risk of water infiltration.

In the master specifications made available by multiple industry organizations for use by design professionals, the sections for sheet metal flashing and trim and roof specialties generally include provisions pertaining to interface conditions with adjoining work. However, these sections do not specifically address saddle flashing. It is strongly recommended that parts 1 through 3 of project technical specifications be developed to include the following project-specific provisions for saddle flashing:

- **Part 1: General**
 - **Shop drawings.** The shop drawing in the section should be expanded to require project-specific details and specifically list required interface details for the design professionals review, including saddle flashing and other critical interface conditions.
 - **Mock-ups.** The mock-ups section should be expanded to include saddle flashing and other applicable interface conditions, including the detailing of the roofing, cladding, flashings, weather-resistant air barrier, thermal insulation, and weeps at the saddle flashing. The saddle flashing mock-up may be incorporated into the building as an in-place mock-up or incorporated into a larger field mock-up of the exterior walls, windows, and other building enclosure components (Fig. 9).
- **Part 2: Products.** This section should be expanded to include project-specific requirements for saddle flashing, including the sheet metal material type, gauge, finish, and fastener requirements.
- **Part 3: Execution**
 - **Fabrication.** This section should be expanded to include requirements for saddle flashing, including prefabricated saddles with fully soldered seams, and upturned back legs that integrate with the side flanges.
 - **Installation of roof flashings.** Project-specific installation steps should be included within this section for the integration of the coping, saddle flashing, weather-resistant air barrier, through-wall flashing, and roof counterflashings.
 - **Performance testing.** Performance testing requirements for saddle flashing conditions, including water infiltration testing methods, test durations, number of tests, and pass/fail criteria, should be included in this section.

SADDLE FLASHING DETAIL DEVELOPMENT

A series of details were prepared by the author for use as a reference guide for design professionals, construction manager, build-



Figure 9. Example of construction mock-up incorporating a saddle flashing condition at the parapet-to-high-rising wall condition. Photograph provided courtesy of M+A Architects of Columbus, Ohio.

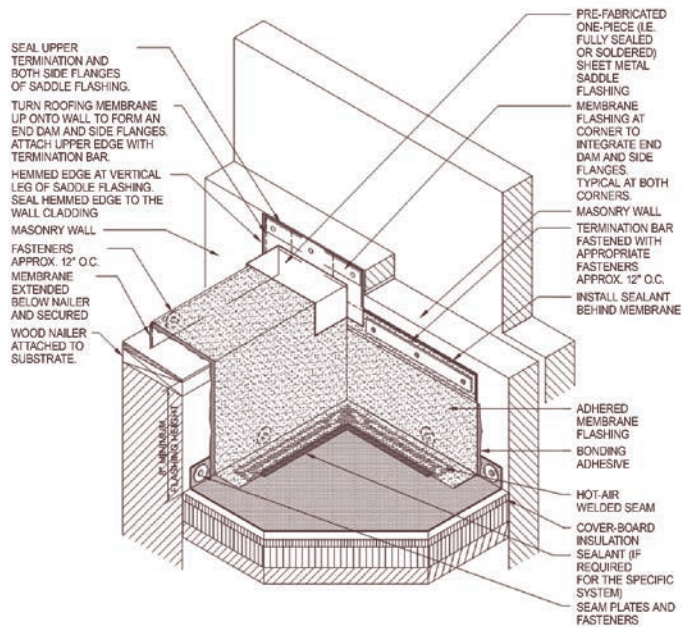


Figure 10. Saddle flashing detail (step 1).

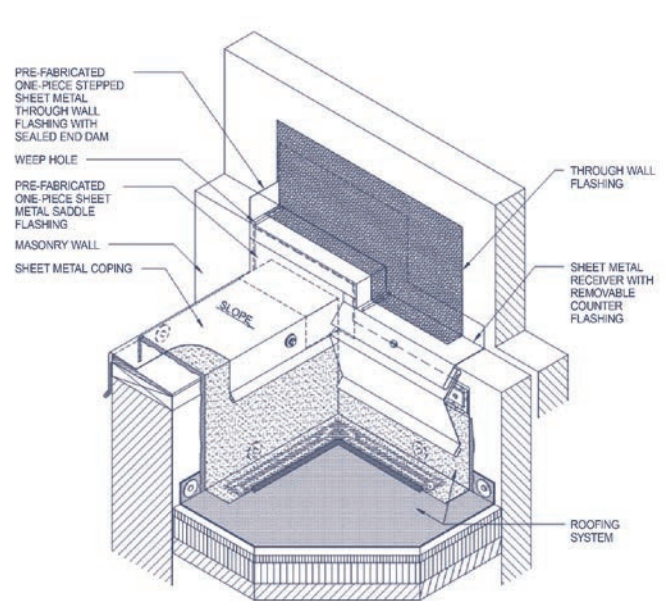


Figure 11. Saddle flashing detail (step 2).

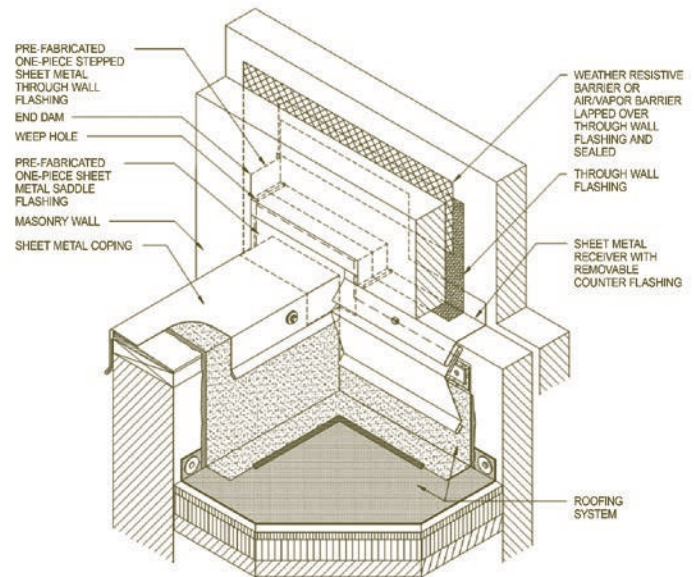


Figure 12. Saddle flashing detail (step 3).

ing enclosure consultants, manufacturers, contractors, and industry organizations to develop and properly integrate the sheet metal saddle flashing components, weather-resistive air barrier, roofing membrane, through-wall flashing, and weeps (Fig. 10–12). Three isometric details were developed to depict the installation steps of the saddle flashing condition; these details are to be used along with two adjoining roof-to-wall conditions that are illustrated in *The NRCA Roofing Manual: Membrane Roof Systems*.⁷ Details TP-1 and TP-7 from *The NRCA Roofing Manual: Membrane Roof Systems*, 2019 edition, for use with thermoplastic polyolefin roofing systems were selected to establish the configuration of the parapet condition and the roof-to-wall condition with counterflashing. The detailing of the saddle flashing condition may be made more or less challenging, depending on the position of the roof counterflashing relative to the coping. Where feasible, the number of cladding systems and the arrangement of the cladding and roofing system components should be considered during design to minimize the number of complex construction details.

It should be noted that NRCA's details TP-1 and TP-7 do not incorporate exterior wall insulation and weather-resistive air barriers because these conditions often vary for a given building design, climate zone, and other project objectives. Therefore, to maintain consistency with other NRCA details, the saddle flashing details described in this paper were developed without thermal insulation at both wall conditions and with only the weather-

resistive air barrier at the high-rising wall. These saddle flashing details will need to be further developed and adapted for project-specific conditions, and any use of the details remains the sole responsibility of the design professional and construction team.

The isometric details were shared with NRCA and the IMI for review and possible incorporation into their design manuals.

When detailing saddle flashing in drainage wall applications, the designer must also consider how to maintain continuity of the air and moisture control layers when compared to mass and barrier-type walls. A minimum of three details (as discussed later) must be incorporated into the design drawings to more accurately convey the design intent. Incorporation of additional steps may be beneficial to provide a more comprehensive understanding of the design approach. These details are often easier to design and install for new construction projects than for existing buildings where accessibility and an overall understanding of as-built conditions are limited.

For step 1 of the saddle flashing installa-

tion sequence (Fig. 10), the exterior cladding (brick masonry) is installed up to the point where the through-wall flashing is installed. This involves coordination between the exterior cladding trade (i.e., mason), roofing contractor, and the contractor responsible for the through-wall flashing (this is often the masonry subcontractor but, in some cases, may be a weather-resistive air barrier installer). The roofing membrane and roof flashing are extended up and over the parapet. On the outboard side of the parapet, the roofing membrane is lapped down over the blocking and sealed to the weather-resistive air barrier (not shown in the detail in Fig. 10) to maintain



Figure 13. An early stage of the saddle flashing mock-up before the installation of the sheet metal through-wall flashing, saddle flashing, and coping.

Figure 14. An intermediate stage of the saddle flashing mock-up with the sheet metal saddle, sheet metal drip edge, two-piece counterflashing receiver, and end dam underway.



air/water barrier continuity. At the terminal end of the parapet, the roofing membrane is lapped up, secured, and sealed to the high-rising wall to manage and redirect water that migrates beneath the coping to the top of the roofing membrane, and ultimately to drain to the exterior. After the roofing membrane is secured and sealed to the high-rising wall, a prefabricated, one-piece (i.e., fully sealed or soldered) sheet metal saddle is installed at the parapet-to-higher wall interface.

Step 2 of the installation sequence (Fig. 11) involves installation of the coping, sheet metal through-wall flashing, two-piece counterflashing, membrane through-wall flashing, and weeps. This step involves multiple trades. At this point in the installation sequence, the trade responsible for the flashing installation needs to be available to install the flashing components. Watertight continuity of the stepped sheet metal through-wall flashing needs to be maintained, and fully sealed or soldered end dams must be incorporated at the terminal ends of the flashing. Placement of weeps should meet or exceed the minimum design standards as recommended by the BIA or IMI. An additional weep should be considered at stepped through-wall flashing conditions to manage

additional moisture that may collect on the through-wall flashing assembly by lateral migration of moisture within the masonry drainage cavity.

Step 3 completes the saddle flashing installation sequence (Fig. 12) by lapping the weather-resistive barrier over the through-wall flashing and the installation of the brick masonry. With the sheet metal and membrane flashings

installed, the area is ready for the installation of the weather-resistive air barrier. If sheet-applied weather-resistive air barriers are used, they may be installed earlier in the sequence, and the weather-resistive air barrier in the area around the saddle flashing can be temporarily lifted and taped out of the way to allow for the installation of the through-wall flashing. The bottom termination of the weather-resistive air



Figure 15. A later stage of the saddle flashing mock-up with all sheet metal components installed and self-adhered flashing membrane in place. The next steps included laying the brick masonry with weeps and installation of a masonry control joint (not shown).

barrier should be lapped, taped, and sealed to the through-wall flashing in accordance with the manufacturer's installation instructions to maintain continuity of the air control layer.

MOCK-UP DEVELOPMENT

The IMI and the Bricklayers and Allied Craftworkers (BAC) of Local 5 Ohio constructed three mock-ups to demonstrate a parapet-to-wall interface condition and further evaluate and explore the feasibility of installing the saddle flashing detail with the masonry, roofing, weather-resistive air barrier, flashings, and weeps (Fig. 13–15). The mock-ups were based on details developed by the author and included in this paper, but they were adapted to include concrete masonry unit backup, a weather-resistive air barrier, rigid board cavity insulation, and a masonry control joint. The saddle flashing mock-ups were built in collaboration with Wiss, Janney, Elstner, Associates, Inc. (WJE), IMI, BAC, Tremco Sealants & Waterproofing (Tremco), and Warren Roofing & Insulating (Warren). Materials were provided courtesy of IMI, Tremco, and Warren. The masonry apprentices at the training center were also excited to learn about the saddle flashing mock-ups. An online video¹¹ prepared by Tremco highlights the construction of the

mock-up and the collaborative effort of the team.

NEXT STEPS

IMI and WJE plan to use the constructed mock-ups as an educational tool for design professionals, construction managers, building enclosure consultants, manufacturers, contractors, and industry organizations to enhance the construction industry's understanding of saddle flashing conditions. The possibility of conducting water infiltration performance testing on the mock-ups has been considered. The IMI and WJE will develop a set of saddle flashing details to incorporate into IMI's online Masonry Detailing Series.

CONCLUSION

Lessons learned from the development of the details and construction of the mock-ups include the following:

- Except for EIFS and stucco applications, there are limited saddle flashing details available from recognized construction industry organizations for reference by design professionals and contractors. However, saddle flashing details can be found in design standards dating back to 1954.

- Trade organizations and manufacturers are encouraged to develop and provide design professionals with example saddle flashing details incorporating the air and moisture control layers.
- The saddle flashing detail in SMACNA's *Architectural Sheet Metal Manual* is intended to provide guidance for the design and installation of custom-fabricated sheet metal saddle flashing; it does not include the integration of the saddle flashing with the air and moisture control layers.
- The series of details in Chapter 15: "Details and Practice" of ASTM International's *Moisture Control in Buildings*, second edition, may be useful in developing project-specific details that incorporate the weather-resistive air barrier and roofing at parapet to high-rising wall conditions. These details must be further developed for project-specific conditions, including incorporation of sheet metal saddle flashings at the intersecting walls to prevent rainwater and melting snow from migrating into the masonry air cavity.
- Three-dimensional models are strongly recommended to develop the saddle flashing design and convey the design intent in a clear and concise manner to contractors.
- Depending on the overall complexity of a given condition, more than three details may be necessary to more clearly convey each step of the installation sequence and the design intent to contractors.
- Expansion of applicable technical specifications is strongly recommended to include project-specific shop drawings, integration of the air and moisture control layers, installation requirements, and mock-ups and performance testing for saddle flashing conditions.
- The design objectives associated with the air and moisture control layers and maintaining their continuity at the saddle flashing condition should be discussed and clearly understood by all parties, including the design professional, construction manager/general contractor, trade contractors, and manufacturer representatives for each system.
- Onsite mock-ups are most effective when all parties, including the design professional, contractors, and manu-

facturer representatives, collaborate in the review, critique, and improvement of the detail condition.

- Construction sequencing and constructability should be carefully reviewed during the design and construction of the mock-up to confirm and adjust the saddle flashing detail so that it is constructible, sequenced properly, and performs as expected.
- Performance testing, including water infiltration testing, is useful in evaluating the performance of, and refining, the saddle flashing detail.
- Preconstruction meetings should include discussions pertaining to requirements of the saddle flashing conditions and integration with the air and moisture control layers.

For further reading, the author has written a blog in Build Meets World titled “An Architect’s Guide to Parapet-to-Wall Detailing” in October 2020 and co-authored an article in the Construction Specifier Failures column, titled “It is time to saddle up!” in the December 2020 issue.^{12–13}

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Diary of a BECxP: Delegated Design Dilemmas

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ABSTRACT

Delegating the design of portions or even the entirety of the building enclosure to specialty contractors has become common practice. However, issues with the delegated design process persist throughout the industry. How can project participants take full advantage of the benefits of delegated design while minimizing its risks? Presenters will draw from research and professional experiences to assist designers, contractors, owners, building enclosure consultants, and building enclosure commissioning providers (BECxPs) with the delegated design process. We will provide a brief overview of the motivations for using delegated design, common problems associated with the process, and inconsistent policies and requirements in various jurisdictions.

We will also outline strategies for successfully implementing delegated designs in both traditional and modern project delivery methods. In traditional design-bid-build projects, specifications play a critical role in defining the expectations for project team members. In contrast, in newer project delivery methods, specialty designers and contractors are contracted early in the design process. With the advent of building enclosure commissioning, early project involvement of building enclosure consultants and BECxPs can add value in the form of additional quality assurance to protect stakeholder interests.

SPEAKERS



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Diary of a BECxP: Delegated Design Dilemmas

Delegating the design of portions of the building enclosure to specialty contractors has become common practice. How can project participants take full advantage of the benefits of delegated design while minimizing risk and avoiding common pitfalls? This paper draws from both research and professional experience to assist designers, contractors, owners, building enclosure consultants, and building enclosure commissioning (BECx) providers (BECxP). The authors present an overview of the motivations for using delegated design, common problems encountered, contract and specification language examples, and summaries of inconsistent policies and requirements in varying jurisdictions.

Strategies are available to successfully implement delegated design within both traditional and modern project delivery methods. In traditional design-bid-build projects, contract drawings and specifications define project requirements. Meanwhile, newer project delivery methods that include design-assist and integrated project delivery render opportunities to employ specialty contractors early in the design process. With the advent of BECx, early involvement of qualified building enclosure consultants and BECx providers in a project can prove beneficial during both the design and construction phases.

BACKGROUND AND DEFINITIONS

Delegated design is the transfer of design responsibility for some portion of the project to a party other than the designer of record (DOR). The American Institute of Architects (AIA) defines delegated design as “design that is to be completed by the contractor or their subcontractors.” Ultimately, delegated design solutions require specific input from a licensed professional retained by a specialty contractor, supplier, or fabricator.

The transfer of design responsibility to specialty contractors has been standard practice in structural engineering for decades for projects including deep foundations, shoring systems, precast concrete framing, cold-formed steel framing, steel connections, and open web wood trusses. While delegated design for building enclosure components and systems is not new, it is becoming more widespread.

For some recent projects, DORs have written project specifications that attempt to delegate the entire building enclosure design, including transitions and interface conditions. A trend toward the increased use of delegated design results in more project control ceded to the contractor.

DORs may choose to use delegated design when they lack the knowledge needed to design specialized systems, such as curtain walls, metal panel cladding, insulated precast concrete wall panels, or connections of these components and systems to the building structure. More recently, delegated design items have included systems such as air barriers. As part of the delegated design process, the DOR is responsible for providing performance and design criteria for the delegated design elements. Design responsibility is typically delegated by means of owner-contractor agreements and subcontractor agreements to a specialty contractor with expertise in a specific discipline. The specialty contractor must employ a design professional licensed in the state or region where the building will be constructed to complete the design such that it conforms to the DOR's specified criteria.

BENEFITS OF THE DELEGATED DESIGN PROCESS

One typical benefit is that through their involvement in the design process, contractors and their specialty subcontractors gain a better understanding of the systems and components they will eventually install, hopefully limiting requests for information and change orders. Another benefit is that the unique knowledge of the specialty contractors' licensed design professionals often makes them more qualified to design portions of the project and enables

them to complete the design more efficiently than the DOR. Their expertise and efficiency should theoretically improve design quality and reduce overall design fees for the project. Because contractors are responsible for means and methods, they will be able to select a design solution that works with the tools and resources available to them, hopefully reducing construction costs. Although the use of delegated design alters the traditional process of fully documenting the project before project award, it can accelerate the project schedule, which is a main driver behind many modern and complex construction projects.

PITFALLS OF THE DELEGATED DESIGN PROCESS

Delegated design may represent a growing trend in the building enclosure industry, but the process does not always go smoothly. Before considering delegated design for certain aspects of the project, the DOR should verify if the professional licensing board in the state or

In traditional design-bid-build projects, contract drawings and specifications define project requirements. Meanwhile, newer project delivery methods that include design-assist and integrated project delivery render opportunities to employ specialty contractors early in the design process.

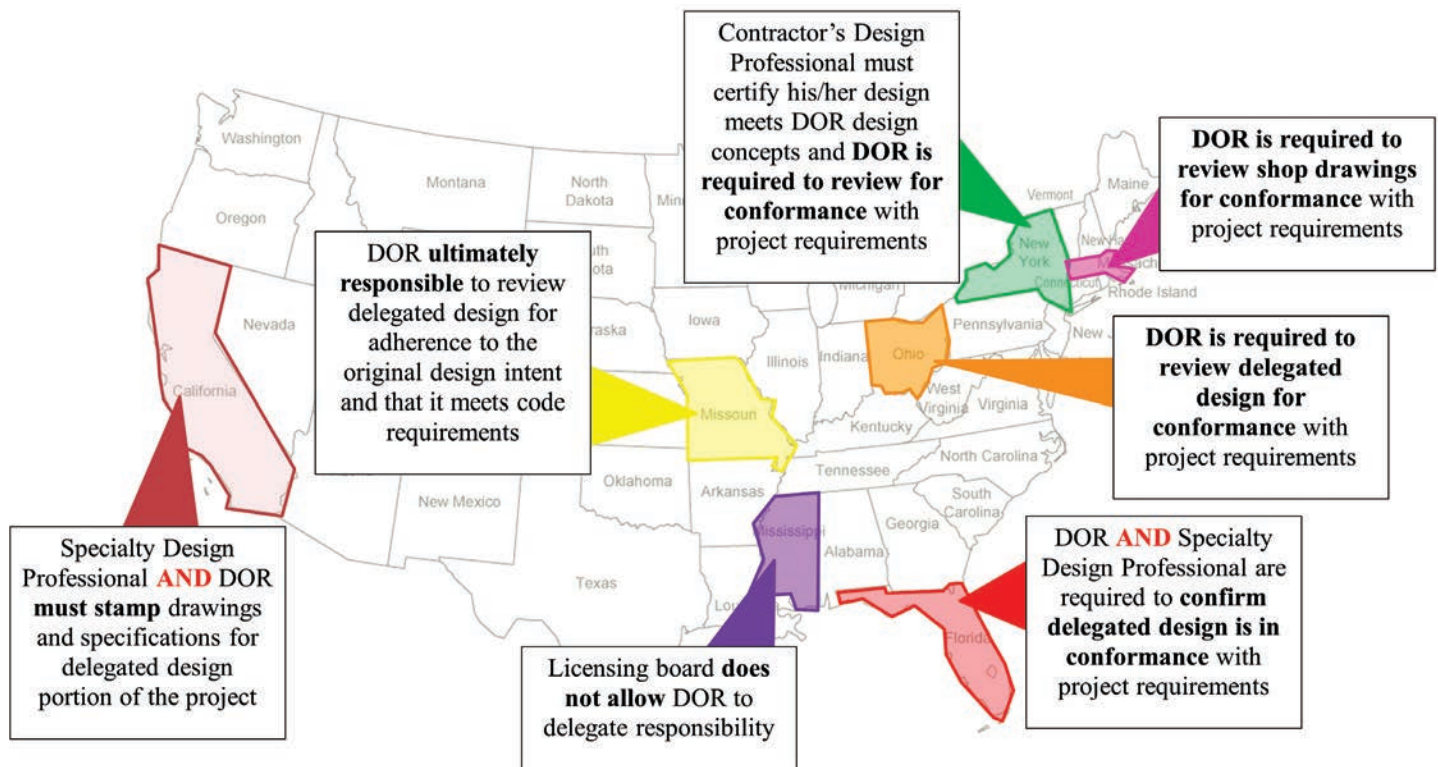


Figure 1. Limited summary of professional licensure regulations regarding delegated design. Note: DOR = designer of record.

region where the project is located has special regulations regarding delegated design (Fig. 1). Not all states allow the DOR to delegate design responsibility for any portion of a project. States such as Missouri and Mississippi require the DOR to remain in responsible charge of the design, even when shop drawings are prepared by a specialty subcontractor. California goes a step further by requiring both the contractor's licensed professional and the DOR to stamp specifications and drawings for delegated design portions of the project. In states where delegated design is expressly permitted, there may be specific requirements for the contractor's licensed professional and/or the DOR to certify that the delegated design meets performance and design criteria specified by the DOR. Regardless of project location, the DOR should review delegated design documents for conformance with specified performance and design criteria and to uphold the health, safety, and welfare of the public.

Even when it is clear that delegated design is legally permissible, a DOR who intends to specify delegated design for portions of the project should hold early discussions with the owner. Unless delegated design items are explicitly excluded from the DOR's contract, the owner should reasonably expect them to be included as part of a complete design by the DOR. Failure to communicate the DOR's intention to include delegated design require-

ments for certain building enclosure systems may result in loss of trust and confusion with the owner.

The DOR's intention to use delegated design must also be clearly communicated to the contractor in the contract documents. In cases where delegated design requirements are not clear, the contractor may not appropriately budget or schedule for the associated tasks. The contractor cannot be involved in the delegated design process to the degree necessary without an agreement from the owner to be paid for preconstruction services because funds must be allocated to "buy" delegated design services from specialty subcontractors.

It is often unclear who is responsible for coordinating and completing the design of interfaces between systems or components designed by the DOR and those designed by specialty subcontractors. Similar ambiguity surrounds requirements for record drawings, the role that the DOR and contractor will play in developing them, and coordination of details at transitions with adjacent assemblies designed by various parties. Inadequately detailed interfaces often become problematic during construction and, if overlooked, after occupancy. These "undetailed details" must be addressed on the fly during construction, often leading to inadequate in-situ performance and contention between various parties.

DIFFERING LEGAL STANDARDS

In general, designers and contractors are held to different legal standards. Designers are typically required to prepare documents with a standard of care similar to that of other designers doing similar work in the same geographic area at the same point in time. A certain degree of errors and omissions are expected and acceptable. However, contractors are held to a contract standard, requiring them to complete the project according to the drawings and specifications, and often to guarantee or warrant performance. When the project specifications include delegated design responsibilities, the contractor can inadvertently assume risk beyond what would be typical for a designer. These risks can sometimes be addressed through additional insurance or by including contract language to clarify that the contractor will only be held to a professional standard of care for delegated design services.

STANDARD CONTRACT LANGUAGE

The contract documents, including the owner-contractor agreement, are the vehicle for delegating design responsibility to the contractor. The term "delegate" can be considered a misnomer, however, because the DOR typically has no contractual relationship with the contractor. As such, the DOR cannot explicitly delegate design services to the contractor. What takes place is a form of design alloca-

3.12.10 The Contractor shall not be required to provide professional services that constitute the practice of architecture or engineering unless such services are specifically required by the Contract Documents for a portion of the Work...

3.12.10.1 If professional design services or certifications by a design professional...are specifically required of the Contractor by the Contract Documents, the Owner and the Architect will specify all performance and design criteria that such services must satisfy...

Figure 2. Excerpts from AIA A201 Sections 3.12.10 and 3.12.10.1.

tion and shifting responsibilities by means of separate owner contracts with the DOR and contractor.

AIA standard agreements are widely used. The standard AIA owner-contractor agreements incorporate AIA A201¹ as the general conditions by reference. The following summarizes the provisions applicable to delegated design (including those shown in **Fig. 2**) given in AIA A201-2017 Section 3.12.10:

- The contractor cannot be required to provide professional design services unless specifically required by the contract documents for a portion of the work.
- The contractor cannot be required to provide professional design services in violation of applicable law.
- If professional design services are specifically required of the contractor by the contract documents, then the owner and DOR are required to specify all performance and design criteria.
- The contractor is entitled to rely on the adequacy and accuracy of the performance and design criteria provided in the contract documents.
- If the contract documents require the contractor's licensed design professional to certify that the work has been performed in accordance with the design criteria, the contractor shall furnish such certifications to the DOR.

Further, AIA standard general conditions do not consider shop drawings and submittals to be part of the contract documents (**Fig. 3**). For traditional design-bid-build projects, submittals and shop drawings

serve as a quality assurance measure to demonstrate how the contractor proposes to implement the DOR's design. This traditional treatment of submittals and shop drawings may no longer hold true for projects incorporating the delegated design process, depending on final specification language that may supersede standard general conditions.

A coalition of organizations in the architecture, engineering, and construction industries, including the Associated General Contractors (AGC), has developed a set of standard contracts referred to as ConsensusDocs.² ConsensusDocs 200 Section 3.15 provides a similar set of requirements related to delegated design:

- If the design of a particular system or component to be incorporated into the project is specifically required of the contractor by the contract documents, then the owner is required to specify all required performance and design criteria.
- The contractor shall not be responsible for the adequacy of performance and design criteria provided in the contract documents.
- As required by the law, the contractor shall procure design services and certifications necessary to satisfactorily complete the work from a licensed design professional. The signature and seal of the contractor's licensed design

professional shall appear on all drawings, calculations, specifications, certifications, shop drawings, and other submittals related to the work designed or certified by the contractor's licensed design professional.

In contrast to AIA A201, the AGC standard contract language typically considers approved submittals (including shop drawings) to be part of the contract documents.³

The Engineers Joint Contract Documents Committee (EJCDC) has issued a less frequently used family of contract documents. Again, the language is somewhat similar to that of the other contract documents regarding signed and sealed documents and performance criteria provided by the owner and/or DOR. The following summarizes EJCDC C-700⁴ requirements for delegated design:

- If professional design services or certifications by a design professional related to systems, materials, or equipment are specifically required of the contractor by the contract documents, the owner and DOR must specify all performance and design criteria.
- The contractor shall provide required design services and/or certifications by a properly licensed professional. The signature and seal of the contractor's licensed design professional shall appear on all drawings, calculations, specifications, certifications, shop drawings, and other submittals related to the work designed or certified by the contractor's licensed design professional.
- Shop drawings and other submittals related to the work designed or certified by the contractor's licensed design professional, if prepared by others, shall bear the licensed design professional's written approval when submitted to the engineer.

Similarly to AIA standard contracts, the EJCDC standard contracts do not specifically consider shop drawings and submittals to be part of the contract documents. If AIA or

3.12.4 Shop Drawings, Product Data, Samples, and similar submittals are not Contract Documents. Their purpose is to demonstrate how the Contractor proposes to conform to the information given and the design concept expressed in the Contract Documents for those portions of the Work for which the Contract Documents require submittals...

Figure 3. Excerpt from AIA A201 Section 3.12.4.

EJCDC standard contracts are used, language must be added to the supplementary conditions or project specifications before shop drawings and approved submittals related to delegated design elements are unequivocally considered contract documents.

AIA, AGC, and EJCDC standard contracts all require the DOR to provide the contractor with performance and design criteria for delegated portions of the project. Responsibility for design intent (identifying appropriate performance and design criteria) remains with the DOR. The standard contracts only allocate the responsibility for providing a design solution to the contractor as part of the delegated design process.

DELEGATED DESIGN AND BECx

When portions of the building enclosure design are delegated, a BECxP has the unique opportunity to assist in protecting the owner's interests by providing an added layer of quality assurance to confirm that delegated designs are coordinated throughout the project.

The following industry documents describe the BECx process:

- ASTM E2813-18, *Standard Practice for Building Enclosure Commissioning*⁵
- ASTM E2947-16a, *Standard Guide for Building Enclosure Commissioning*⁶
- NIBS Guideline 3-2012, *Building Enclosure Commissioning Process BECx*⁷

According to ASTM E2813, BECx is a process that begins with the establishment of the owner's project requirements (OPR) and endeavors to confirm that the exterior enclosure and those elements intended to provide environmental separation meet or exceed the expectations of the owner as described in the OPR, and as defined by the contract documents.

Delegated design impacts building enclosure performance because, as stated in NIBS Guideline 3, "due to the integration and connectivity of building enclosure systems, a performance deficiency in one system can result in less than optimal performance in other systems." Therefore, if a delegated portion of the building enclosure or its interfaces with adjacent components and systems are poorly designed or detailed, or are otherwise not coordinated with one another, the performance of the entire building enclosure will likely suffer.

NIBS Guideline 3 also asserts that "the most reliable means to achieve performance

targets during construction is to assure that an expert with technical knowledge of the design and installation of the systems being proposed for the building is integrated into the design process and to visually observe the installation of a statistical sampling of the work" and that "the most effective commissioning process ideally begins at project inception." A qualified BECxP, in conjunction with the owner and DOR, can identify delegated design items and potential associated problem areas early during the design process.

TYPICAL BECx ACTIVITIES

ASTM E2813-18 and ASTM E2947-16a describe requirements for two levels of BECx: fundamental and enhanced. For both levels, BECxPs provide architecture- and/or engineering-related services on behalf of the owner. Their services typically include independent design reviews of enclosure-related drawings and specifications during the design phase, and direct and substantive participation during the bidding and negotiation, preconstruction, construction administration, and occupancy and operations phases of the project. The differences between the fundamental and enhanced BECx levels include the latest point in the project delivery process when the BECxP may be engaged (design development vs. schematic design), the minimum number of independent design reviews during the design phase (1 vs. 3), and minimum testing requirements during the preconstruction and construction phases.

The BECx process described in ASTM E2813, ASTM E2947, and NIBS Guideline 3 assumes project delivery by means of design-bid-build. However, NIBS Guideline 3 acknowledges that the BECx process will vary based on the project delivery method, and that many of the activities described can be applied to any project delivery method. As such, there is some latitude for the BECxP to adapt to projects that include significant delegated design.

All three documents reference the BECxP as performing an independent design review of the drawings and specifications and state that the BECxP should pay close attention to interface details and review the design documents for constructability, performance requirements, and continuity of the building enclosure. This task is particularly important when many portions of the building enclosure design are delegated and the building enclosure design is complex. During the design review(s), the BECxP should note locations where adjacent or interconnected systems and

components are delegated to different design professionals and identify areas where clarifications regarding design and detailing of interface conditions are recommended. During specification review, the BECxP should verify that delegated design elements are clearly identified and that complete performance and design criteria are provided. Best practice is to include delegated design requirements in Division 01, such that technical specification sections can reference and expand on those general requirements.

The three referenced BECx documents also include similar language requiring the BECxP to provide technical assistance during the review of building enclosure-related submittals and shop drawings for conformance with the contract documents, as well as aspects such as constructability, coordination of interface conditions, installation tolerances, sequence of installation, and material compatibility. BECxP involvement during submittal review can provide significant benefits because this provides an extra layer of assurance that interface conditions are detailed and that delegated designs are in general accordance with the DOR's specified performance and design criteria. Clearly, DOR drawings for a project employing delegated design will generally not include all final interface details because so much of the design is yet to be completed by the contractor and the specialty designers.

BECx also typically involves mock-ups during the construction phase. Both fundamental and enhanced BECx require first installation mock-ups, but standalone mock-ups covering interface conditions between various components and systems are also highly beneficial because they provide an opportunity to identify and resolve issues before they are constructed on the building. The authors have had significant success with projects employing the following strategies associated with preconstruction mock-ups:

- Identifying delegated design components and systems early in the project, well in advance of the mock-up design and construction.
- Holding a meeting with the project team, including building enclosure subcontractors, to review delegated design project requirements and interface and coordination issues that will be addressed during the mock-up.
- Requiring building enclosure coordination and interface details be developed and approved by the DOR and contractor in advance.



Figure 4. Preconstruction mock-up constructed in two phases.

- Constructing the mock-up in two phases, with phase 1 including the structure, exterior sheathing, air and water barriers, cladding attachments, fenestration, barrier walls, roofing system, and primary sealant joints (**Fig. 4**).
- Reviewing in-progress construction, including interface details, and performing limited field quality-control testing of the phase 1 mock-up before completing the mock-up during phase 2.

Establishing requirements for a two-phase mock-up is suited for inclusion in a dedicated Division 01 specification section. The BECxP, who is often tasked with developing the project-specific BECx specification, can develop and review such requirements with the project team early during the design phase.

SPECIFICATIONS FOR DELEGATED DESIGN REQUIREMENTS

Specifications should define the scope and clarify expectations for delegated design services. **Figure 5** shows an example of language that is often included for this purpose in Specification Section 013300 Submittal Procedures, Section 014000 Quality Requirements, or another appropriate Division 01 section. (Currently, there is no dedicated number or title defined by the Construction Specifications Institute for “delegated design.” As

1.7 DELEGATED-DESIGN SERVICES

A. Performance and Design Criteria: Where professional design services or certifications by a design professional are specifically required of Contractor by the Contract Documents, provide products and systems complying with specific performance and design criteria indicated.

1. If criteria indicated are insufficient to perform services or certification required, submit a written request for additional information to DOR.

B. Delegated-Design Services Certification: In addition to Shop Drawings, Product Data, and other required submittals, submit digitally signed PDF file paper copies of certificate, signed and sealed by the responsible design professional, for each product and system specifically assigned to Contractor to be designed or certified by a design professional.

1. Indicate that products and systems comply with performance and design criteria in the Contract Documents. Include list of codes, loads, and other factors used in performing these services.

C. Adjacent or Interconnected Products and Systems: Where delegated design services are required for multiple adjacent or interconnected products and systems, the Contractor will coordinate and assign responsibility for the detailing of interface conditions by the responsible design professionals and provide fully coordinated shop drawings.

Figure 5. Example of Division 01 article with requirements for delegated design services.

2.1 PERFORMANCE REQUIREMENTS

A. **Delegated Design:** Engage a qualified professional engineer, as defined in Section 014000 "Quality Requirements," to design glazed aluminum curtain walls.

B. **General Performance:** Comply with performance requirements specified, as determined by testing of glazed aluminum curtain walls representing those indicated for this Project without failure due to defective manufacture, fabrication, installation, or other defects in construction.

1. Glazed aluminum curtain walls shall withstand movements of supporting structure including, but not limited to, story drift, twist, column shortening, long-term creep, and deflection from uniformly distributed and concentrated live loads.

2. Failure also includes the following:

- a. Thermal stresses transferring to building structure.
- b. Glass breakage.
- c. Noise or vibration created by wind and thermal and structural movements.
- d. Loosening or weakening of fasteners, attachments, and other components.
- e. Failure of operating units.

C. **Structural Loads:**

1. Wind Loads: As indicated on Drawings.
2. Other Design Loads: As indicated on Drawings.

Figure 6. Example of insufficient performance requirements for a curtainwall system.

such, these authors often observe general delegated design requirements tucked within other Division 01 sections.) Regardless of location, it is imperative that the DOR include general delegated design requirements within Division 01, such that those general requirements and definitions need not be reintroduced within each technical specification section that includes delegated design.

Technical specification sections for specific building enclosure systems and components (typically found in Divisions 03 through 09) should explicitly state when delegated designs are required. They should be performance-based rather than proprietary or prescriptive so that they specify only the design requirements and not the design solution. Specifications should include all per-

formance and design criteria that the specialty contractor will need to complete the design and list all required submittals.

Figure 6 includes an example of insufficient performance requirements specified for the delegated design of a glazed aluminum

curtainwall system.

The same specification section may also require that a signed and sealed delegated design submittal be provided indicating compliance with the specified performance requirements (**Fig. 7**).

Although the curtainwall in the example has been specified to be designed to withstand movements of the supporting structure, the specifications fail to provide information as to the magnitude of anticipated movements. Similarly, no requirements related to curtainwall system deflection are provided. The specialty contractor's design professional cannot be expected to reanalyze the entire structure. The DOR should provide anticipated building movements as part of the performance specification requirements or elsewhere within the contract documents.

Additionally, the specifications do not include requirements related to water penetration, air infiltration, energy performance, or other similar items. During the design phase, a qualified BECxP would identify these issues so that project specifications could be appropriately updated. Ultimately, the project specifications should include information such that the listed performance requirements meet or exceed those established by the OPR. The specialty designer should then provide substantiation of the stated requirements by means of the delegated design submittal process.

COORDINATION WITH FIELD QUALITY-CONTROL TEST REQUIREMENTS

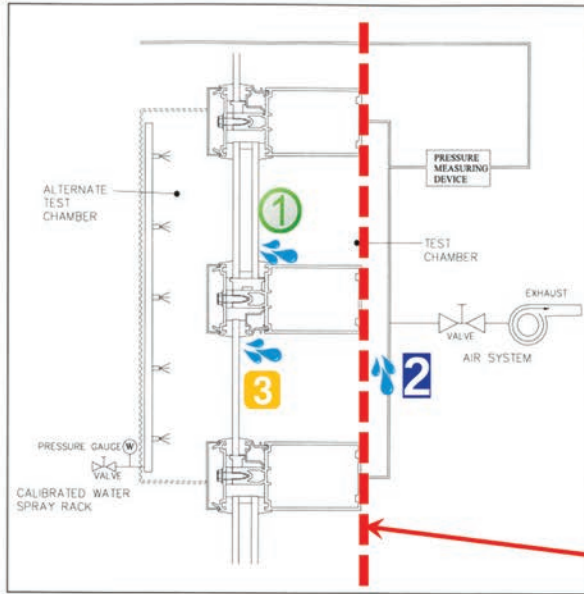
Field quality-control testing requirements are typically listed in Part 3 of individual specification sections. An example of incomplete field performance requirements related to water penetration of a glazed aluminum curtainwall may include language such as the following: "Test for water penetration in accordance with AAMA 503 and ASTM E1105 requirements. Test at a pressure of 10 psf." Although this language references AAMA

1.3 ACTION SUBMITTALS

A. **Delegated-Design Submittal:** For glazed aluminum curtain walls indicated to comply with performance requirements and design criteria, including analysis data signed and sealed by the qualified professional engineer responsible for their preparation

Figure 7. Example of submittal requirements for a curtainwall system.

Water Penetration/Leakage



ASTM E 1105-15:

- No water penetration.

AAMA 503-14:

- Water leakage (if more than 0.5 oz.).

ASTM E 1105-15:

- Water penetration.

AAMA 503-14:

- Water penetration & leakage.

ASTM E 1105-15:

- No water penetration.

AAMA 503-14:

- Water leakage? No exterior drainage provisions...

Innermost plane for water penetration

Underlying Drawing From AAMA 503-14

Figure 8. Comparison of ASTM E1105 and AAMA 503 definitions of water penetration and water leakage.

and ASTM standards, it fails to specifically indicate failure criteria. Figure 8 summarizes the failure criteria for AAMA 503⁸ and ASTM E1105.⁹

As indicated, failure criteria differ depending on the chosen standard. AAMA 503 provides criteria for both water leakage and water penetration, while ASTM E1105 only addresses water penetration. Ambiguity regarding definitions of water penetration and leakage will persist if not specifically defined within the project specifications.

At location 1 in Fig. 8, for example, ASTM E1105 would not recognize water accumulation as water penetration, while AAMA 503 would consider 0.5 oz of water or more accumulated on the horizontal surface as water leakage. Therefore, the example specification language is unclear as to whether water entering through the curtainwall and pooling on a horizontal mullion but not crossing the “innermost plane” by spilling over the edge of the mullion would be considered a violation of the performance specification. Similar ambiguity would exist at location 3. The only place where both standards agree is location 2, where water crossing the innermost plane (noted in dashed red) would constitute water penetration.

If these issues are not addressed during the design phase, ambiguities and incomplete specification language can lead to conflict over whether or not the DOR’s performance

requirements have been met. A BECxP can assist in addressing potential confusion over field quality-control testing requirements by recommending that specifications clearly include the following information:

- component or system to be tested
- quantity and timing of tests
- locations of tests
- test standard or description of test
- test method or methodology
- pass/fail criteria
- party responsible for testing and reporting
- reporting requirements
- required additional testing in case of failed tests
- party responsible for costs associated with failed tests

These items can be defined in a Division 01 BECx specification section drafted by the BECxP with approval by the DOR and owner.

DESIGN LOADS AND CONNECTIONS

The DOR’s drawings are the most effective means for communicating overall dimensions, quantities, locations, design loads, and other quantitative requirements for delegated design systems or components. The drawings

should also clearly indicate attachment locations between the delegated systems and structure so that the DOR’s design assumptions are easily understood. To avoid conflicting information, each of these items should be shown in a single location.

For example, the DOR may specify loads applied to a precast concrete wall system on the framing plan (Fig. 9a) and required embed

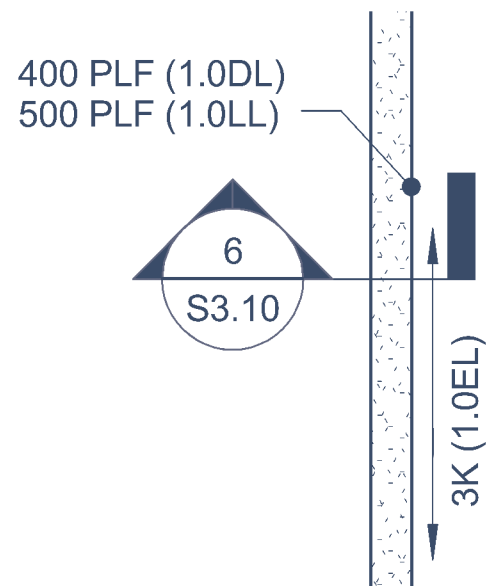


Figure 9a. Excerpt of designer of record drawing depicting loading for a delegated precast concrete wall panel.

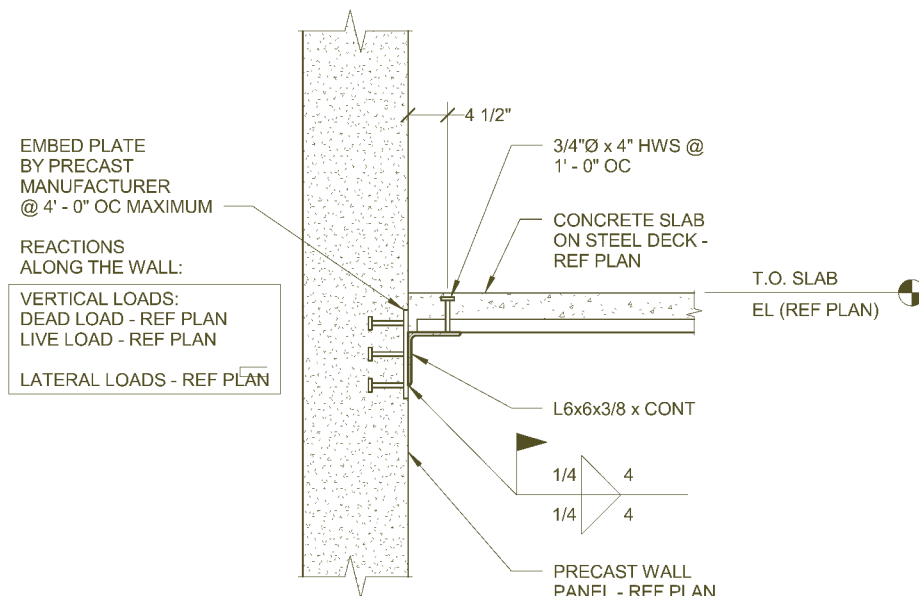


Figure 9b. Designer of record detail depicting delegated precast concrete wall panel.

spacing for the connection between the wall panel and the elevated slab in a connection detail (**Fig. 9b**). These requirements are properly only included in one location.

INTERFACE CONDITIONS

Interface conditions can be especially problematic when early coordination of separate designs does not occur. There is a lack of consensus as to whether it is the responsibility of the contractor or the DOR to coordinate details where two delegated design systems interface. Qualified BECxPs should use their unique role to assist in identifying interface conditions and suggest that the DOR clarify which entity is responsible for coordinating

transition detailing.

Specialty subcontractors do not prepare delegated designs until after their contracts have been awarded. Therefore, coordination of interface details generally occurs during the construction phase. The BECxP should provide technical assistance during submittal reviews regarding conformance with the contract documents and coordination of interface conditions. If several delegated design systems interface, it may be prudent to recommend coordination meetings, preconstruction mock-ups, and field quality-control testing of these conditions.

Figure 10 shows a rudimentary example of a situation where interface conditions can

become problematic, especially if details are repeated on a project. If two specialty designers provide flashing details compatible with their delegated design system, but transitions between systems is not addressed, issues associated with the “holes” in the building enclosure may manifest, potentially resulting in the need for repairs post-occupancy.

DEFERRED SUBMITTALS

Because delegated designs are typically completed during the construction phase, documentation for these components is often not available when the DOR’s drawings and specifications are first submitted to the building department for permit. The building department will frequently require the delegated design documents be provided as a deferred submittal before either the installation or inspection of delegated design components.

The *2018 International Building Code* (IBC 2018)¹⁰ defines deferred submittals as “those portions of the design that are not submitted at the time of the application that are submitted to the building official within a specified period.” Section 107.3.4.1 of IBC 2018 further states that “deferred submittal items shall not be installed until the deferred submittal documents have been approved by the building official.” Informal survey results from building departments throughout the United States reveal that building department requirements regarding deferred submittals vary widely in practice (**Fig. 11**). Many locales require deferred submittals to be submitted and approved before construction. In these cases, building departments may provide use-

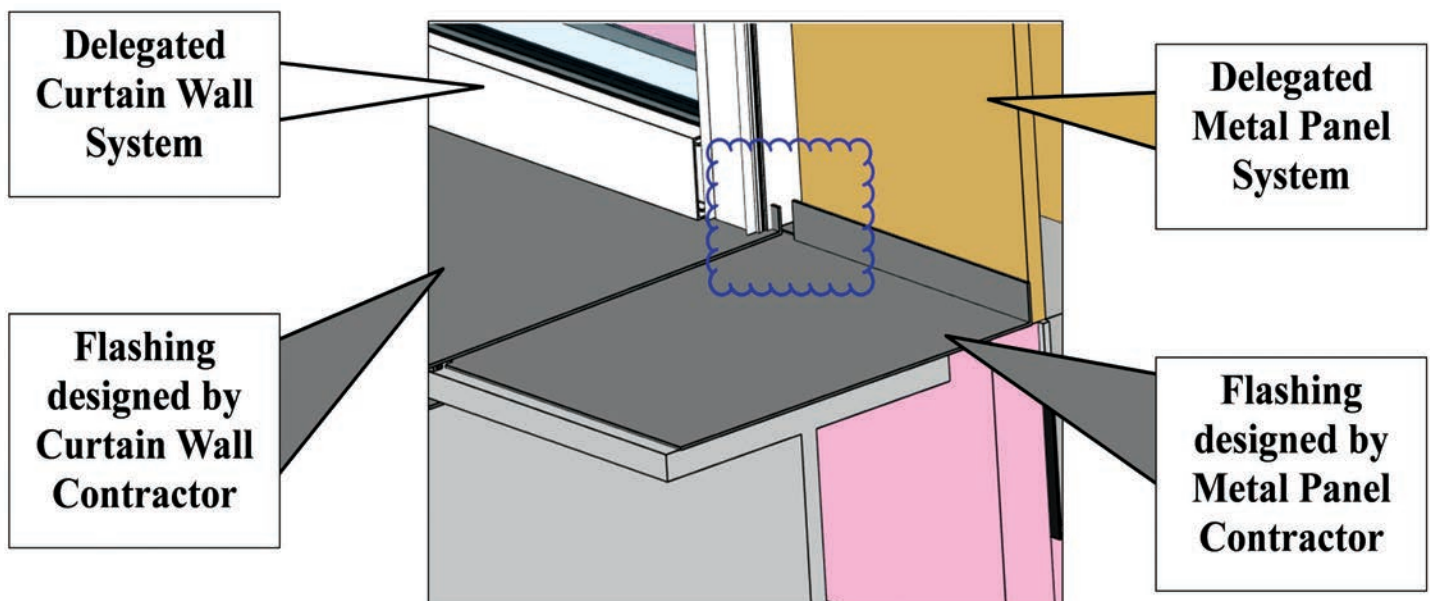


Figure 10. Example of a potentially problematic interface condition between delegated systems.

ful guidelines or checklists to assist with the deferred submittal process. In other locales, there may be no clear policy, or the in-place policies may be unclear or incomplete. It therefore becomes important for the project team to become familiar with local requirements before embarking on a project that includes delegated design and deferred submittals.

STRATEGIES FOR MODERN PROJECT DELIVERY METHODS

In the traditional design-bid-build project delivery method, the DOR's drawings and specifications are typically completed before the contractor is selected. Projects incorporating significant delegated design do not lend themselves well to traditional approaches because the specialty delegated designs are completed partially or wholly during the construction phase.

Modern project delivery methods, such as design-assist and integrated project delivery, sometimes alter contractual relationships and the division of liability. The main shift, however, relates to the time when the contractor and specialty subcontractors become involved in the project. Instead of waiting until the construction phase, the general contractor (GC) and key specialty subcontractors are selected during the design phase of the project. Due to the early involvement of specialty subcontractors, these project delivery methods are often referred to as "collaborative design."

Contractual relationships for design-assist projects vary considerably. Design-assist is typically considered a subset of the construction manager (CM) at risk project delivery method where the CM is contracted with the owner or directly with the DOR to provide input during the design process. The DOR may also contract with specialty subcontractors as subconsultants, though this contractual relationship remains rare.

Contracts for integrated project delivery are developed such that the owner, DOR, and GC or CM share in the success or failure of the overall project. The AIA provides a free guide to integrated project delivery to assist project teams in navigating such projects.¹¹ The guide states that "where assigned work scopes require a constructor to perform design services, it will need to handle that task consistent with registration requirements. This is no different than in the case under a non-integrated approach." As such, the unique contractual arrangement required for integrated project delivery should not have a significant impact on delegated design responsibility when compared to more

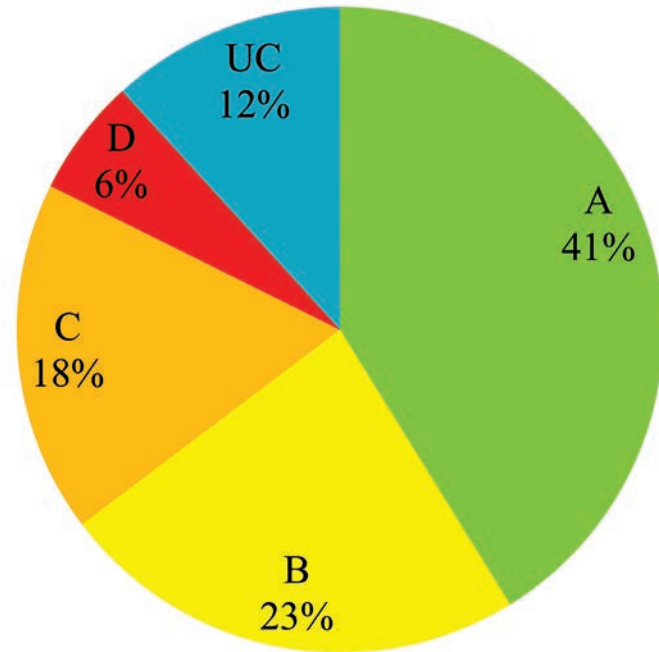
traditional approaches. No matter the delivery method, the DOR is still required to provide performance and design criteria for delegated design systems and components included as part of the project.

Because collaborative project delivery methods involve selection of the contractor early during the design phase, there is the opportunity for specialty contractors to begin developing their delegated design documents before the DOR's drawings and specifications are complete. This is becoming the norm for complex buildings and makes it even more important that the BECx process commence early, thus allowing the OPR to guide the DOR and delegated designers alike.

CONCLUSION

While delegating the design of building enclosure systems and components might

Building Department Deferred Submittal Policies in the United States



A = Submission and approval required before Installation

B = Submission and approval required before inspection

C = Documentation required on site and available during inspection

D = No Policy

UC = Unclear policy

Figure 11. Informal survey results from building departments in the United States regarding deferred submittal policies.

seem simple in concept, best practices are still evolving and confusion reigns in the industry. Experienced BECxPs can play a valuable role in identifying potential problem areas and providing additional quality assurance during both the design and construction phases. By working together to apply the strategies listed within this paper to both traditional and modern project delivery methods, the project team can minimize risks associated with the delegated design process even as more control of project design is ceded to contractors and their specialty subcontractors. 

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Steep-Slope Roofs in the Wind

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ABSTRACT

Do you work on projects that may involve steep roofs? The Roofing Industry Committee on Weather Issues (RICOWI) has inspected hundreds of steep roofs as part of its Wind Investigation Program (WIP). These posthurricane investigations have led to a better understanding of the strengths and weaknesses of the wind performance of metal panel, tile, and asphalt shingle roofs. This presentation will discuss the systems and their strengths, and describe where consultants and inspectors can focus to ensure a wind-resistant steep roof.

Since the inception of the RICOWI WIP in 1996, there has been wind-tunnel, full-scale, and laboratory-designed wind research and testing. This research has resulted in better products and systems, but the fury and duration of hurricanes test every aspect of design and installation. Using photos from six WIP investigations, the presenter will show participants how systems have improved, and where more attention is needed. This information can be used to design roofs for all climates and wind zones.

SPEAKER



David Roodvoets

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David Roodvoets has had a leadership role in all six RICOWI hurricane investigations. He has worked with Asphalt Roofing Manufacturers Association on asphalt shingle wind resistance and test standards, and has been involved with poststorm wind damage investigations for 40 years. Roodvoets has worked with wind research engineers in testing of asphalt shingles, vegetative systems, photovoltaic systems, and single-ply and ballasted roof systems. As a result of this work, manufacturers have incorporated improved design and installation requirements, and changes have been developed, advocated for, and incorporated into the International Code Council's family of codes.

Steep-Slope Roofs in the Wind

Buildings have roofs to separate the interior of the building from the exterior; their main function is to keep water out of the building. So, why aren't all roofs low-slope? Can you prove that a roof with a 6/12 pitch will be better at keeping the water out than a roof with a 2/12 pitch? Is a 6/12 pitch roof less expensive than a 2/12 pitch roof? Thought not. But there are more steep-slope roofs in North America than low-slope roofs. The reason is current aesthetics. The slope of the roof really depends on when and where the building was built. Before World War II, most houses had roof pitches of 6/12 or greater. Starting in the 1950s, 3/12 slopes became popular, and since the 1990s, 10/12 and steeper roofs have been popular.

Slope is unlikely to play a role in the wind performance of steep-slope roofs. Field data from the six hurricane studies conducted by the Roofing Industry Committee on Weather Issues (RICOWI)¹⁻⁵ are inconclusive. Studies conducted in the 1990s by Cermak Peterka Petersen Inc. for the Asphalt Roofing Manufacturers Association indicated that the wind speed at 5 mm off the top of the shingles was somewhat faster over shingles on a 9/12 pitch roof than on a 3/12 pitch roof.⁶ This produced slightly higher pressure differentials but was not considered to be a significant factor in shingle damage. Because there are so many variables, it is not possible to sort out slope in the RICOWI Wind Investigation Program data.

Wind tunnel research on steep-slope roofs demonstrates that the uplift pressures vary greatly over the roof and depend significantly on wind direction and, to a lesser extent, slope. Peterka et al.⁷ found that the highest uplift was when the slope was 2/12, occurring near the peak of the rake edge of gabled roofs. The peak uplift is at the ridge and just on the leeward side of the ridge. The RICOWI inspections clearly support the wind tunnel data, with ridge cap or similar damage being the most commonly witnessed. After the ridge, the corners have higher uplift pressures and are

most vulnerable on all types of steep-slope roofs. However, there are clear factors that can be used to differentiate the performances of the systems. This paper reviews the changes in installations and products with the expectation that the remaining weak links for wind resistance can be reduced or eliminated.

STATE OF THE ART IN 2004

RICOWI was formed in 1990 after Hurricane Hugo and wind design conferences held at Oak Ridge National Laboratory (ORNL) in 1989. An immediate goal was to get more industry coordination on building code issues. Following Hurricane Andrew in 1992, many industry members believed the information on roofing performance was incorrect. This created a sense of urgency to provide a mechanism to inspect roofing systems after

hurricane events and responsibly report the facts. Consequently, many talented individuals in the industry and academia developed a training course that was delivered to nearly 150 participants at ORNL in 1996. For the first time, a large number of roof consultants and manufacturers' technical personnel had an understanding of the fundamentals of wind engineering and a standardized way to document storm damage.

No major hurricanes came inland in a populated area of the United States until 2004, when four major hurricanes made landfall in Florida. All of them met the RICOWI requirements for deployment; however, due to the time constraints of volunteers and financial resources of RICOWI, assessment teams were only deployed after hurricanes Charley and Ivan. What did they see and learn?

TILE ROOFS IN 2004

Hurricane Charley hit the Punta Gorda area of Florida with 140 mph winds. Tile roofs are popular in this area, and many single-family homes there were built before 1997 with tile roofs installed using mortar paste as the adhesive to hold the tiles to the deck (Fig. 1-3). For tiles to



Figure 1. Hurricane Charley: Likely 140 mph winds. Typical damage in this older subdivision. Tiles using mortar as the adhesive.



Figure 2. Hurricane Charley: 130 mph and greater winds. Typical ridge damage with downslope breakage due to tile debris. Mortar adhesive.



Figure 3. Hurricane Charley: 130 mph winds. Ridge damage on this roof.



Figure 4. Hurricane Charley: Likely 130 to 140 mph winds. New units, foam adhesive. Very minor damage.



Figure 5. Hurricane Irma: 110 to 120 mph winds. Typical tile damage. Foam adhesive; damage limited to tiles missing from ridge.



Figure 6. Hurricane Irma: 100 to 110 mph winds. Tiles installed with two nails; displaced ridge tiles damaged downslope tiles.

adhere properly, 27 things that had to be done correctly or the system would become vulnerable to wind damage. Hurricane Charley's 140 mph winds were more than adequate to take advantage of these vulnerabilities, resulting in serious damage to all types of roofs and buildings including many of the roofs with mortar adhesive.

An alternative to mortar adhesive is the use of nails or screws to secure the tile. This did not appear to be a common practice, however, and tiles that were installed with only one nail were often damaged by Charley's 140 mph winds.

Foam adhesion of tile had been developed in response to the poor performance of mortar adhesive found after Hurricane Andrew. In 2004, the practice of adhering tiles with expandable foam was still a relatively new process (Fig. 4). It requires fewer steps than the mortaring process; the main requirements are the correct amount and placement of foam

under each tile. Most of the roofs that had been installed with the foam process were mostly intact. The weak link was inadequate foam on the ridge and hip tiles. Hip and ridge tiles were vulnerable when the foam had not risen sufficiently to adhere. When the ridge tiles were dislodged, they often tumbled down the slope, breaking tiles and creating missiles.

FEMA 488⁸ provides more details on the impacts on tile roofs from these hurricanes. Mirmiram et al.^{9,10} provide more details on tile installation and testing. Numerous other FEMA reports look at the whole building and are available at www.fema.gov/multimedia-library.

In 2004, the weak link for tile roofs was the use of mortar adhesive, which has now been mostly abandoned in the United States. Other problem areas were inadequate nailing and insufficient foam adhesive.

TILE ROOFS IN 2017 AND 2018

In 2017, RICOWI investigations after Hurricane Irma in Florida found tile roofs in Naples and the Keys with no observed catastrophic losses. There were many roofs with dislodged ridge and hip tiles, which almost always resulted in damage

to other tiles on the roof (Fig. 5–6). In most cases the damage was minor; however, some roofs were significantly damaged, and investigators observed missile impacts in residential areas. Missile damage is confirmed by random broken tiles with intact roof ridges; the source of the missiles is not always evident. It did not appear that any of the inspected tile roofs were leaking.

One large tile roof had been installed with two nails per tile; this roof had significant ridge damage and subsequent downslope breakage. It appeared that nails used to secure the ridge were not long enough to grip the deck (Fig. 7).

Hurricane Michael inspections focused on Panama City, Fla., where there were fewer tile roofs. Those that were inspected were in the 130 to 140 mph wind zone. They had lost a few ridge tiles, again due to inadequate foam adhesive.

The remaining weak link in tile installation is using enough adhesive, primarily on the ridge tile. Because of the underlayment used, roofs with damaged tiles were not found to be leaking.

METAL-PANEL ROOFS State of the Art in 2004

The 2004 RICOWI wind investigations viewed buildings that ranged from more than 30 years old to recently built. In general, there was a significant amount of progress in strengthening the structures, with newer buildings having improved performance. This was due to the use of computer-aided design to build most commercial metal buildings and significant wind studies that identified many of the weak links in previous designs. One building in downtown Punta Gorda had no damage, which stood out as everything around it was severely damaged.



Figure 7. Hurricane Irma: Winds 100 to 110 mph. Inadequate adhesion.



Figure 8. Hurricane Irma: 100 to 100 mph winds. Missile impact damage.

State of the Art in 2018

Metal buildings and metal-panel roofs may not show environmental damage due to age for many years. A building that was built many years ago can appear to be relatively new unless inspected carefully. Then corroded fasteners may be the first thing noticed. Corroded fasteners have been an issue in the past and continue to be a weak link in buildings that are not carefully constructed or buildings for which the manufacturer's requirements were not followed. Electrogalvanized fasteners do not have the longevity required for most modern environments. Hot-dipped galvanized fasteners are a minimum requirement and corrosion-resistant fasteners may be required. Fastener corrosion appears to be a more significant issue on roofs that are near saltwater coasts and remains one of the weak links that limit the service life of metal buildings.

Metal-panel roofs are often chosen to re-cover existing systems and often the old roof remains. Inspectors have frequently found new metal panels that were not solidly fastened to the structure; instead, they were fastened to old metal panels or poorly fastened to substitute structures (**Fig. 8, 9**) A fastening deficiency is usually not found until there is a high-wind event. Attachment details need to be carefully considered when retrofitting any metal-panel roof over an exist-



Figure 9. Hurricane Michael: 140 mph winds. This metal-panel roof was blown off. One of the weak links was the edge fasteners totally missing the edge nailer. This roof also had significant internal pressurization from failed soffits.

ing system. Fasteners for roof re-cover need to be attached to the purlins for best wind performance.

The breach of a wall or window can increase internal pressure significantly. This breach can result in loads that exceed the design loads of the system. Without internal

pressurization, metal-panel systems most often survive above-code winds. However, when the weak point is on a windward face, the metal roof can fail in peel, similarly to the failure of membrane roofs. Lack of solid perimeter securement was found when a peel failure was observed (**Fig. 9–10**).

Corroded fasteners have been an issue in the past and continue to be a weak link in buildings that are not carefully constructed or buildings for which the manufacturer's requirements were not followed.

Figure 11. Hurricane Michael: 140 mph winds. The brick wall was inadequately supported and collapsed, allowing this building to be overpressurized. The roof damage stopped at a floor-to-roof separator.



Figure 10. Metal panels where the perimeter was not fastened to the edge nailer.



Metals roofs are sometimes punctured by debris. Debris can open seams, and falling trees and other objects have damaged metal-panel roofs. Damage from debris appears to not be a major factor in metal roofs.

The weak link found in recent inspections was lack of attachment of retrofit roofs and corroded fasteners (**Fig. 12**). The best structures can still fail when the walls are breached, and unfortunately this can be the weak link.

A metal roof manufacturer gives the following advice:

- Lower sloped rooflines reduce wind shear.
- Consider limiting the roof pitch to less than 6/12.
- Hip roofs deflect wind better than gable roofs.
- The deeper the roof overhang of a building, the greater the lifting force of strong winds on that structure.
- The most wind-resistant buildings have no overhang at the eave at all, as in most prefabricated steel buildings.

ASPHALT-SHINGLED ROOFS

State of the Art in 2004

Florida was a unique place for roofing installations in 2004. Whereas most asphalt-shingled roofs in the United States are installed by going across the roof, in Florida, an installation method called racking was

most often used. In this method, the roofer installs the shingles by going vertically up the roof slope, usually three shingles across. This requires the shingle furthest to the left to be lifted to attach the final (fourth or sixth) nail. This frequently results in having no nail or a permanent bend of the shingle, preventing the shingle tab from adhering.

In 2004, many asphalt-shingle suppliers tested their shingles at wind speeds up to 110 mph according to ASTM D3161 Class F.¹¹ However, most shingles installed before 2004 had likely been tested according to ASTM D3161 Class A (60 mph). Although high wind speed testing was not required by code, many

roofs had limited damage. The code also called for six nails in high-wind areas.

Research conducted in the 1990s by Peterka et al.⁷ helped the industry understand the value of shingle stiffness as well as the importance of sealant strips. Peterka's research demonstrated the importance of having strong adhesive strips, and that nailing, while absolutely required, was not the primary factor in shingle wind-resistance. In 2002, the industry began developing ASTM D7158,¹² which provides for classification of shingles to Class H or 150 mph and measures shingle stiffness and sealant-strip resistance to wind uplift load.

The 2006 *International Residential Code*¹³ required shingles installed in high-wind areas to be Class F. The 2009 edition¹⁴ required



Figure 12. Hurricane Michael: 140 mph winds. The roof on this building, located less than 2 miles from the building shown in Fig. 10, appears to be 100% intact.



Figure 13. Hurricane Michael: 140 mph winds. This open metal building had cladding and roof loss. Many of the connections were corroded.

Figure 14. Hurricane Michael. Racking installation.



asphalt shingles to be ASTM D7158 Class H if installed in wind zones of 120 mph or greater. Nontabbed shingles were required to meet ASTM D3161 Class F in these wind zones.

State of the Art in 2018

In Florida, roofers frequently installed asphalt shingles using the racking method. As previously noted, this system is vulnerable to high-wind damage (Fig. 13–17). Assessment teams observed 132 asphalt-shingled roofs after Hurricane Michael, which was typical of the area where winds reached 130 to 150 mph. About 90% of the roofs in this area were at least partially covered with blue tarps and were expected to leak if uncovered. Data indicated that about 75% of the observed roofs were at least 12 years old and therefore unlikely to be in accordance with current codes. Most newer roofs, that is, those installed since 2015, were performing well. The ridge remained one of the weak links in the system. Missing ridge vents were often a source of potential leakage. The lack of sealant on the initial row of shingles was one of the damage initiators (Fig. 15). When the edge is not secured, the shingles can peel up the roof slope, and is more likely to happen when the shingles are installed using the racking method.

Synthetic roof underlayment was common; however, in the worse cases of shingle blow-off, the underlayment was also dislodged. Adequate nailing is important for all nonadhered underlayments. The Insurance Institute for Business & Home Safety's (IBHS's)

FORTIFIED program recommends three approaches to underlayment that are likely to prevent a leaky roof if the shingles are blown off.¹⁵ The simplest approach is to tape all the seams of the roof deck using plywood or oriented strand board as the primary water barrier. The second option is the use of two layers of ASTM D226 #30 felt installed with multiple secure nail tabs. The third option is the use of a membrane that is fully adhered to the entire wood deck; however, not all roofing manufactures approve of this method.

The remaining weak links for asphalt shingles are proper installation of the hip and ridge shingles and ridge ventilation. Adequate resistance to the uplift at these points requires nails that are long enough to penetrate the deck.

High-wind areas require additional adhesive in the starter row and at the rake edges.

OTHER ROOFING SYSTEMS

Two other steep-slope roof types were observed: metal shingles and cedar shakes and shingles. Metal shingles, being relatively new, had little corrosion, but often lacked attachment to the substrate. The cedar roofs had corroded fasteners.



Figure 15. Hurricane Michael. Corner of roof with damage. Excessive overhang of starter course. First course not sealed.



Figure 16. Hurricane Michael. Relatively new roof 2018 with some ridge and corner damage, older roofs in background with damage.

Figure 17. Typical damage to a roof installed using the racking method.



CONCLUSION

RICOWI, the Special Interest Group on Dynamic Evaluation of Roofing Systems, and IBHS have contributed substantial data on the performance of roofing systems in high winds. Hurricanes and documented roof inspections after windstorms have confirmed wind tunnel data, contributing to a substantially better understanding of steep-slope roof performance in high winds, and these data have been used by manufacturers to develop better products. Codes have required better testing, and contractors continue to be better trained. This has resulted in more wind-resistant roofs, not only for hurricane-prone regions but everywhere roofs are installed. 

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Continuous Insulation: Wall Assembly Case Study Comparisons

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ABSTRACT

Continuous insulation presents challenges with regard to the overall wall assembly's design, performance, and construction. This program at the advanced level will evaluate the comparative differences in eight commercial steel-framed wall assembly designs standardized to an NFPA 285-compliant assembly under ICC 2018 in Climate Zone 5 (due to the requirement for an interior vapor retarder). The presentation will begin with an overview of the eight designs' components and each assembly's benefits and challenges. The presenter will explain the rationale for the choice and location of the continuous and total insulation, sheathing (if any), and weather and vapor control layers, and highlight concerns regarding condensation management and thermal breaks. The eight assemblies will then be compared for their NFPA 285 compliance and evaluated through WUFI hygrothermal modeling over four climate seasons. The models will also be evaluated for their structural cladding load and wind-load resistances, and, finally, they will be comparatively ranked by cost of construction and speed of production. Rather than focusing on the benefits of one construction material or assembly, this program comparatively reviews eight distinctive entire wall assemblies. The presentation will use three-dimensional modeled imagery to help illustrate the designs' integrated assemblies.

SPEAKER



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G. David Schoenhard, RRO, AIA, BECxA, CSI, CDT, LEED AP, has over 40 years of experience in the design, detailing, and construction of institutional, commercial, research, and multifamily residential architecture. As the principal and manager of DSS-Philly, an architectural building enclosure consulting firm in the Philadelphia region, he brings his decades of experience and discipline to design, implement, and remediate building enclosures on behalf of other architects, owners, and contractors. He also actively researches comparative building enclosure assemblies and is an AIA Education Provider. He is certified as a BECxA, RRO, CSI, LEED AP, and CIT.

Continuous Insulation: Wall Assembly Case Study Comparisons

While many professional presentations tend to focus on one construction material or one building enclosure strategy in isolation, this leaves vast gaps when trying to understand and compare entire wall assemblies. The everyday challenge of integrating multiple wall materials while meeting building and energy codes, climatic restraints, and construction budgets can become daunting and overwhelming. The result, unfortunately, is for the designer to rely on office standards or to follow precedents set by previous projects. “This is the way we have done it, so that is how we will do it.” For better or for worse, and unfortunately often the latter, this results in constructed walls that age prematurely, fail progressively, or perform less efficiently than expected.

EIGHT WALL ASSEMBLIES MEET A COMMON BENCHMARK

This paper presents and evaluates eight substantially different commercial wall assemblies by describing and comparing their components, conducting hygrothermal analyses, assessing their ability to support cladding loading, and ranking them by cost and speed of production. To create a “level playing field” of comparison, all eight wall assemblies were intentionally noncombustible with steel-stud framing, in accordance with the 2018 *International Building Code*¹ and the 2018 *International Energy Conservation Code*² (IECC), and located in Climate Zone 5, which by code requires an interior vapor retarder. They all incorporated code-compliant continuous insulation, total insulation, an air barrier, water-resistant barrier, as well as the aforementioned interior vapor retarder. They were all subjected to 30 psf of wind loading, and, for construction takeoff purposes, each wall assembly was theoretically 12 ft high by 300 ft long. Finally, each wall was compliant with the vertical and lateral fire propagation requirements of NFPA 285,³ which requires

compliance of the entire wall assembly, not just one compliant material (Fig. 1). Therefore, for this comparative analysis, each wall assembly included an exterior ¼ in. thick fiber-cement wall panel, which is considered a lightweight, non-combustible cladding. Finally, the interior of each assembly was completed with ½ in. thick fire-rated gypsum drywall. As an additional parameter, the vertical cladding support tracks were intentionally decoupled from the locations of the vertical studs, thus allowing the cladding to have left-right layout adjustability.

CONTINUOUS INSULATION SETS THE THEME

The requirement for continuous insulation is driven by the energy code because of its nearly 100% efficiency, whereas batt insulation located between the studs is barely 50% effective. Using the IECC prescriptive *R*-value method in Climate Zone 5 requires a minimum of *R*-7.5ci of continuous insulation and *R*-13 of between-stud batt insulation. As a second compliance route, the IECC *U*-factor method requires an assemblage of

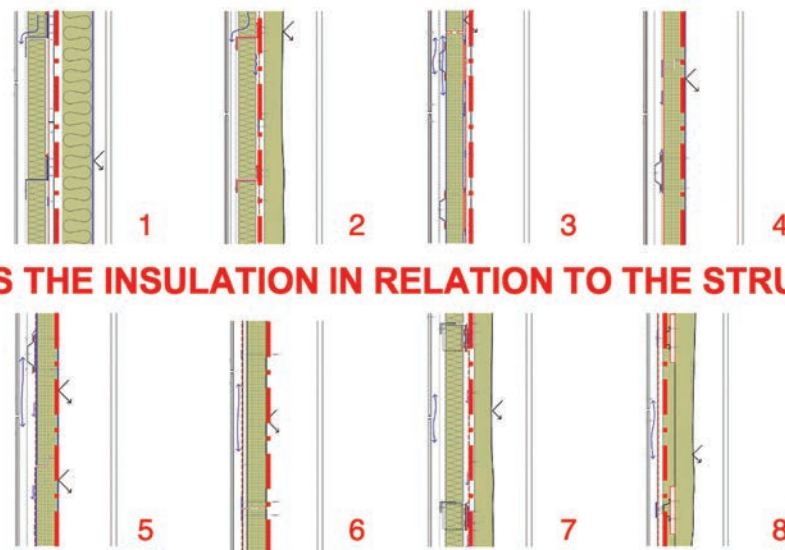


Figure 1. Stock image of NFPA 285 vertical and lateral fire propagation testing.

values. The sum of each of the individual *R*-values for each layer and air films, along with the tabulated effective *R*-value for the between-stud batt insulation (if any), results in a minimum requirement of *U*-0.064, which as a reciprocal equates back to an *R*-value of *R*-15.625. Both methods are used within the eight wall assemblies to ensure their minimum code compliance and their options for additional enhanced higher performance.

Because continuous insulation is so central to this comparative study, it is important to understand its current definition. Section C202 of the 2018 IECC states that continuous insulation is “... continuous across all structural members without thermal bridges other than fasteners and service openings.” It also states that it may be located on either the exterior or interior, or be integral to the assembly. This study of eight wall assemblies explores continuous insulation in all three locations (Fig. 2).

While continuous insulation is required and impacts the composition and performance of the overall wall assembly, it is not the single most important component. All the components come together synergistically to form a



WHERE IS THE INSULATION IN RELATION TO THE STRUCTURE?

Figure 2. Overview of the eight wall assemblies and location of continuous and total insulation in relation to the structure.

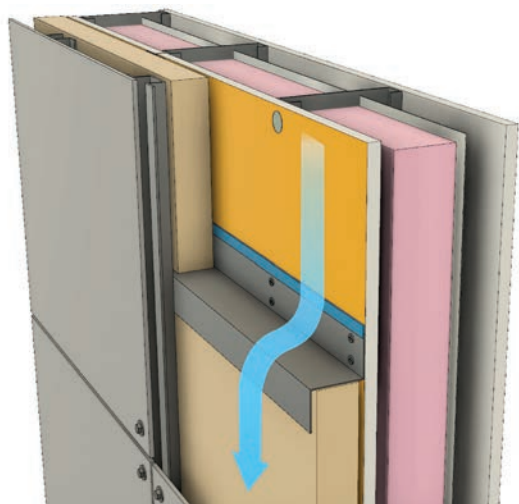


Figure 3. Wall assembly #1: Typical horizontal galvanized Z girt, continuous exterior mineral wool insulation, and between-stud foil-faced batt insulation as interior vapor retarder.

composite whole, as discussed in the following sections.

WALL ASSEMBLY #1: TYPICAL HORIZONTAL Z GIRT WITH MINERAL WOOL CONTINUOUS AND BETWEEN-STUD BATT INSULATION

Wall assembly #1 (Fig. 3) begins like all of the eight assemblies: with 6 in. steel-stud framing at 16 or 24 in. on center. Gypsum sheathing is located on the exterior, to which a vapor permeable, air- and water-resistant barrier (AWB) with a permeability rating greater than 10 perm is applied. The assembly is Class A-rated with a flame spread (FS) ≤ 25 , with smoke developed ≤ 450 . The AWB can be self-adhering sheet-applied, fluid-applied, or pre-applied to the sheathing panels. This exercise does not consider mechanically fastened, non-adhered sheet membranes. The figures in this paper show AWB preapplied to the sheathing panels with their joints and fasteners capped with a fluid-applied flashing sealant. In wall assembly #1, galvanized Z girts are horizontally applied directly atop the AWB and fastened through the upturned leg and the sheathing to the stud flanges behind. Semirigid, water-resistant-treated mineral wool insulation panels are friction fit between the girts to provide the continuous insulation. As in all eight assemblies, the $\frac{1}{4}$ in. fiber-cement panels are face-fastened to $\frac{3}{4}$ in. deep vertical cladding tracks fastened to the horizontal girts, which also provides necessary rainscreen back ventilation. This assembly uses FS 25, R-15 fiberglass or mineral wool batt insulation with a code-

required Class II vapor-retardant foil facing that is friction fit between the steel studs. Finally, $\frac{5}{8}$ in. type-X gypsum drywall is applied to the interior, which in this exercise intentionally used mold-resistant panels.

Why is this assembly so often used as the “office standard”? It uses common materials that are readily available, the wall encloses quickly to become construction weathertight, and this assembly is free of NFPA 285 compliance because it does not contain any plastic foam insulation.

What, however, are its challenges that somehow do not disqualify it from being the “office standard”? Each steel horizontal girt extends through the depth of the continuous insulation, thereby forming a thermal bridge. Even with the batt insulation

blanketing its inward side, the cavity-side face of the gypsum sheathing at each girt is close to the same exterior cold winter temperature, thus risking localized condensation buildup. In winter, moisture vapor and liquid condensation within the stud cavity can become trapped by the interior vapor retarder and remain there until the wall’s exterior warms up, allowing the wall to dry by reevaporizing outward. Where does the moisture come from if there is an interior vapor retarder? It comes from leaks in the vapor retarder and from occasional seasonal inward vapor drive from the exterior, such as when the rained-on wet wall is warmed by the sun and the moisture vapor drives inward toward the cool, dry interior, where it becomes trapped by the vapor retarder within the stud cavity. This inward vapor drive is also common during the warmer humid seasons and results in the exterior continuous insulation zone being actively wet with condensation and rainscreen back-drainage. The WUFI hygrothermic models, which will be discussed later, illustrate these condensation risks and moisture buildup issues. While new mineral wool is excellent at draining moisture, each horizontal girt acts as a stop or resting surface that encourages absorption into the lower fibers of the insulation. Atmospheric moisture is also dust-laden, so over time the mineral wool’s filtering adds dust to the felted voids. When moisture is present, it reduces the insulation’s efficiency and hastens the eventual corrosion of the galvanized Z girt. This assembly is not

compatible with the superinsulation approach of Passive House design. Doing so with batt insulation is problematic because it creates a receptor for moisture and the differential temperature is insufficient for the moisture to be driven back out of the wall. Moisture therefore tends to accumulate, thus risking mold formation on organic paper surfaces.

With all these challenges, what is so appealing about this typical zee assembly? It is perceived as being cheaper, but this report’s cost and production assessment will show that this is unfounded. This assembly requires multiple construction steps on the exterior side of the wall’s sheathing, and the risk of damage to the AWB and of resultant water leakage is quite high. Moisture can also accumulate between the back leg of the Z girt and the AWB. The self-sealing tests of the AWB are laboratory tests, not actual field tests; accumulated water can accelerate the sheathing’s deterioration and be sucked in under differential air pressure during high windstorm events.

WALL ASSEMBLY #2: ENHANCED ZEE WITH BACK-SPRAYED POLYURETHANE FOAM

Having presented most of the wall components in the previous section, this section focuses on the unique qualities of wall assembly #2, which are intended to improve or enhance the deficiencies of assembly #1 (Fig. 4). Instead of galvanized Z girts, this wall uses fiberglass Z girts, which removes the corrosion and thermal bridging issues of assembly #1. Instead of between-stud batt insulation, this assembly uses at least 2 in. thick

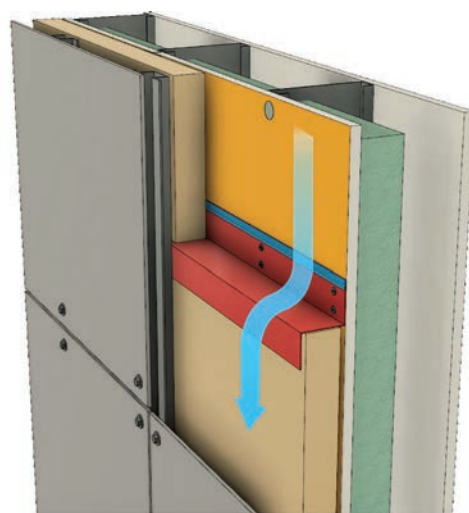


Figure 4. Wall assembly #2: Enhanced fiberglass Z girt, continuous exterior mineral wool insulation, and between-studs urethane back-spray as dual-face vapor retarder.

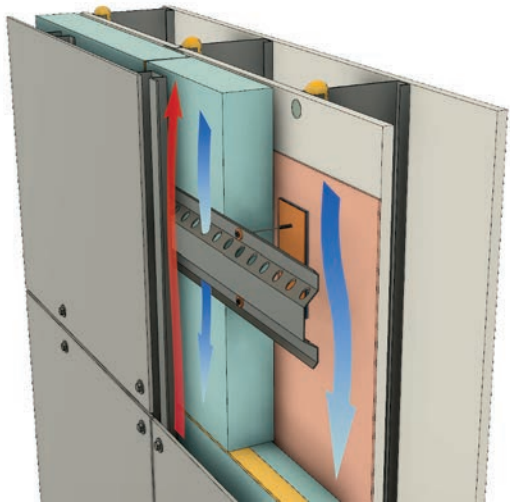


Figure 5. Wall assembly #3: Rigid phenolic continuous and total insulation, located 100% outboard on air- and water-resistant barrier, vapor retarder, and back-drainage.

closed-cell, back-sprayed polyurethane foam (ccSPF). The rigid foam acts as a Class II vapor retarder from both the inward and outward vapor-drive directions, and it functions as an additional air barrier. The foam insulation outgasses before building occupancy, and the newest generation of blowing agents is more environmentally friendly.⁴ The back-insulation can also be superinsulated up to 3% in. thick for a total wall R-value of R-32.28 (using the R-value method). The reason for the 3% in. SPF and not a full 6 in. stud depth is to comply with NFPA 285 certification requirements and to allow cavity space for back-wiring.

This assembly approach has some benefits, but the cost analysis given in this paper shows that the benefits come at a cost. The exterior-side mineral wool is still prone to active-seasonal condensation and rainscreen back-drainage. The back leg of the Z girt can be protected from water accumulation with an additional cap bead of sealant.

WALL ASSEMBLY #3: PHENOLIC 100% OUTBOARD AS APPLIED RIGID INSULATION

Instead of between-stud insulation of any form or mineral wool exterior insulation and girts, assembly #3 places 100% of the insulation outboard of the AWB-clad sheathing (Fig. 5). It uses rigid phenolic foam insulation panels instead of the more common rigid extruded polystyrene (XPS) to be NFPA 285-compliant while still allowing lightweight exterior wall cladding panels (Fig. 1). The insulation is non-moisture-absorbing, and, with a small bead of spray foam around the perimeter edges, the

insulation becomes almost 100% effective except for the through-fasteners of the horizontally oriented hat-channel furring. The insulation panels are intentionally shimmed away from the AWB by $\frac{1}{8}$ in. to allow for downward flowing condensation and back-drainage, while not being large enough to encourage upward air drafts. The horizontal hat-channel furring is factory-perforated to allow through-drainage as well as upward back-venting. An optional additional 3% in. or R-24.28 of SPF may be added to the stud cavity to superinsulate.

There are several challenges to remember with assembly #3. As stated, the rigid foam boards need to be phenolic and not XPS to be NFPA 285-compliant while using lightweight exterior claddings. It is important

to maintain the $\frac{1}{8}$ in. back-drainage cavity with kickout flashings so as not to rely on the outward face of the rigid insulation. The wall encloses quickly for temporary construction purposes, but it still requires multiple construction steps on the outward side of the wall, which affects the wall assembly's overall cost and production speed.

WALL ASSEMBLY #4: ISOCYANURATE ALL-IN-ONE, 100% OUTBOARD AS DURABLE INSULATED SHEATHING

Like assembly #3, assembly #4 places 100% of the rigid insulation outboard of the structure, except that the insulation panel is durable enough to be an all-in-one panel with no gypsum sheathing (Fig. 6). This means that it becomes the sheathing, air barrier, water-resistant barrier, and vapor-retardant barrier from both the inward and outward directions, and it provides 100% of the insulation as continuous insulation. Only the low thermal conductivity stainless-steel fasteners of the panels and hat channels penetrate the panels into the backup studs. As an additional option, it is possible to apply closed-cell hand-sprayed foam to the projecting screw shanks within the stud cavity to remove that condensation risk.

Rigid isocyanurate (ISO) insulation panels are factory-clad with durable prefinished aluminum facers front and back, which function as Class I vapor retarders from both inward

and outward vapor directions. In addition to the panel's horizontal shiplap joints and the optional use of spray foam in all the joints, the exterior side's joints and fasteners are capped with fluid-applied flashing sealants. In this paper, exterior tape is discouraged, and the higher-performance silicone version or the hybrid STPE versions of fluid-applied flashings is preferred to the acrylic or urethane versions. The exterior facer is more durable than the interior's; it is intended to be exposed to the back-drainage cavity and becomes the direct surface to which the horizontal hat-channel furring and claddings are applied. Once the panel is installed and cap-sealed and the horizontal furring applied, the exterior side can be successfully quality control water-tested as no further penetrations will occur to the panel.

While this sounds simple and direct, there are several challenges to be aware of. The stud spacing needs to be 16 in. on center, and without the gypsum sheathing, the assembly is best suited for lower-rise construction without fire-rated assemblies. It is important to use the punched horizontal furring to allow through-drainage and upward ventilation. It is also important to take extra precautions during construction to protect the exterior panel's AWB facing and at corners. While the facing is considered durable, it is still vulnerable to construction damage. This paper recommends treated wood blocking at door and window openings clad in flashing tape, and as an additional option, application of SPF to just the steel wall framing webs at perimeters and wall

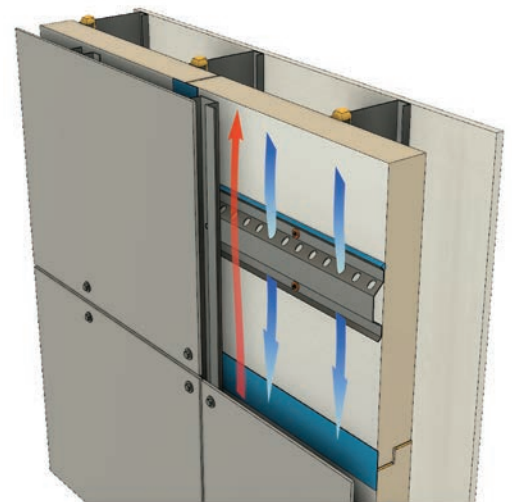


Figure 6. Wall assembly #4: Rigid and durable foil-clad isocyanurate board sheathing as 100% continuous and total insulation, with integral air- and water-resistant barrier and dual-faced vapor retarder.

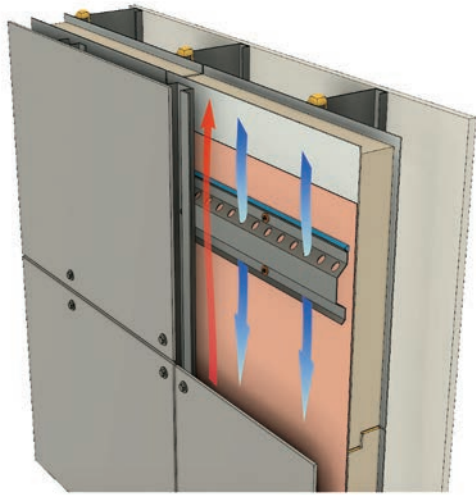


Figure 7. Wall assembly #5: Rigid and foil-clad iso board sheathing as 100% continuous and total insulation, with integral dual-faced vapor retarder and separate durable air- and water-resistant barrier.

openings to improve the thermal performance at these vulnerable locations.

WALL ASSEMBLY #5: ISO 100% CONTINUOUS INSULATION WITH ADDED AWB FACING

Assembly #5 is identical to #4, except that instead of using a more durably clad ISO panel, this assembly uses a less expensive foil-clad panel that requires a field-applied separate AWB facing (Fig. 7). While the panel is cheaper, the installation of the AWB requires an extra material and step. However, the AWB provides an additional opportunity to ensure that the wall assembly is weathertight.

WALL ASSEMBLY #6: BONDED ALL-IN-ONE, 100% OUTBOARD, STRUCTURAL INSULATED SHEATHING

Instead of the rigid ISO of assemblies #4 and #5, assembly #6 uses high-density urethane rigid insulation factory-bonded to a magnesium oxide exterior sheathing panel with factory-applied AWB precoat (Fig. 8). This is referred to as structural insulated sheathing (SIS). Once panels are fastened to the studs with stainless-steel fasteners and the joints are spray-foam filled, the wall is temporarily construction weathertight. Because of the factory-applied AWB coating, once the joints and fastener heads are

capped with fluid-applied flashing sealant, the wall is permanently durable. As an option, spot-spraying SPF on the inward screw shanks omits the small condensation risk at the fasteners. The magnesium oxide exterior sheathing panel is structurally considered a fastener base with fastener pullout and shear-testing. Additional horizontal cladding girts are therefore not necessary and the exterior cladding with its vertical support and ventilation tracks may be applied directly to the fastener-base SIS panel face. Quality control water testing can be conducted efficiently once the vertical cladding tracks are applied and before the cladding. The combination of high-density urethane and exterior magnesium oxide provides a panel that is both NFPA-certified as well as being fire-rated. From a construction standpoint, it assembles and closes in very quickly, as well as being well suited to panelization. Fire-rated and midrise projects are well suited to this type of assembly.

With all these advantages, what are this assembly's challenges? It is manufactured by one company, and thus it is considered sole-sourced. Also, the material cost of the panels is at a premium, although the construction time savings is an offsetting benefit. Extra care needs to be taken to not over-torque the fasteners and strip the panel threads. It requires some effort to research, understand, locate distribution, and document this assembly outside of the more familiar "office standard."

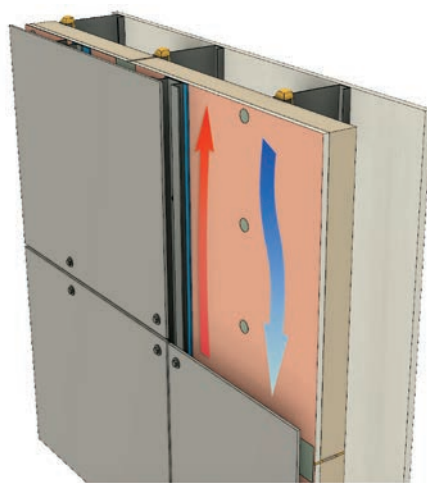


Figure 8. Wall assembly #6: Structural insulated sheathing with 100% outward rigid urethane insulation, fastener-base sheathing with pre-coated air- and water-resistant barrier as dual-faced vapor retarder.

WALL ASSEMBLY #7: CLIP AND RAIL, WITH OUTWARD MINERAL WOOL AND INWARD CCSF

Semirigid mineral wool located as exterior-side continuous insulation is integral to assembly #7 (Fig. 9). The use of thermally broken structural brackets fastened through to the studs atop the AWB and sheathing, along with infinitely adjustable structural cladding rails provides the ideal venue for continuous mineral wool insulation. The cladding system's adjustability can accommodate designs with intricate wall profiles and changes in cladding materials. Consequently, this assembly is common in high-design projects. Back-sprayed SPF completes the insulation and provides the code-required, outward-driving Class II vapor retarder. Assembly #7 is NFPA 285-compliant and may be as fire-rated as necessary. Superinsulating is also possible with additional back-sprayed ccSPF.

What are some of this assembly's challenges? As shown by the WUFI modeling, the outward framing system and mineral wool are subjected to active multiseason inward vapor-driving condensation as well as back-cavity rainscreen drainage. The back-cavity spatial voids need to be limited in size so that they do not inadvertently become flue stacks. The construction wall encloses quickly, yet there are still multiple exterior construction steps that each requires high levels of skill and quality control supervision, and each step is prone to wind damage until fully completed. Assembly #7 is a finicky assembly, yet it provides the greatest assembly flexibility along with high

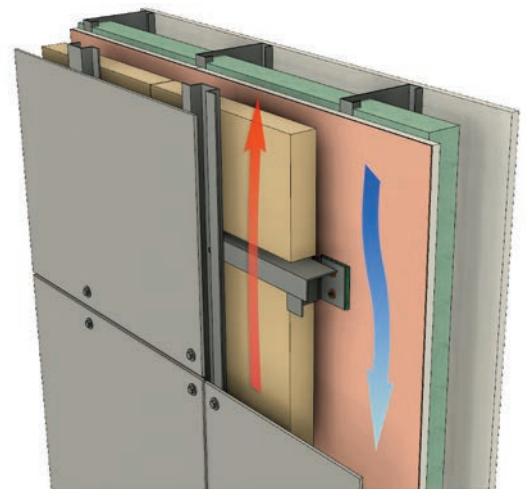


Figure 9. Wall assembly #7: Clip-and-rail cladding support fastened outboard of air- and water-resistant barrier with continuous exterior mineral wool insulation and between-stud urethane back-spray insulation as dual-faced vapor retarder.

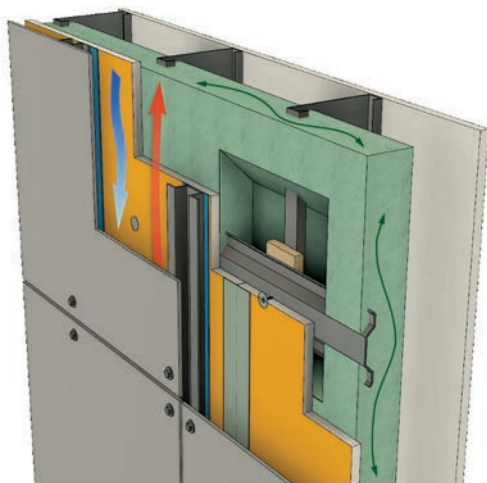


Figure 10. Wall assembly #8: Back-lattice of crisscross framing with thermal isolation pad at intersections, exterior air- and water-resistant barrier, and back-spray of closed-cell urethane for 100% continuous and total insulation, and as dual-faced vapor retarder.

levels of fire safety. However, according to the WUFI model, the outward zone is actively wet with condensation and rainscreen back-drainage, which will degrade the assembly's performance over time, and the regular exposure to freeze-thaw cycles weakens the integrity of the water-tight connections.

WALL ASSEMBLY #8: BACK-LATTICE CONTINUOUS INSULATION, 100% INWARD

Assembly #8 takes the vertical stud framing concept and turns it on its side (Fig. 10). While the vertical studs may be stretched out to 24 in. centers, there is a crisscross back-lattice of 1 in. Z- or J-shaped horizontal back-furring as horizontal furring located at 16 in. centers. The horizontal furring is separated at each stud intersection with a ½ in. thick, R-1.55, high-density, urethane thermal isolation pad. The exterior gypsum sheathing is applied horizontally instead of vertically to the horizontal back-furring. None of the structural fastener levels carries through completely; thus there is no through-fastener thermal bridging. Combining the 1 in. Z- or J-shaped back-furring and the ½ in. thermal isolation pad results in a 1½ in. gap between the vertical stud flange to the sheathing. The entire backside of the sheathing is then back-sprayed with 3% in. thick ccSPF, taking care to spray behind the stud flanges, into the belly and over-capping the back-furring, into the outward flanges of the studs, and onto the webs of any perimeter and wall-opening framing. The ccSPF at a

minimum 1½ in. provides an additional air barrier, as well as the Class II vapor retarder, from both outward and inward vapor-drive directions. The entire 3% in. of ccSPF meets the total insulation value of the prescriptive R-value method, and it has been proven to more than comply with the energy code's U-factor requirement by 3D Therm modeling. The required 1½ in. of continuous SPF insulation functions as an air and vapor retarder outboard of the stud flange, while also continuously inboard of the back-furring. The R-1.55 of the thermal isolation pads equates in the energy code to not being a thermal break and thus a thermal isolator. This wall assembly is unique and has achieved NFPA 285 engineering evaluation compliance and has completed ASTM E331⁵ and ASTM E2357⁶ testing, and ASTM E119 one-hour fire testing..

With the complete 3% in. of back-sprayed ccSPF, which functions as the required vapor retarder and continuous insulation, this wall assembly performed extremely well in WUFI hygrothermic modeling, which will be reviewed in the following section. The wall assembly is resistant to both inward and outward vapor drive, and the seasonal rainscreen back-drainage and exterior-side condensation is free to collect and drain without wetting any outward insulation.

There are fewer construction components on the exterior side of the assembly. Once the AWB coated sheathing panels are capped with fluid-applied flashing sealants, the construction is complete and a permanent weathertight enclosure is ensured. The only remaining outward activity is the installation of the finished cladding which can occur when the weather is favorable. Because the horizontal furring is located behind the sheathing, the exterior vertical cladding may be applied anywhere and fastened directly through the AWB-faced sheathing, where quality control water testing can be conducted efficiently. Because the ccSPF is entirely on the interior side, it is weather- and season-independent. This assembly is also well suited to prefabricated panelization.

What are this assembly's challenges? It requires a designer, a detailer, and the contractor's understanding of the back-lattice concept because it effectively places the wall on its side and uses a complete ccSPF back-spray. The high-density urethane thermal isolation pads and the specialized Z- and J-shaped back-furring for the framing intersections need to be specially ordered, and special detailing is needed at wall openings and panelized perimeters. Typically, a simple galvanized sheet metal angle frames the vertical edges, and flex-flash-protected, fire-retardant-treated, 2 × 6 in. wood blocking rings the window and door openings to ensure the fire assembly and the thermal efficiency at the openings.

HYGROTHERMIC MODELING OVER FOUR CLIMATE SEASONS FOR CLIMATE ZONE 5

For the purposes of this hypothetical exercise, Pittsburgh, Pa., located in Climate Zone 5, was chosen as the location for the WUFI models because it contains a wealth of climate data. Again, this study intentionally chose Climate Zone 5 because of the code's requirement for an interior vapor retarder. Each of the eight assemblies was comparatively WUFI modeled over a data period of three years with examples chosen to illustrate each of the four climate seasons. Some introductory explana-

While continuous insulation is required and impacts the composition and performance of the overall wall assembly, it is not the single most important component. All the components come together synergistically to form a composite whole.

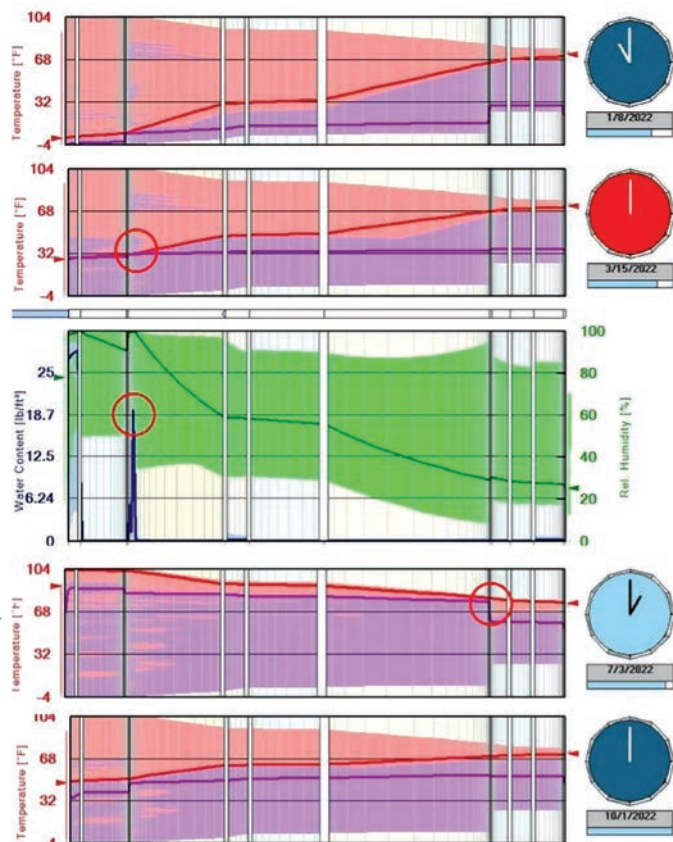


Figure 11. WUFI for wall assembly #1: Note active condensation in outward cladding support and mineral wool and potential for captured moisture at the interior vapor retarder during summer.

tions are helpful when looking at the WUFI data graphics. Where the pink and purple areas touch, this corresponds to the dew point or risk for condensation formation on surfaces dense enough to support the change of state from a vapor to a liquid. The accompanying green and blue chart shows the moisture buildup, if any. The direction of the seasonal outward or inward vapor drive is indicated by the direction of the downward sloping pink line.

Wall assembly #1, Typical Zee, shows two high-risk areas (Fig. 11). In March, there is significant condensation buildup on the cladding hardware, leading to nighttime ice formation on the face and back and within the continuous mineral wool insulation. In July, another risk area is located deep within the wall at the cavity side of the vapor retarder layer: the summertime vapor drive is so intense that moisture nearly condenses at this location or on the nearest dense surface, such as the face of the adjacent studs or sheathing.

Wall assembly #2, Enhanced Zee, shows one location of moisture buildup in July at the outer face of the AWB-clad sheathing and behind the continuous mineral wool insulation (Fig. 12). This area must drain freely and be flashed efficiently, but each horizontal Z girt is a shelf that collects moisture before it continues its downward path.

Wall assemblies #3, #4, and #5, with 100% continuous insulation outboard of the structure, shows no risks except that moisture will form on the outward side of the insulation panel and cladding hardware as long as the moisture is free to flow downward and outward, though freezing and thawing cycles can weaken the fastener to panel watertightness over time (Fig. 13). The inward and outward vapor drive over four seasons is devoid of condensation risks because of the dual-sided,

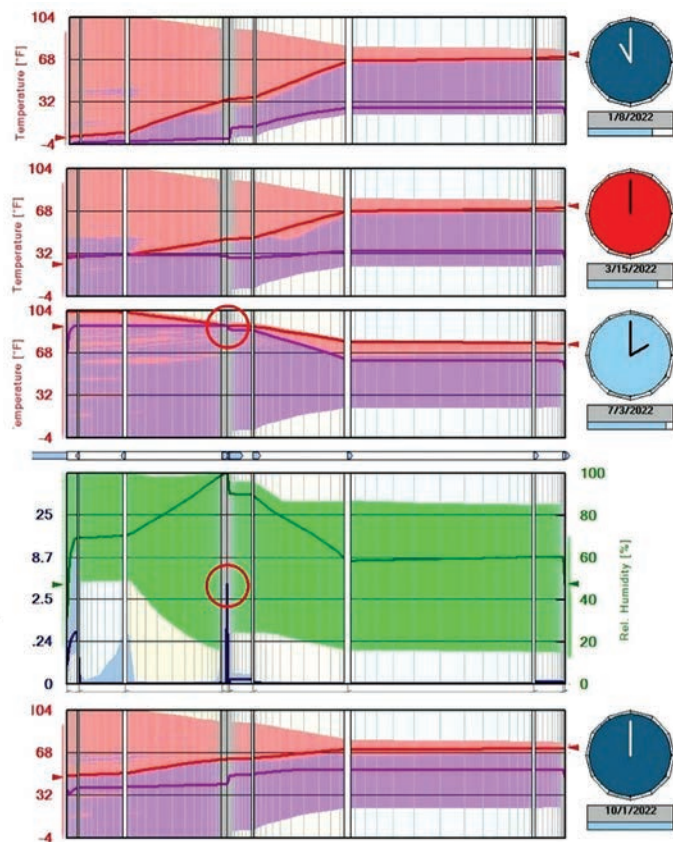


Figure 12. WUFI for wall assembly #2: Note active condensation at the exterior cladding support and mineral wool.

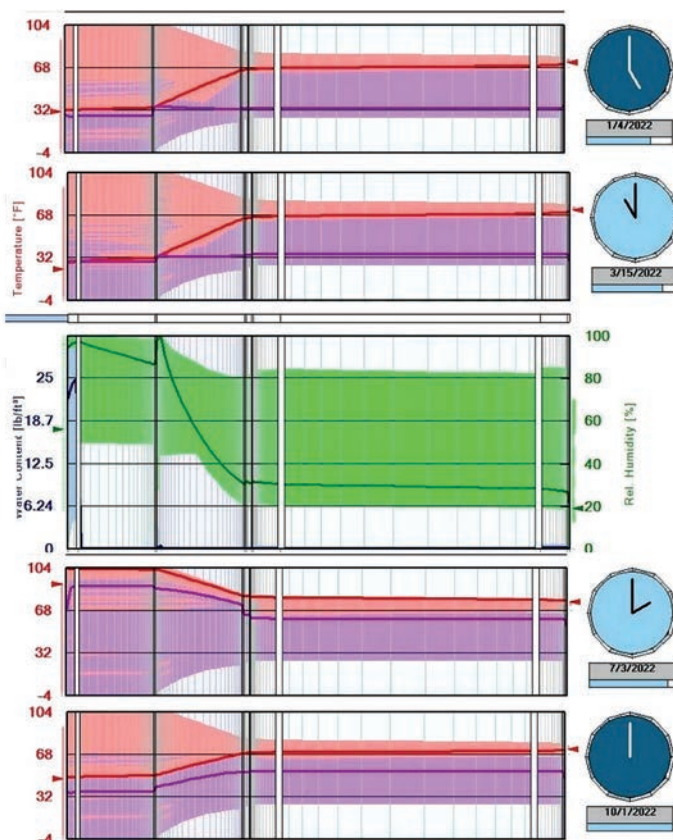


Figure 13. WUFI for wall assemblies #3, #4, and #5: These assemblies perform extremely well in all four seasons.

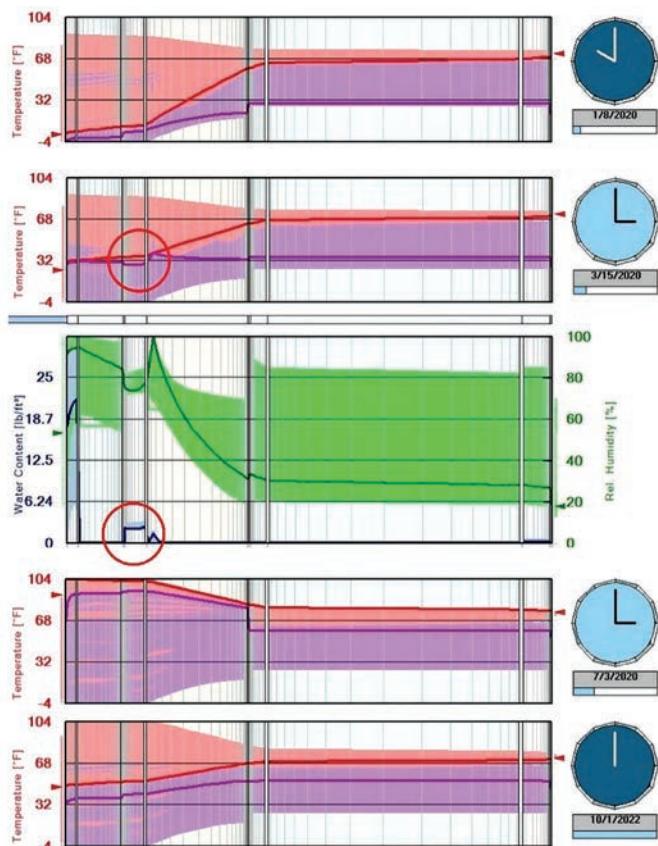


Figure 14. WUFI for wall assembly #6: This assembly performs extremely well in all four seasons with insignificant moisture in the exterior sheathing.

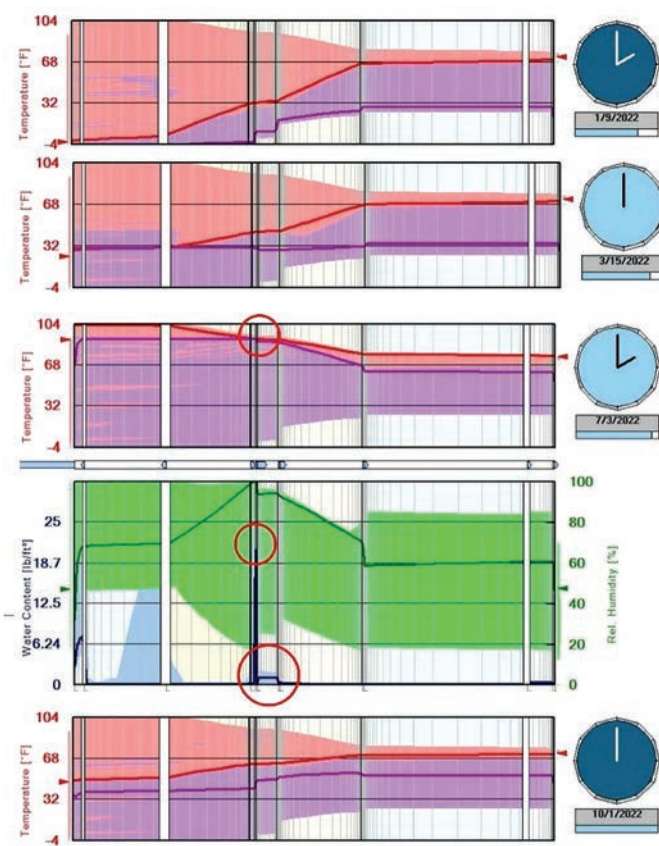
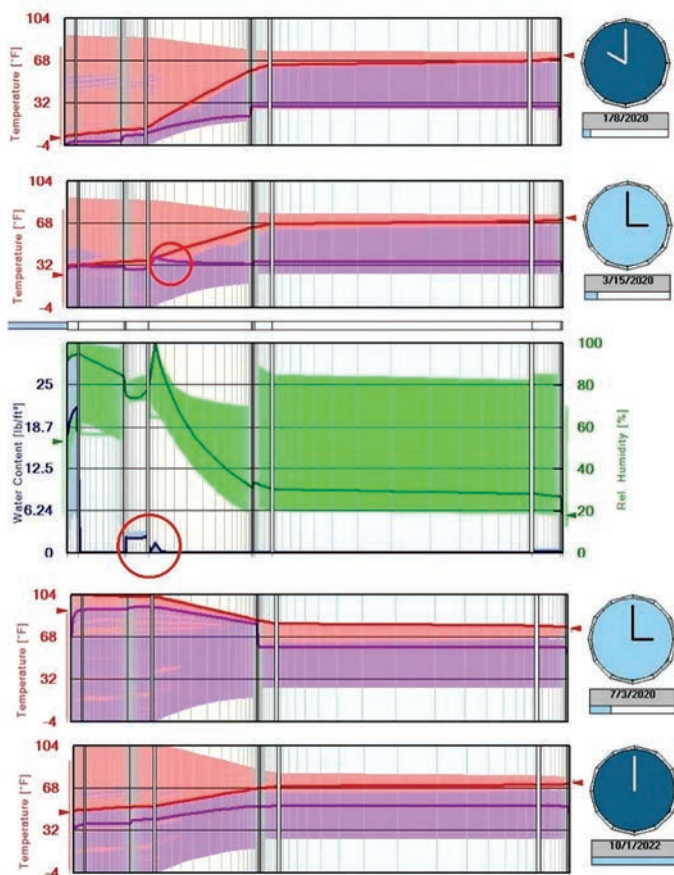


Figure 15. WUFI for wall assembly #7: Note active condensation in outward cladding support and mineral wool on face of the air- and water-resistant barrier.



vapor-retardant-clad, rigid insulation panels, which prevents the passage and collection of moisture-laden air.

Wall assembly #6, Bonded All-In-One (SIS), shows a small amount of moisture buildup in March within the magnesium oxide sheathing panel as vapor is blocked during its inward drive by the rigid urethane foam; however, the quantity of moisture buildup is insignificant (**Fig. 14**). It is important to ensure that the AWB on the panel's face is vapor permeable to allow outward revaporization.

Wall assembly #7, Clip and Rail, shows significant moisture buildup and activity in March at the outer face of the AWB-clad sheathing, which is behind the continuous mineral wool insulation (**Fig. 15**). The insulation becomes temporarily wet but then dries to become effective again. It is unclear how the buildup of atmospheric dust in rainwater affects the long-term performance of mineral wool.

Wall assembly #8, Back-Lattice, similar to assembly #6, performs splendidly. It shows a small amount of moisture buildup in March within the gypsum sheathing panel as vapor is blocked during its inward drive by the rigid spray-urethane foam, but the quantity of moisture is insignificant (**Fig. 16**). To test the moisture performance of this wall assembly further, assembly #8 was also subjected to WUFI modeling for Houston, Tex., (Climate Zone 2, hot/humid) and for Green Bay, Wisc., (Climate Zone 6, cold/humid) (**Fig. 17**).

Figure 16. WUFI for wall assembly #8: This assembly performs extremely well in all four seasons with insignificant moisture in the exterior sheathing.

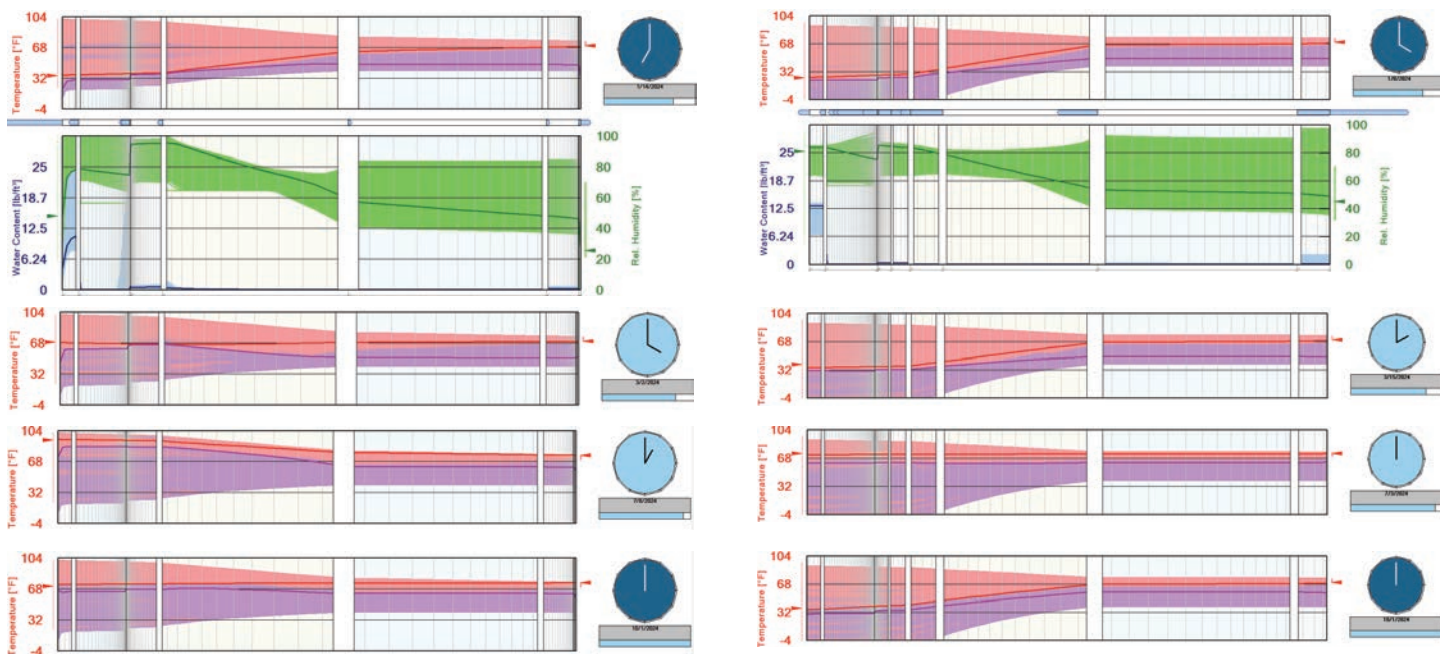


Figure 17. WUFI for wall assembly #8 in Climate Zones 2 and 6: This assembly performs as well as that modeled for Climate Zone 5.

HOW DO THE EIGHT WALL ASSEMBLIES COMPARE WITH SUPPORTING CLADDING LOADINGS

The ability of the eight wall assemblies to support cladding loading varies from a low of 3 psf to a high of 20 psf. The theoretical 12 ft high wall has been engineered for 25 to 30 psf of wind loading (both positive and negative) (Fig. 18). The Z girts in the #1 and #2 assemblies, by their deflection-prone depth and shape, limit the load carrying capacity to 3 psf, which is still sufficient for lightweight

fiber cement and aluminum composite material claddings. The back leg of the Z girt tries to pry the fasteners out of the studs. The use of the horizontal hat channel fastened atop the rigid insulation in assemblies #3, #4, and #5 holds steady by compressing against the rigid insulation and supports about 15 psf of cladding loading, which is sufficient for terra-cotta claddings. The #3 phenolic foam assembly has a compressive strength of 15 psf as opposed to 25 psf for rigid ISO, and therefore results in slightly less supporting capacity. The #7 clip-and-rail assembly in its most basic

form can support about 10 psf, but with additional fasteners and stronger brackets it can be upgraded to 20 psf. Finally, the #8 back-lattice assembly is capable of 20 psf and even higher with adjustments to the horizontal back-furring gauge and spacing.

TIME IS MONEY; HOW DO THE ASSEMBLIES RANK BY COST AND PRODUCTION SPEED

With the assistance of a professional construction estimator, the eight wall assemblies for takeoff purposes were compared, with each being 12 ft high by 300 ft long. We first compared and ranked all eight assemblies by cost per square foot to purchase and construct, and found that the four cheapest assemblies, from least to most expensive, are the #4 ISO, the #5 ISO, the #6 Bonded All-in-One, and the “office standard” #1 Typical Zee (Fig. 19).

We then ranked all eight assemblies according to their speed of production or how long it would take to build a 12 × 300 ft wall assembly of each type. We found that the top four assemblies, in order of the fastest to the slowest to build, are the #6 Bonded All-in-One, the #4 ISO, the #8 Back-Lattice, and the #5 ISO (with the separate AWB).

Finally, combining these two rankings gives a ranking of the cheapest and fastest assemblies: the #4 ISO, the #6 Bonded All-in-One, the #5 ISO (with the separate AWB), and the #8 Back-Lattice.

For lower-rise projects, the ISO panels, such as assemblies #4 and #5, are both



Figure 18. Comparison of cladding support loadings ranging from 3 to 20 psf.

cheaper and faster. However, on higher and more demanding projects, the #6 Bonded All-in-One and the #8 Back-Lattice are the two cheapest and fastest solutions.

Where does this leave the #1 Typical Zee, which is so often used as the “office standard”? While its components may be less expensive, it takes longer to construct. Then how about the #7 Clip and Rail, which is often selected for high-design projects? That assembly is both more expensive and more time-consuming to construct. As a proviso, contractors in other regions will discover different ranking results, so before deciding on one or another assembly, reconfirm your own cost and time rankings.

CONCLUSION

It is hoped that this paper has been found interesting and useful. Full-size mock-up laboratory testing is continuing for three of the wall assemblies: #1 Typical Zee, #2 Enhance Zee, and #8 Back-Lattice (Fig. 20). To date, the ASTM E331,⁵ ASTM E2357,⁶ and ASTM E283,⁷ testing has been conducted with all three assemblies passing the code minimums of $< 0.04 \text{ cfm/ft}^2$ @ 75(Pa) $\approx 1.6 \text{ psf}$. In addition, for the ASTM E331 testing, assembly #8 excelled up to 30 psf, which $\approx 108 \text{ mph}$ wind speed. Assembly #8 has also passed one-hour E119 fire-testing, as well as 3D Therm analysis. The next round of testing will further analyze all three assemblies by subjecting full-size mock-ups in real time using microanalyzed thermal chambers with heat, cold, and moisture to conduct ASTM E1424⁸ and ASTM E2268⁹ thermal testing. This testing will study the resultant effectiveness of the insulation when hot, cold, and wet, and will study the AWB and flashings by comparing the three assemblies including those with SPF, mineral wool, and the #8 Back-Lattice arrangement. 

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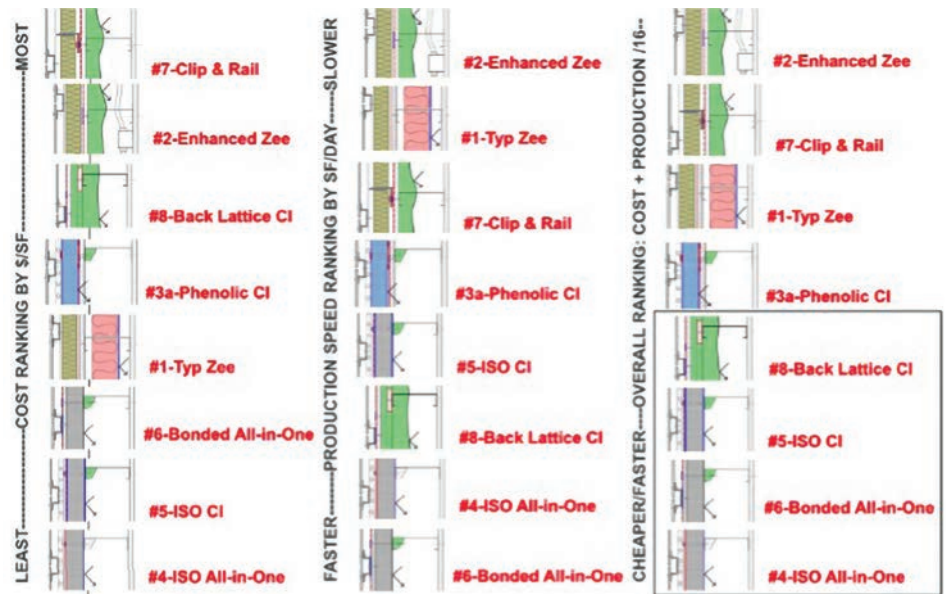
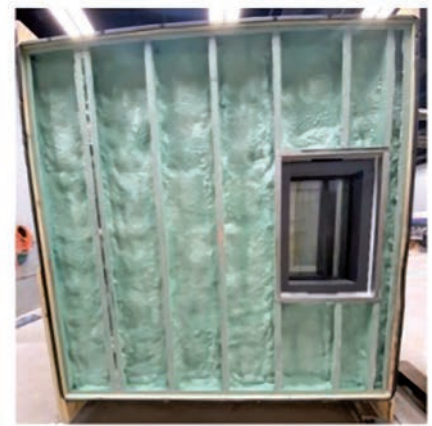


Figure 19. Comparison of assemblies based on cost of construction, by speed of construction, and by combined cost and speed of construction.



E283 & E2357 (Air Leakage): $\leq 0.04 \text{ cfm/ft}^2$ @ 75(Pa) $\approx 1.6 \text{ psf}$ per Code
E331 (Water Penetration): 6.2psf, 9psf, 12psf, 15psf, 18psf, 21psf, 25psf, & 30psf,
E1424, E2268 (Thermal)

Figure 20. View of performance testing of wall assembly #8.

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Polyvinylidene Fluoride Coating Failures

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ABSTRACT

Polyvinylidene fluoride (PVDF) coatings have been a reliable part of construction since the 1960s, but over the past 15 years, we have witnessed an increasing number of premature PVDF coating failures. This paper will review changes the industry made that led to these failures and how to avoid them through proper specification and testing.

This paper will demonstrate that the failures can be attributed to changes in the industry's use of chromium phosphate pretreatment wash—the tried and true method. The American Architectural Manufacturers Association's specification AAMA 2605 initially included chromium phosphate wash as a mandatory requirement. However, because there are concerns about the environmental impact of chromium, manufacturers' use of the wash became voluntary in 2004. Alternative washes such as phosphoric acid are being used instead of chromium phosphate, leading to poor adhesion and a lack of corrosion protection.

This paper will also review the steps and costs involved in repair and recoating procedures, and how to modify technical specifications and implement testing to mitigate premature failure.

SPEAKER



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Polyvinylidene Fluoride Coating Failures

Polyvinylidene fluoride (PVDF) coatings come in a variety of colors and finish options, have high chemical and ultraviolet resistance and excellent resistance to everyday wear and tear, and can even self-extinguish during a fire. They can also be cohesive with virtually any architectural style. PVDF coatings can be specified as a two-coat or three-coat system, ranging in thickness from 30 microns to 40 microns. The corrosion inhibitor primer is generally 5 microns. For better scratch resistance for roof panel application, specify a three-coat process.

However, over the past 15 years we have witnessed an increasing number of premature PVDF coating failures. All major manufacturers/fabricators are aware of this issue but are keeping it quiet until they can address it satisfactorily.

While coating failures may sound relatively benign compared with other building issues, the cost of repair can be very significant. Issues range from coating delamination to high levels of aluminum corrosion, especially in coastal areas, where it can cost tens of millions of dollars per building to repair.

This study will go into the fundamental changes the industry made that led to these failures and how to avoid them through proper specification and testing. We will also cover the predecessor and predominant alternative to PVDF coatings—anodized aluminum—and why PVDF coatings can still be the better option despite the increased failure rates.

Finally, this study will review coating repair/recoating procedures, the steps and costs involved, how to modify technical specifications for new construction, and how to implement postapplication testing to mitigate premature failure.

THE RISE OF ARCHITECTURAL ALUMINUM AND METAL FINISHES

When architectural aluminum arrived on the scene in 1920s, it was hailed as a modern marvel and a sign of a major advancement in construction. However, pure aluminum is not strong enough for architectural use, but aluminum alloys (typically aluminum mixed with silicon or copper) are ideal.¹ Due to its light weight, light color, structural integrity, and durability, architectural aluminum is com-

monly used for exterior building elements such as curtain wall extrusions, window frames, spandrel panels, decorative façade features, and metal roof panels.

Most aluminum extrusion manufacturers provide PVDF coatings for their extrusions. Naturally occurring oxides on uncoated aluminum surfaces are susceptible to various forms of corrosion that can compromise the aluminum. In most cases, a protective coating or metal finish is added to prevent corrosion and increase the lifespan of the metal.

There are two primary types of architectural metal finishes in use today that this paper will focus on: anodizing and PVDF coatings. While there are pros and cons to each finish type, they both result in more durable, corrosion-resistant metal and provide color and finishing options. Choosing the right architectural finish for a project can affect warranty duration, durability, and overall system longevity.

ANODIZING 101

Before the inception of PVDF coatings, anodizing was the preferred choice for an attractive and durable architectural finish. Color availability with anodized finishes is generally limited to bronze, clear, black, and champagne.

Anodization is an electrochemical process that increases the thickness of that oxide layer that protects the base metal. Anodization creates a “conversion coating.” It literally converts, or alters, the aluminum surface (as compared with a topical application, such as paint). This makes the aluminum more durable, corrosion resistant, scratch resistant, visually attractive, and flexible during fabrication. Anodized aluminum first appeared in industrial applications in the 1920s, but it was not until the 1950s that it became hugely popular for architectural use.²

To oversimplify a complex electrochemical process, anodizing involves submerging an anode and a cathode in an acid electrolyte (chemical solution), then passing an electrical current between them. The current

releases hydrogen at the cathode causing reduction and releases oxygen at the surface of the anode, creating oxide buildup or oxidation. When anodizing aluminum, the aluminum acts as the anode—hence the term anodizing. The oxide buildup acts as a protective layer.

There are different primary types of anodizing: Type I, Type II, and Type III. Each type utilizes a different acid electrolyte for different physical and chemical traits.

- Type I or chromic acid anodizing (CAA) was initially known as the Bengough-Stuart process. It was first used industrially in 1923 to protect Duralumin seaplane parts from corrosion. Today, it is most often used in aerospace and military defense applications. Unfortunately, CAA has limited utility for decorative or exterior building applications due to its naturally dark color.
- Type II or sulfuric acid anodizing (SAA) is the most common method. Only 33% of the coating sits above the substrate; the other 67% directly penetrates and integrates with the aluminum substrate. This makes it extremely hard and durable. Additionally, the porous nature of the aluminum oxide readily accepts paints and lacquers, making it ideal for decorative and exterior building applications.
- Type III or hard/hardcoat anodization also uses sulfuric acid as the electrolyte, but it produces a much thicker

Choosing the right architectural finish for a project can affect warranty duration, durability, and overall system longevity.

Coating/oxide thickness (ASTM B244/B487)	-
• Class I	0.07 mil / 0.0018 microns
• Class II	0.04 mil / 0.001 microns
Coating/oxide weight (ASTM B137)	-
• Class I	4.18 mg/cm ² (27.0 mg/in. ²)
• Class II	2.40 mg/cm ² (15.5 mg/in. ²)
Corrosion resistance (ASTM B117)	-
• Type II (Class I)	Excellent (3000 hr of exposure)
• Type II (Class II)	Intermediate (1000 hr of exposure)
Common warranty duration	One year standard

Table 1. Anodized architectural aluminum statistics and specifications

coating than Type I or II anodization. Type III coatings have excellent corrosion resistance, but mediocre chemical resistance. Therefore, it is not commonly used for architectural finish applications. Type III is typically specified for applications with extreme potential for wear and tear, such as mechanical valves and pistons.

Architectural aluminum extrusions are typically Type II anodized and are commercially available in either Class I or Class II. Class I has a minimum finish thickness of 0.07 mil (0.0018 microns), while Class II has a finish thickness of 0.04 mil (0.001 microns).³ Thicker coatings spend more time in the processing tanks to give them that heavier coating.

MANUFACTURING OF ANODIZED ALUMINUM EXTRUSIONS

The commercial manufacturing process for anodized aluminum has several steps. Once several racks' worth of extrusions are ready to be anodized, they first need to be cleaned with an alkaline solution to remove debris, oils, or other contaminants from the aluminum surface. The next steps are the alkaline etching and desmutting processes. Etching involves dipping the racks into an acidic solution to reduce the appearance of minor surface defects. Desmutting is the process of removing excess metal from the aluminum surface after etching.

Finally, the extrusions are ready to be anodized. Typically, this involves the extrusions being immersed in 15% sulfuric acid solutions and charged with an electrical current to form the aluminum oxide layer. The

longer an extrusion is immersed in the anodization tank, the thicker the oxide coating.

Once the aluminum oxide layer is formed to the desired thickness, color is added by electrodepositing various amounts of tin for various colors. As mentioned previously, anodized aluminum extrusions are typically available in clear, black, champagne, and various bronzes. The last step is the sealing process, which closes the aluminum oxide pores. This coat helps protect the oxide layer and color layer from the elements. There are multiple sealing options. The most common processes use deionized water, potassium dichromate, and nickel acetate.

SPECIFYING ANODIZED ALUMINUM AND WARRANTY CONSIDERATIONS

ASTM B580-79(2019), *Standard Specification for Anodic Oxide Coatings on Aluminum*,⁴ is used to specify anodized oxide coatings for aluminum. There are several considerations when specifying anodized aluminum for architectural use: aluminum dimensions, corrosion resistance, air pollution/salt levels, up-front costs versus eventual repair costs, aesthetics, and more.

Due to shorter warranties, inability to perform field repairs, lack of color availability, lack of color uniformity between batches, and inferior performance, anodized aluminum is not as commonly specified for architectural purposes. Additionally, anodized aluminum does not have a high chemical resistance. It can be affected by acidic air pollutants, especially in coastal areas. Generally, in coastal areas, it is best to specify anodization that is thicker than Class I, up to 10 mil.

Since the 1980s or 1990s, most projects have chosen PVDF coatings over anodized window and curtain wall extrusions. However, anodized extrusions are still specified for midrange storefronts or lower-cost building exteriors, such as for schools or local municipal buildings. Anodized aluminum is also commonly used for large custom shapes, such as screens, handrails, and artwork, that can be dipped in tanks similar to hot-dipped galvanizing.

Most manufacturers offer a standard one-year warranty on anodized aluminum extrusions, with some five-year or 10-year warranties available from select manufacturers (Table 1).⁵⁻⁷

ANODIZED ALUMINUM FAILURES

There are at least 14 types of aluminum corrosion methods. The predominant form of aluminum corrosion is atmospheric corrosion. This is loss of material due to wind-driven abrasives. The relative softness of the aluminum makes it particularly susceptible to this form of corrosion. Anodization is one method of protecting the aluminum. As mentioned above, it chemically alters the surface of the aluminum to a hard oxide, which can withstand the effects of atmospheric corrosion.

Many of the other forms of aluminum corrosion involve water and the difference in electrical potentials, which are set up in the form of dissimilar metals, salts, or microscopic grain boundaries. Exposure to harsh environments (such as alkaline atmospheres or salty ocean spray) can leave anodized aluminum susceptible to corrosion if water is present. The conditions erode the protective oxide layer, leaving the aluminum vulnerable.

Figures 1 and 2 show a lanai railing replacement project for an 11-building, 364-unit residential development in Ka'anapali, Maui, Hawaii. Figure 1 shows significant corrosion on the anodized aluminum guardrail. The extent of the corrosion differed from unit to unit. A possible reason for this could be that certain railings were cleaned more than others, which unevenly removed salt deposits (chlorides).

Additionally, we observed that galvanic corrosion was taking place on the railings due to the materials used, even though it is not easily visible. Not visible in Fig. 2 is the galvanized steel fastener securing the base of the aluminum railing picket to the aluminum rail. Salt-laden rainwater trapped at the base of the picket likely set up the galvanic reaction with the steel fastener (Fig. 3).

The consultant, Allana Buick & Bers, was retained for a railing replacement project at a nine-story, 463-unit residential building in Lahaina, Maui. Several anodized aluminum railings showed typical signs of corrosion and some pinholing. In addition, we also observed white rust and hazing along the bottom rail. This is a common indicator of corrosion of the fasteners and a dissimilar metal reaction.

Unlike PVDF coatings, anodized aluminum cannot be repaired in the field. Each piece must be replaced. While this is not cost prohibitive for individual balconies or lanai, it is not a practical option for most building exteriors.

PVDF COATINGS 101

PVDF is a nonreactive thermoplastic fluoropolymer (plastic) used in high-performance architectural coatings. PVDF's coating properties, such as high chemical resistance, ultraviolet resistance, mechanical strength, color/gloss retention, and ease of processability, make it a superior alternative to regular paint for coating metal. Unlike anodized aluminum, color options are virtually limitless. Additionally, PVDF coatings are uniform in appearance, unlike anodized finishes.

PVDF coatings came into use in the 1950s for use in coating mechanical parts. It was not until the 1960s and 1970s that they came

into use for architectural purposes. They reached peak popularity in the 1980s and 1990s and have now become ubiquitous for both commercial and residential applications.

Architectural PVDF coatings are resin based and come in a variety of proprietary and nonproprietary formulas. Different PVDF-to-resin ratios and additives produce different architectural properties.

Seventy percent PVDF coatings (that is, a makeup of 70% PVDF and 30% resin) are the most weather resistant, chemical resistant, and fade/chalking resistant. These are most

often used for high-performance building exteriors. They are not recommended for roof panel applications, where additional longevity and scratch resistance are desirable. While not as durable as 70% PVDF coatings, 50% PVDF coatings are still a viable (and less expensive) alternative for certain less-demanding architectural

applications, but typically not for high-performance building exteriors. Seventy percent PVDF coatings meet AAMA 2605 standards.⁸ Fifty percent PVDF coatings do not. They meet the less-stringent AAMA 2604 requirements.⁹

MANUFACTURING AND APPLICATION OF PVDF COATINGS

PVDF is typically synthesized by the polymerization of monomers of vinylidene difluoride. This process was originally developed in the 1940s. The reaction takes place in a temperature-controlled, pressurized emulsion. The resulting material is processed for various applications. Pure PVDF, in its powder form, is the key ingredient in PVDF architectural resin coatings.

PVDF coatings are available in liquid (wet) coatings and powder (dry) formulations. While powder coatings are generally cheaper, wet coatings are typically preferred for exterior architectural use because powder coatings are not ultraviolet resistant. Additionally, mica and other metallic-based colors are not available in dry/powder PVDF coatings.

The wet PVDF coating application requires a precise, multistep process. After an initial hot alkaline cleansing wash, PVDF coatings require a chemical conversion coat for the aluminum surface area prior to application. The conversion coat protects the metal from



Figure 1. Corrosion (white oxide layer) on anodized aluminum guardrail.



Figure 2. Galvanic corrosion on anodized aluminum guardrail.



Figure 3. Steel angles used to repair aluminum pickets.

corrosion. Additionally, it operates as a binder between the aluminum substrate and the color top coat by adding significant surface area between the two coats.

Historically, the process relied on a chromium phosphate (CP) or chromium chromate (CC) conversion coat, but AAMA revised the standard in 2005 to allow non-chrome alternatives. These are discussed in detail later in this paper.

After a surface has been pretreated, there are three types of multilayer spray coating systems: two-coat, three-coat, and four-coat. Two-coat and three-coat are the most common systems for exterior architectural applications. Each layer requires 10- to 15-minute curing intervals between each coating layer at between 230°C and 250°C.¹⁰

- **One-coat (primer):** The conversion coat is typically 5–10 microns thick. It adds increased durability and protection for the aluminum substrate and increases adhesion between the primer and additional coats.
- **Two-coat (color top coating):** The color top coating is typically the thickest layer and is generally 25–30 microns thick. This layer adds enhanced durability in addition to decorative color.
- **Three-coat (clear top coating):** A clear top coating is generally 10–15 microns thick. This layer adds even more protection and increases color retention and luster.

FORENSIC ANALYSIS OF INCREASED PVDF COATING FAILURES

Until recently, there appeared to be few



Figure 5. Polyvinylidene fluoride coating failure: Corrosion at aluminum curtain wall frame.

Figure 6. Polyvinylidene fluoride coating failure: Corrosion at aluminum curtain wall frame.

downsides to specifying PVDF coatings. In our capacity as a forensic expert for construction defect litigation specializing in the building enclosure, Allana Buick & Bers has personally observed the increase in PVDF coating failures. We have been investigating failed building exteriors for more than 30 years. The rate of PVDF coating failures has significantly increased in the past 8–10 years alone. Because these systems are expected to last 40 to 50 years before recoating, failures within 10 years of application represent a significant loss of product life expectancy.

Common modes of failure include filiform, discoloration, bubbling, cracking, and delamination from the aluminum surfaces. Filiform corrosion is when the aluminum starts to corrode at the edges and the moisture and corrosion spread under the coating in a tiny wormhole. Filiform corrosion is not easily detectable and can pop up 12 to 24 in. away from the aluminum edge.

Failure of protective coating allows for premature degradation of the aluminum extrusions and reduction of useful life. To make matters worse, many coating issues initially go undetected. To spot them on mid- and high-rise buildings, there typically needs to be an intentional survey with exterior building swing stage drops.

As we investigated more and more instances of PVDF coating failure, we began to suspect that there was a more systemic issue rather than simply a rash of manufacturing defects and improper applications.

One of the more prevalent instances of PVDF coating failure we observed was at a 419-unit, 58-story residential high-rise in

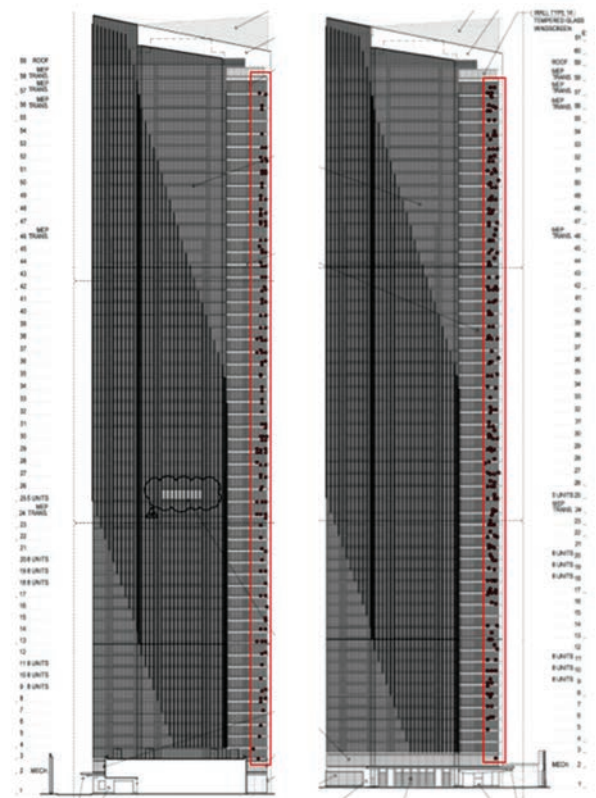


Figure 4. Prominent coating failure at east/west building elevation drops.

San Francisco, California. The building consists largely of an aluminum-framed curtain wall system and aluminum panels and was completed in 2009. Allana Buick & Bers was retained to investigate exterior building defects and from a swing stage, we were able to document widespread coating failure. We observed PVDF coating failures at both horizontal and vertical framing members.

Figure 4 shows the individual instances of coating failure ranging from the top to bottom of the east and west building elevations. The red boxes indicate sample drop zones for our inspection. The black dots indicate observed areas of coating failure. We also performed drops on the north and south elevations and observed a similar rate of failure. Due to the sample size of our visual observations and high rate of failures, we determined that the coating failure issue was widespread.

Figures 5 and 6 show some typical examples of severe corrosion and bubbling at the aluminum curtain wall frames. Forensic testing found chromium present on some samples but not others. This led us to determine that while a chrome-based primer was applied, it was either not applied uniformly or not applied in the specified amount.

To remediate the coating failure (and other



Figure 7. Polyvinylidene fluoride coating failure: Corrosion at aluminum window wall frame.



Figure 8. Polyvinylidene fluoride coating failure: Corrosion at aluminum window wall frame.



Figure 9. Polyvinylidene fluoride coating failure: Corrosion at window wall tie-back ports.

façade defects), we recommended installing an overcladding over 100% of the existing curtain wall. The overcladding consisted of manufacturing new aluminum break metal to completely envelope the existing extrusions. The cost to rectify these coating failures for the entire curtain wall façade was estimated at \$45,476,874.

Another recent instance of widespread PVDF coating failure was at a 108-unit, 21-story, podium-style mixed-use residential building, also in San Francisco. Generally, the building consists of precast concrete panels, stucco walls above the roof, and aluminum-framed window wall assemblies.

During a visual investigation of the window wall assembly, we documented various PVDF coating failures at the aluminum framing and at tie-back anchor ports. **Figures 7 through 9** show some typical examples of

severe corrosion and pitting observed at the aluminum window wall frames and tie-back anchor ports during swing stage drops. We ultimately concluded that the conversion coating used did not include CP or CC.

To remediate the coating failure, we recommended removing 100% of the exterior coating, then recoating the entire window wall system. The cost of recoating all the aluminum framing was estimated at \$1,838,720 (not including other building repairs).

While the previous instances were wet PVDF coating failures, we have also witnessed PVDF powder coating failures. **Figures 10 and**

11 show some typical examples of dry PVDF coating failure at a 99-unit, nine-story residential building in San Francisco. We observed severe discoloration of the PVDF coating at



Figure 10. Polyvinylidene fluoride coating failure: Significant corrosion at window flashings.

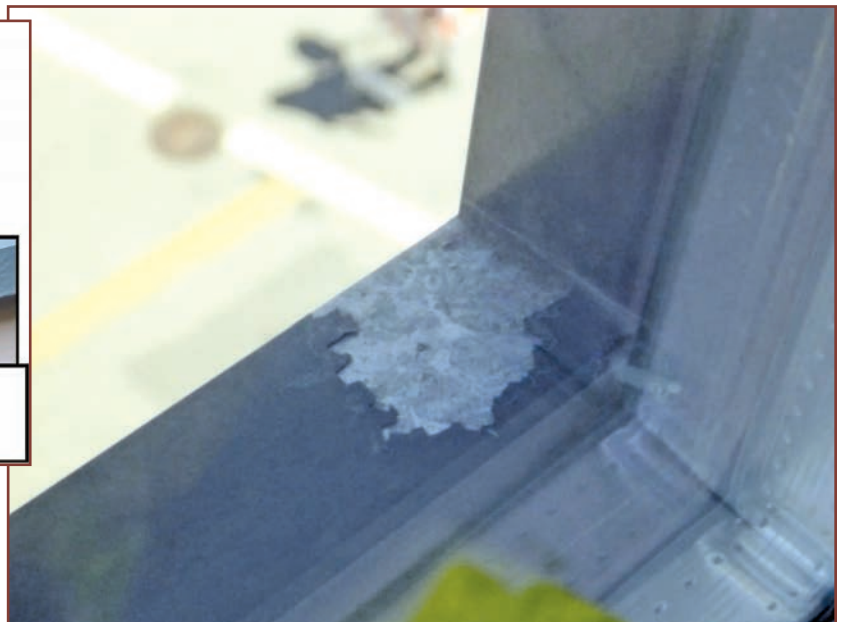


Figure 11. Polyvinylidene fluoride coating failure: Significant corrosion at window flashings.

AAMA 2605	
Coating thickness (ASTM 2605)	0.02–0.3 in.
Chromium content in conversion coat (ASTM D5723)	≥ 40 mg/ft ²
Curing temperature	500°F
Chemical resistance (ASTM D543)	Excellent
Abrasion resistance (ASTM D4060)	Excellent
Pencil hardness (ASTM D3363)	F, minimum
Tensile strength at break (ASTM D638)	6525 psi
Coefficient of friction (ASMT D1894)	0.4 static, 0.3 dynamic
Dielectric strength (ASTM D149)	260 V per mil
Hardness (ASMT D676)	80 (shore D)
Common warranty duration(s)	10–20 years standard

Table 2. Polyvinylidene fluoride coating statistics and specifications

the window ledge flashings, and similar exterior door frames. In Fig. 10 and 11, significant corrosion at the window flashings is visible. We ultimately concluded that several factors were responsible for the premature failure. Just like with the liquid PVDF coating failures, we suspected the cause of failure was the pretreatment wash. In this case, we found that the prewash was not CP, primer was not applied properly, the coating was of improper thickness, and a lack of proper surface preparation led to trapped contaminants.

The cost to recoat exterior aluminum at the window frames, fixed windows, window system mullions, and door sash/frames was estimated at \$2,924,123.

- Primer/conversion coat application: \$433,428
- High-performance top coat finish/PVDF coating applications: \$1,787,815
- Sealant removal and replacement: \$702,880
- **Total coating repairs: \$2,924,123**

WHY PVDF COATINGS ARE FAILING . . . AND HOW TO DO TO PREVENT IT

As mentioned above, PVDF coatings historically relied on a CP or CC conversion coating. From 1979 (AAMA 605.2)¹¹ to 2002 (AAMA 2605-2), the CP/CC conversion coat was a mandatory requirement for PVDF applications. The standard mandated 40 mg per square foot of CP or CC for the aluminum surface area. In 2005, AAMA revised the standard to allow non-chrome conversion coating alternatives (AAMA 2605-05). These changes were made due to safety, environmental, and cost concerns.

The Occupational Safety and Health

Administration (OSHA) also issued new standards in 2006 that significantly lowered allowable limits for human exposure during the manufacturing process (1910.1026 - Chromium [VI]). The permissible exposure limit was reduced from 52 micrograms to 2.5 micrograms per cubic meter of air over an eight-hour period.

Due to the combination of safety/environmental concerns and increased costs of OSHA compliance, insurance costs for manufacturers went up considerably. This resulted in most PVDF coating manufacturers choosing nonchrome alternatives. Unfortunately, we are learning that chrome-base pretreatment was the key to PVDF coatings' longevity, durability, and color retention. The other phosphate alternatives really did not work. Manufacturers are now experimenting with nickel and other types of prewash systems that are not yet commercially available. The key to preventing premature PVDF coating failures is to ensure a CP/CC conversion coat is used and that specific quality assurance/quality control (QA/QC) materials testing is performed to verify CP/CC content and coating thickness.

Specifying PVDF Coatings to Prevent Premature Failure

ASTM D3222, Standard

Specification for Unmodified Poly(Vinylidene Fluoride) (PVDF) Molding Extrusion and Coating Materials,¹² governs PVDF coatings. Since the 1980s or 1990s, most anodized architectural finishes have been replaced with PVDF coatings, particularly in mid- and high-rise buildings.

There is currently an ASTM committee reviewing these standards in light of the increased failures. While the committee deliberates, several steps can be taken to proactively mitigate premature PVDF coating failure.

Based on our field observations and forensic analysis, we recommend modifying the technical specifications for all aluminum extrusions to mandate the use of a chrome-based conversion coating, including when used for metal panels and roofing. To ensure proper application, QA/QC testing should be mandated at the coating application plant and on-site.

We recommend specifying ASTM D5723¹³ testing. ASTM D5723 is the test method to determine how much chromium is deposited through the conversion coating using X-ray fluorescence spectroscopy. We also recommend using a spectrophotometer to confirm color and gloss uniformity (**Table 2**).

THE COATING REPAIR PROCESS

There is a reason preventing premature coating failure is so critical: it can be extremely costly to repair and can be detrimental to a building's integrity if ignored. Luckily, PVDF coatings can be repaired in the field. While the process itself is not complicated, the coating repair process can be time consuming and very expensive.



Figure 12. The coating repair process: Sanding down to bare metal. Courtesy of Stuart Dean.

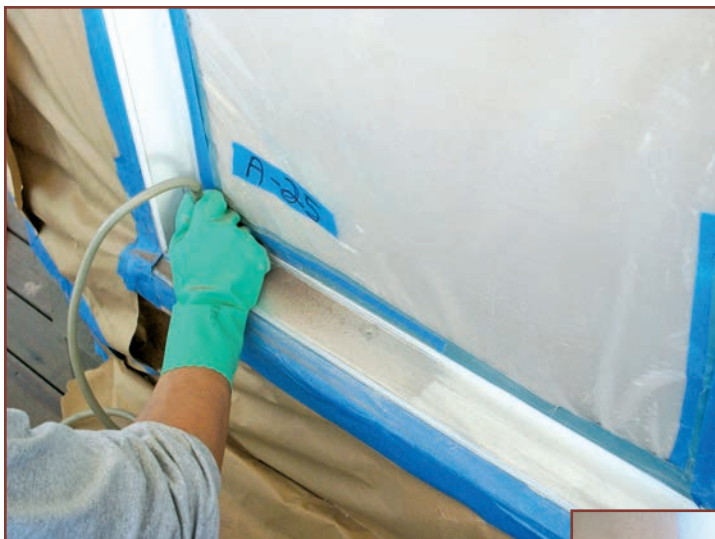


Figure 13. The coating repair process: Microblasting to remove oxidation. Courtesy of Stuart Dean.

When doing a complete recoat, all perimeter sealants and any exposed sealants (that is, any sealants in contact with the metal) need to be fully removed prior to recoating and replaced afterward. Partial recoats usually requires application of a clear coat, which may or may not be required in a total recoating protocol.

The first step is to sand all affected surfaces down to the bare metal (Fig. 12). The next step is to remove corrosion-causing chlorides from the aluminum by chemically treating it and microblasting affected areas to remove oxidation cells (Fig. 13).

Next, the bare metal is treated with an acid etching chemical and the corrosion-resistant chromium-based primer is applied to the bare metal. Following that, an epoxy primer is applied to the entire metal unit and sanded down lightly in preparation for the top coat (Fig. 14).

PVDF COATINGS VERSUS ANODIZED ALUMINUM: ARE PVDF COATINGS STILL BETTER?

While the industry is not ready to publicly acknowledge this problem, there is a clearly documented issue with premature PVDF coating failures. However, there are ways to mitigate premature failure while the industry collectively figures out how to proceed.

Despite the increase of failures, PVDF coatings are still the best choice for most projects (assuming they are properly specified and tested). Here is why PVDF coatings are still a better choice for most projects than anodized aluminum:

- **Durability and longevity:** The oxidizing layer of anodized aluminum is typically only 0.07 mil and is susceptible



Figure 14. The coating repair process: Top coat application. Courtesy of Stuart Dean.

ble to corrosion, particularly in coastal climates. Thicker, more customized coatings cost more. PVDF coatings (when used with a chrome-based conversion coating and properly applied) will outlast anodized aluminum.

- **Warranty considerations:** Anodized aluminum extrusions are typically under warranty for 5–10 years, depending on a variety of factors. PVDF coatings commonly come with a 10- to 20-year warranty.
- **Cost:** The initial cost of anodized aluminum can be lower than PVDF coating. However, when factoring in eventual replacement costs (because field repair is not an option), anodized finishes cost more over time. Many manufacturers have also adopted PVDF coatings as their standard of care and most architects specify them.

Anodized coatings are inferior on most scales, and can end up costing more than PVDF coatings.

- **Aesthetics/color availability:** Anodized aluminum is available in limited color options: bronze, clear, black, and champagne. PVDF coatings are available in an array of colors and can be custom made to match virtually any building exterior.

When PVDF coatings are properly specified to include a chrome-based conversion coating, PVDF coating can still last the lifespan of a new building, even in coastal environments. While the ASTM committee is still in deliberation, we fully expect the standard will be revised to once again mandate this practice. However, proper verification testing will still be critical. 

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Low-Slope Lessons from 30 Years of Hurricane Events

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ABSTRACT

The Federal Emergency Management Authority (FEMA) deployed Mitigation Assessment Teams (MATs) after Hurricanes Irma and Michael impacted Florida in 2017 and 2018. Industry representatives, academics, regulators, insurers, and representatives of other interests all participated in the MATs, which were deployed in affected areas after the storms to study wind damage, report observations, and make recommendations on how to improve construction methods and help reduce the chance of damage from future storms. This presentation will review the recommendations from the MAT reports and show how high winds can impact construction. It will cover wind damage to roof assemblies, as well as water damage to structures and contents resulting from wind-driven rain, and focus on the specific recommendations from FEMA as well as the roofing industry response.

SPEAKER



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Chadwick Collins's entire 15 year career has been on the technical side of the roofing industry, ranging from field technical services to product and system testing along with code and standard development. His experience comes from working for two manufacturers and an engineering consulting firm prior to joining the Asphalt Roofing Manufacturers Association's (ARMA's) team. He holds a bachelor of science in mechanical engineering, was previously a Registered Roof Observer, and is currently a licensed drone pilot and member of ASTM, ICC, and IIBEC.

Low-Slope Lessons from 30 Years of Hurricane Events

Roof damage associated with hurricanes is not a new concept. Video footage and images showing catastrophic damage are commonplace in news coverage and social media posts, and detailed storm damage research reporting has become more commonplace in the past five decades. However, many people are not aware of, or do not fully understand, the process that the Federal Emergency Management Agency (FEMA) undertakes after a hurricane event with the deployment of Mitigation Assessment Teams (MATs). These teams are composed of participants from the construction industry, academia, regulators, insurers, and other stakeholders who deploy to affected areas after the storms to study building performance, report observations, and make recommendations on how to improve performance in future events through a variety of strategies, including product standards, education, installation techniques, and building inspections.

The roofing industry continues to be a key participant in these MATs as well as a key area of focus for wind-related observations. Another important step that the roofing industry and other stakeholders have undertaken is reviewing the MAT reports and responding to recommended actions.

HISTORY OF FEMA MAT REPORTS

The process of deploying a MAT to evaluate building performance after a catastrophic event has been occurring for more than 30 years. These efforts are a result of a federal, state, local, and private sector partnership to pool resources to quickly assemble and deploy investigation teams. Going back to Hurricane Andrew in Florida and Hurricane Iniki in Hawaii, both in 1992, MATs have issued reports following hurricanes, flooding (Iowa in 2016), and man-made events (Oklahoma City bombing in 1996; World Trade Center in 2001) (Fig. 1). The developed recommendations and suggested mitigation activities are meant to lead to greater resistance to future hazard events.

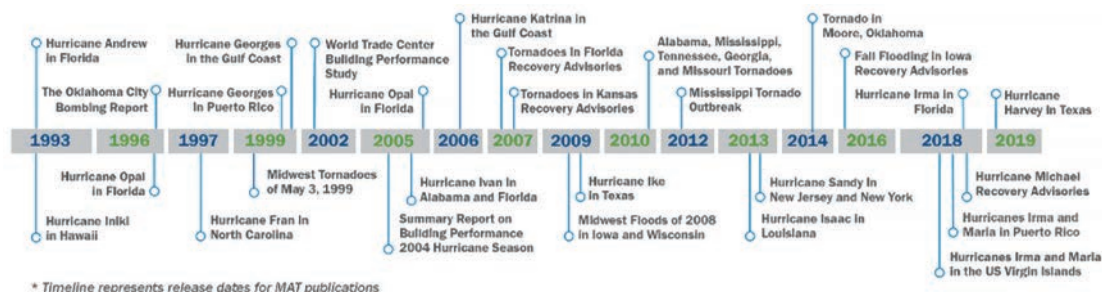


Figure 1. Timeline of Federal Emergency Management Agency Mitigation Assessment Team publications. Source: <https://www.fema.gov/emergency-managers/risk-management/building-science/mitigation-assessment-team>.

FEMA MAT PROGRAM INITIATIVES

The MAT program provides a means for experts in construction materials, techniques, and performance to assess how building systems function during exposure in various disaster events, including tropical storms and hurricanes, tornadoes, flooding, earthquakes, snow loading, and terrorism events. FEMA draws these experts from the design community and also engages academics, regulators, manufacturers, builders, and other stakeholders to ensure broad participation from all aspects of the construction industry. The observations of the team members form the basis for the findings and recommendations in the reports and provide a path to improved building performance in future events. With each successive investigation, the FEMA MAT program can build on previous successes and assess how prior recommendations did or did not work.

In the two and a half decades since the FEMA report on Hurricane Andrew,¹ there has been an evolution in the focus of the findings and the recommendations. It is interesting to note the contrast in the technical guidance. As an example, the Andrew report cites structural design concerns that likely led to damage scenarios, but also notes the enclosure breaches that led to total building failure. The report identifies issues with product and material standards

and workmanship, and also notes concerns about building department oversight from a plan review and inspection perspective and that “inadequate training of the inspectors and supervisors are factors that may have contributed to the poor-quality construction observed” after Andrew.

The report also includes recommendations for improved performance based on concerns such as building materials and techniques, quality control, retrofit efforts, and code compliance. The report’s stated goal is to “enhance the performance of buildings in future hurricanes.” That goal set the table for building improvement after Andrew and for subsequent decades. While many of the Andrew report’s recommendations for improved code compliance and building materials improvements

The observations of the team members form the basis for the findings and recommendations in the reports and provide a path to improved building performance in future events.



Figure 2. Damage to the Pensacola Naval Hospital in Florida from Hurricane Ivan.

have been addressed, the opportunity to work towards future improvements remains. The industry response to windstorm events has shifted from maintaining the structural integrity of the building to avoiding damage to its contents from wind-driven rain and reducing the likelihood of business disruptions and the need for residents to relocate after an event as their home is being repaired or rebuilt. This shift has resulted in the new paradigm of resilient building design and the goal of keeping communities in place after natural disasters wherever possible.

The MAT report on Hurricane Ivan (FEMA 489)² included a field observation that the damage and peeling of metal edge flashing led to the blow-off of the modified-bitumen roof membrane on the Pensacola Naval Hospital (**Fig. 2**). The report noted that while the concrete deck limited water intrusion into the building, the blow-off created debris that damaged windows and antennae. Damage to the roof membrane that leads to issues with other systems is an important element of evaluating roofing response to wind events: water intrusion that damages the interior of buildings or destroys building furnishing or contents is one of the more costly impacts of roof damage.

The damage or removal of rooftop equipment, including heating, ventilation, and air conditioning (HVAC) and solar photovoltaic assemblies, can also result in breaches in the roof membrane. Once breached, the membrane can be subject to further damage or blow-off, and the openings in the roof assembly created when rooftop equipment is damaged can certainly lead to water intrusion. **Figure 3** from the MAT report on Hurricane

Harvey in Texas (FEMA P-2022)³ illustrates how damage to rooftop HVAC systems can result in punctures of roof membranes. The Harvey MAT report also notes concerns regarding the vulnerability of rooftop solar equipment subjected to high winds; this is also a steep-slope issue. The report recommends conducting a wind vulnerability assessment of the roof before installation of rooftop equipment on existing buildings. While many design requirements are easily addressed during the design and construction of roof assemblies on new buildings, retrofitting often adds additional complexities and challenges. FEMA's U.S. Virgin Islands (USVI) Recovery Advisory 5⁴ contains recommendations on the

design, installation, and maintenance of solar equipment on existing buildings.

One clear example of the industry response regarding damage assessments of low-slope roofs is the development of ANSI/SPRI/FM 4435/ES-1.⁵ The findings of MAT reports and other reported post-storm observations were key in identifying the edge securement of low-slope roofs as a critical design point and served as a catalyst for the development of the edge securement standard. The recognition of this industry work can be seen in the direct reference to ANSI/SPRI/FM 4435/ES-1 in the Hurricane Michael report:

Recommendation #FL-23b.

Copings and edge flashings should comply with ANSI/SPRI/FM 4435/ES-1 to prevent blow-off. The MAT observed many coping and edge flashing blow-offs. Blown-off copings and edge flashing can result in roof membrane lifting and peeling, and they can puncture roof coverings and cause other damage or injuries.

This shows how the MAT reports interpret the damage observed. What would have been observed as a failure of the roofing system 30 years ago now not only identifies the key failure (edge securement) but acknowledges that the roofing industry has developed a methodology and has the products to address the issue in question and assigns the responsibility to other stakeholders.



The red arrows indicate where HVAC units were blown off their curbs (the curb openings were temporarily covered with plywood). Emergency patches had been installed at membrane punctures (blue dashed arrow). The gas lines (green dotted arrow) had ruptured.

Figure 3. Roof membrane punctures from damaged heating, ventilation, and air-conditioning equipment on Rockport-Fulton Middle School in Rockport, Tex. Source: FEMA P-2022.



Figure 4. Cover of the Federal Emergency Management Agency's Mitigation Assessment Team report for Hurricane Michael in Florida.

HURRICANE MICHAEL IN FLORIDA

FEMA's latest MAT report was FEMA P-2077 on Hurricane Michael in Florida and was published on February 1, 2020 (Fig. 4).⁶ The pre-MAT deployed approximately two weeks after the event, with the 18-member MAT deploying from January 6 to 10, 2019, in Bay, Calhoun, Franklin, Gulf, and Wakulla Counties.

The Michael report notes the 88-day delay between the pre-MAT and MAT resulted in the ability for the MAT to observe some sites and buildings initially observed by the pre-MAT to be lost. The report also notes that the desired response window for a MAT is 30 to 45 days following an event.

This report follows the same format, breaking down the damage into two major categories: flood and wind. The MAT studied "the performance of non-residential buildings and facilities that had been retrofitted to improve building performance during high-wind events, as well as the performance of commercial buildings and non-retrofitted critical facilities. [...] The MAT observed some damage to the MWFRS [main wind-force-resisting system] and building envelope systems at several different types of critical facilities and commercial buildings of varying age and size."⁶

The following list summarizes the conclusions and recommendations that continue to be documented in MAT reports.

- Inspections of building enclosure components are performed inconsistently,

even though some jurisdictions require such inspections.

- Improvements in wind calculations, uplift testing, and edge securement practices have proven effective in the ability of roofs to withstand expected design pressures.
- Insufficient securement of rooftop equipment continues to be observed. This issue has expanded from HVAC and hoods to now include rooftop-mounted photovoltaic arrays.
- Improperly installed products continue to be a source of roofing system failures.
- There are particular issues with retrofits and re-covering/replacement installations where the main wind-force resistance systems or wind vulnerabilities were either not adequately assessed or addressed.
- Damage from wind-borne debris, some originating from the roof, continues to be observed.

BUILDING INDUSTRY STAKEHOLDER RESPONSE

From the beginning, multiple building industry stakeholder groups have participated in the MATs and have used the reports to guide responsive actions. Through research initiatives, standards revisions and updates, educational programming, and proposed updates to model building codes, the industry response has provided a comprehensive and multipronged strategy to improve performance in and reduce damage from future storm events. While the MAT reports for Hurricanes Andrew and Iniki only provided conclusions for steep-slope roofs, later publications (such as Smith⁷) highlighted observations related to low-slope roofs. In fact, Smith estimates that more than 70% of roofs were significantly damaged during Andrew. Relative to low-slope roofs, primary items observed were the lifting and peeling of light-gauge metal edge flashings, wind-borne debris strikes, and failure of the main wind-force-resisting system members (such as decking and deck framing). Responses to these initial findings can be seen in the continual refinement of wind uplift calculations with updates to ASCE/SEI 7,⁸ the development and recognition in the code of ANSI/SPRI ES-1⁵ to address metal edge securement and testing and work as recent as the approved table in the 2021 *International Building Code* (IBC)⁹ for parapet wall requirements for the use of roof aggregate, as mentioned at the end

of the following section.

These efforts from the industry have had the desired impact. Later reports indicate when these types of conditions are observed, the building's original construction can be confirmed to have occurred before many of the guiding documents and code provisions were adopted into the building code.

LOOKING FORWARD

Wind-resistant construction techniques rely on the overarching design goal of providing a continuous load path that transfers the force of the wind from components and cladding through the main structural components of the building, through the foundation, and into the ground. Under this approach the various parts of the building act as part of a chain; damage to one link can result in the failure of the entire chain. As the Andrew report noted, damage to windows and doors led directly to total building collapse. As noted in the Michael report, for buildings designed and constructed in accordance with the 1995 and later editions of ASCE/SEI 7, breach of glazing or doors should not result in collapse from a design-level event. A breach may result in partially enclosed conditions, which could result in increased pressures, but the load/resistance factors or safety factors should be sufficient to avoid collapse.

The chain analogy also applies to the recommendations of the MAT reports that contain a universal thought process. For buildings to perform during storms, we must start with proper design requirements; select materials, products, and systems to meet the design criteria; and include appropriate oversight to ensure that the proper construction techniques and installation instructions are followed. This means that building designers, manufacturers, contractors, and building departments all play a crucial role in the construction process. The industry has come a long way in improving building performance, but as we look to future enhancements, every link in that chain has to do its part. The following paragraphs address the previously summarized MAT report conclusions and recommendations.

- Inconsistently performed inspections of building enclosure components, despite the requirements of some jurisdictions

While inspections are in the purview of building code officials, industry stakeholders continue to create, update, and maintain reference and technical documents as well as edu-

cation modules to inform inspection personnel of proper installation of products.

- Insufficient securement of rooftop equipment (HVAC, hoods, rooftop-mounted photovoltaic arrays, etc.).

Damage from impact of rooftop equipment has always been a part of MAT report observations. However, as uplift design and roofing system securement have improved, damage as a result of the effect of unsecured rooftop equipment has become more apparent. With the increased use of roofs for the installation of photovoltaic arrays, not only has the amount of potential equipment increased, the securement of that equipment is more vital. As such, functioning electrical generating equipment contributes to the ability of the building to become operational after an event. FEMA's USVI Recovery Advisory 2¹⁰ provides guidance to avoid equipment blow-off, and USVI Recovery Advisory 5⁴ has specific information related to rooftop-mounted photovoltaic arrays.

- Damage caused by improperly installed products

Related to the need for inspections is the continued emphasis on proper installation. The IBC⁹ and the *International Residential Code* (IRC),¹¹ along with many adopted code provisions, reiterate the need to follow manufacturers' installation instructions. These, paired with the new training initiatives launched by several stakeholders, continue to highlight not only the need for proper installation, but the efforts by the roofing industry to address this issue.

- Particular issues with retrofits and re-covering/replacement installations where the main wind-force-resisting systems or wind vulnerabilities were either not adequately assessed or addressed

One of the fundamental accepted aspects of a building is that the building will typically outlast the roof installed on it. While roof re-covering or an entire roof replacement is anticipated, it is not anticipated that an assessment and retrofit mitigation effort on the underlying structure is often not required by code. While many industry experts will point to the requirements of such an analysis in the *International Existing Building Code*,¹² it is not as widely adopted as the IBC or IRC, which do not have the same assessment triggers. The *Florida Building Code*¹³ contains retrofit provisions

for the assessment of existing buildings during reroofing. These provisions have been the subject of considerable debate in recent code adoption cycles in Florida as the Florida Building Commission addressed concerns about the need to balance technical feasibility with mitigation efforts while considering the cost implications to building owners. The concerns surrounding mitigation of existing buildings, particularly for critical facilities, has been considered an important part of post-disaster response. In fact, FEMA P-2062, *Guidelines for Wind Vulnerability Assessments of Existing Critical Facilities*,¹⁴ was released in December 2019. It provides designers with guidelines for assessing the vulnerability of critical facilities, and is a tool for building owners, design professionals, and regulatory entities charged with developing mitigation plans.

- Damage from wind-borne debris, some originating from the roof

Related to the securement of rooftop equipment, damage from wind-borne debris remains a two-fold issue for low-slope roofs. First, the resilience of the roofing system to withstand an impact continues to be a consideration that design and consulting professionals need to evaluate during system component selection. Second is when a roofing system could become the source of such debris, such as with ballast or loose aggregate. Even though the *Florida Building Code* requires embedment levels of rooftop aggregate, damage to surrounding buildings from loose or dislodged aggregate was observed during the most recent events in Florida. The roofing system in question did not have any parapet walls, which is at the very core of the recently approved code proposal to the IBC. This approved table provides guidance on the necessary parapet heights to mitigate aggregate blow-off based on wind speed, building height, exposure, and aggregate size. As this provision is adopted by more jurisdictions, as with previous improvements to the code, future events will allow side-by-side assessment of buildings built before and after the provision is in place. 

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Ensuring Durability with Stone Restoration Techniques— Critical Decisions for Common Repairs

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ABSTRACT

Architects, engineers, and preservationists have been specifying restoration repairs of stone masonry and cladding for decades. Execution of these repairs has fallen to craftspeople with a range of stone masonry experience, who often receive inadequate or no expert guidance and instead rely on general industry practices. Although most professionals will agree on many of the basic design principles for commonly applied repairs, each project has unique parameters that can affect the final repair design and its ultimate service life. This presentation will be of interest to design professionals, as well as building owners, managers, and engineers tasked with maintaining buildings constructed of stone masonry or stone cladding. It will summarize best practices for designing and implementing repairs for stone wall systems, and will identify the key decision points that influence the type of materials and repair procedures that we use to optimize durability. The presenter will also challenge some commonly held beliefs regarding popular material choices and repair techniques, and highlight how, in some instances, minor changes in approach can make significant differences in repair performance. This presentation will be pitched at an intermediate level; some prior knowledge of exterior wall systems and stone masonry is recommended.

SPEAKER



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Matthew Farmer, PE, is a principal investigator on evaluations of buildings and monuments, concentrating his practice in the areas of engineering, design, investigation, analysis, and repair of masonry building enclosure systems. His experience includes institutional and commercial projects, as well as work on numerous historic landmarks. Farmer received a bachelor of science in architectural engineering and a bachelor of environmental design from the University of Colorado, and a master of civil engineering from Cornell University. He is a registered professional engineer in the District of Columbia, Maryland, and Virginia, and an active member of ASTM C18 (Dimension Stone), ASTM C27 (Cast Stone), and the Masonry Society.

Ensuring Durability with Stone Restoration Techniques—Critical Decisions for Common Repairs

Natural stone is perhaps the oldest and one of the most durable materials used in our built environment. While the stone type can range in hardness and durability, stone conveys a sense of permanence—literally and figuratively—that is not replicated by any other material. Throughout history, stone has been used to construct civilization's most prized and important structures in an effort to stand the test of time. Whether to build structures that symbolize our democracy, house our governments, pay tribute to our leaders, allow us to worship, or perform as critical infrastructure, stone is sought after as the material of choice (Fig. 1 and 2).

If stone is such a durable material, why then should we have to consider repairs at all? First, the inherent durability of stone extends the maintenance cycle, but does not eliminate it. The time between repair interventions can be substantially greater than that of other building materials (decades rather than years), but repairs will eventually be necessary. Often it is not the stone itself that is to blame for deterioration, but the manner in which it is used or attached to the structure that initiates the need for repair. Sometimes it is circumstances completely beyond our anticipation, such as a natural disaster or in-service damage from vandalism, that require us to repair even the most durable of our building materials.

Second, all stone types are not created equal for the environment in which we place them; for example, a sedimentary stone (such as brownstone) or softer metamorphic stone (limestone) will not stand up as well to harsher weather as an igneous stone, such as granite (Fig. 3), but may perform extremely well in a milder climate. Alternatively, limestone may perform well at a higher elevation of



Figure 1. The Washington Monument, Washington, DC. Construction began in 1848.

Figure 2. The Cathedral of Mary Our Queen, Baltimore, Maryland. Construction began in 1954.



a structure, but not at grade, where increased moisture and deicing chemicals are present (Fig. 4). Using a “weaker,” less durable stone for some applications does not automatically lead to repairs, provided the stone used is well suited, well detailed, and of good quality for the particular application.

Stone masonry mass walls can serve both as a primary structure and as a primary enclosure material. Repair of stone can be essential to maintain established, as-designed load paths; excessive deterioration can compromise structural integrity and risk partial or full collapse.



Figure 3. Granite is used as the base course of many limestone buildings.

Figure 4. Limestone at grade is prone to freeze/thaw-related deterioration and cryptoflorescence.



Figure 5. Large spall failure at a limestone cornice.

While it may not be a structural concern, deteriorated or unstable stone can be a safety hazard if present above an area where pedestrians or vehicles pass by (Fig. 5).

As an enclosure material, stone masonry mass wall assemblies often serve as the primary barrier between our interior and exterior environment. The walls prevent infiltration of environmental moisture and excessive air movement, plus they serve as thermal mass that buffers the interior environment against rapid heat loss or gain. Stone repair is necessary to maintain weather barrier integrity and prevent reduction in the quality of our interior environments (such as excessive moisture, humidity, or air infiltration). If left unrepaired, stone deterioration can also accelerate as more

of the previously protected and concealed stone surfaces are exposed to greater amounts of moisture.

TYPES OF STONE DISTRESS

The subject of this paper is the critical decisions that are necessary to design durable stone repairs; therefore, it is important to first understand some of the common forms of stone damage that can compromise its performance, accelerate its deterioration, or lead to more significant problems such as water leakage or structural failure.

The more common forms of stone damage that are repaired generally fit into the following broad categories.

Cracking/Spalling

A spall is a location where a piece of stone has broken off from the parent material, leaving a

void. An incipient spall is a piece of stone that has cracked and largely separated from the parent material but remains in place and at risk of complete separation.

Physical damage to the stone compromises its ability to carry load or facilitates excessive moisture or air infiltration (Fig. 6). Cracking and spalling are related in that cracks, depending on their geometry and proximity to stone unit joints or edges, can create a spall (Fig. 7).

Delamination

A delamination is the separation of a stone surface, typically along bedding planes, seams, or rifts inherent with the geologic formation of the stone. The binders are weakest along these planes; exposure to thermal cycling, moisture infiltration, and other environmental effects causes the outer layers of stone to progressively disengage from the inner layers (Fig. 8). In rare instances, delaminations can result from non-environmental causes, such as joint material incompatibility or loading.



Figure 6. Cracks that will allow water to enter the stone.



Figure 7. Incipient spalls located along a stone joint.

Stone repair is necessary to maintain weather barrier integrity and prevent reduction in the quality of our interior environments (such as excessive moisture, humidity, or air infiltration).



Figure 8. Failure of "face bedded" stone facade units along the bedding planes.



Figure 9. Displaced stone coping unit.



Figure 10. Displaced stone facade unit.

Displacement

Displacement is movement of a stone unit or portion thereof along a joint or crack boundary from its original position (**Fig. 9** and **10**). If the displacements are excessive, the load path can be compromised or the stone may be unstable. Displacements can be caused by sudden changes in load, corrosion of embedded ferrous metals, or impacts.

Joint Material Deterioration

Joint materials (typically mortar or sealant) serve several purposes in a stone assembly, including limiting air and water infiltration. Mortar is also used to transfer and evenly distribute load between stone units as well as bond the stones together to prevent them from moving. Joint material deterioration can lead to excessive water infiltration, stress concentrations as joint material between stone units breaks down, changes in load path, or stone instability (**Fig. 11** and **12**).

Strength Loss

Some marble varieties (and, to a lesser degree, other calcitic stones) lose strength over time. This is a result of hysteresis, a deterioration process whose primary symptoms are cladding panel bowing and disaggregation of the stone surface, commonly referred to as “sugaring” (**Fig. 13**). Thermal hysteresis is the permanent dis-

tortion of stone masonry units from differential expansion of one stone surface relative to another. The crystalline structure of the stone disassociates when heated and then does not return to its original position when cooled, resulting in asymmetric volume change and reduced strength. If the strength loss is excessive in mass masonry, stone damage, such as erosion cracking, anchorage failure, and instability, can result.

Erosion/Scaling

Largely an aesthetic concern, erosion results in the loss of detail

Figure 11. Failed joint mortar has led to water infiltration and efflorescence.



Figure 12. Failed sealant allows water to reach stone anchors and ultimately the building interior.



and material at the surface of stone, most often from constant exposure to water (**Fig. 14**) or airborne abrasives such as sand.



Figure 13. Weakening of a marble cornice due to hysteresis.

Figure 14. Surface erosion and scaling of granite.



Figure 15. Spall caused by corrosion of a stone anchor.

PARAMETERS FOR EVALUATING REPAIR TECHNIQUES

First and foremost, stone repairs should be performed if the structural integrity of the stone assembly is compromised or a risk to the public. If the stone assembly is unstable or load paths have changed, it is imperative that the condition be addressed quickly to avoid further instability or collapse. Temporary repairs, such as shoring or limiting access to portions of the structure, may be warranted until more-durable repairs can be designed and implemented. Any long-term repair strategy should include a sound method for re-establishing the load-carrying capacity of the stone assembly, whether it be the original load path or a modified path that meets the structural requirements.

Perhaps equally important to structural integrity when selecting a repair approach is to confirm that it will slow deterioration of the parent stone. Otherwise, what is the purpose of performing the repair at all? The purpose of the repair should be not only to replace or re-establish the original building fabric, but also to prevent (or at least substantially reduce) further deterioration of the fabric itself. For example, repairing a stone fragment caused by corrosion of embedded anchors without addressing the anchors will not stop the deterioration process, nor prevent failure of the repair and the surrounding stone (Fig. 15).

One must also consider the location and continuity of the existing load paths. If the damaged stone is loaded in bearing, the load path is likely already redirected away from the damaged portion and into the sound stone that remains. Adequacy of the surrounding stone should be verified for the applied load. If stone is damaged at a lateral anchor, it is recommended that the connection be abandoned and a new connection installed to avoid loading the repair, which is usually not capable of accommodating load.

A repair should be evaluated for its own durability and any effect on durability of the parent stone assembly. A repair that is not durable or that requires frequent maintenance may be worse than no repair at all, particularly if access to the repair location is difficult or expensive. A less durable repair may be inexpensive in the near term but can become costly once reduced service life and increased maintenance are factored in. Funding for subsequent repairs and maintenance are also often not known; therefore, a less durable repair may need to remain in place past its useful service life, risking repair failure and increased damage to the parent stone. The most durable repair appropriate for a given application should always be considered when evaluating repair options.

When evaluating repair approaches, one must also consider the potential risk of damaging the stone at or adjacent to the repair site as part of the process (Fig. 16). If the risk is too high or the repair too invasive, then perhaps the repair is not in the best interest of the structure. An alternative approach that may not directly repair the damage but that minimizes the potential for additional damage or slow deterioration may be a better option in the long run.

Whenever a decision is made about whether to perform a stone repair, its importance to the building fabric and its historical sensitivity should be evaluated. If the element is not consequential to the performance of the structure or historically important, and it presents an ongoing maintenance concern, then removal or redesign of the element might be considered as a repair option. However, if the condition is critical to protect other elements or is historically sensitive, then clearly restoration and perhaps preventive maintenance would be more appropriate. Cornices and water table features are examples of stone elements whose presence may be critical not only from a historical perspective, but also as a protecting element for the stone assemblies below (Fig. 17).



Figure 16. Minor chipping that would require a complex dutchman profile to repair.

Two of the most common drivers of stone repair selection are cost and aesthetics. Unfortunately, cost is a reality that any entity responsible for the care of a structure must contend with; funds are never unlimited. When evaluating repairs, it is critical to consider all the costs associated with them. These include the initial cost; required maintenance; life-cycle replacement (service life); access; and the relative cost of doing nothing, which will result in future (perhaps more extensive

or invasive) repairs. It is also important to consider the overall cost of not only the repair itself, but also the access to perform the repair. If access to repair areas is difficult or costly, then it may be more cost-effective overall to perform a more durable repair that may carry a higher unit cost but will require less main-

tenance and replacement over the building service life.

The aesthetics of a repair not only can significantly affect the overall appearance of a structure, but can also influence the motivation for the repairs in the first place. One of the most common misconceptions in stone repair is that the repair will look as good as or better than the original stone assembly, or that it will not be noticeable. This is rarely the case. Often the best aesthetic repair is to do nothing, as the "cure can be worse than the disease." When trying to market for repair funds, the aesthetics are often overpromised, and expectations that something old will look completely new again



Figure 17. A limestone cornice is vulnerable to weathering, but partially shields the limestone facade below.

are unmet. This disappointment can lead to reduced demand and subsequently reduced funds to support the repairs, which results in greater levels of deterioration due to deferred maintenance. Ironically, a successful repair program is often one where the repairs and modifications are not apparent, especially for historic structures (as further discussed in the following section). So it is critical to keep expectations regarding repair aesthetics realistic by communicating throughout the repair design process and encouraging early repair mock-ups.

TREATMENT OF HISTORIC STRUCTURES

In the United States, many stone structures are historic in nature and have been granted some level of landmark status that is accompanied by specific requirements for restoration and preservation. Work on landmark structures is largely influenced by local authorities having jurisdiction and the Secretary of the Interior's Standards for the Treatment of Historic Properties or similar local jurisdiction ordinances. While these standards go into great detail regarding the classification of treatment, limits on intervention, extent of replacement, and integration of new construction into existing historic assemblies, one can distill several simple tenets that are generally applicable to stone repair decisions and include the following:

- Retain as much original building fabric as possible.
- Design repairs to be reversible whenever possible.
- Minimize the level of intervention to only what is necessary to achieve the repair objectives.
- Differentiate any new construction from the original structure fabric, contrasting rather than blending the two types of assemblies.
- Use the gentlest repair or maintenance methods possible that achieve the minimally acceptable result. Avoid the temptation to overreact to the observed distress or damage.

COMMON REPAIRS AND CRITICAL DECISION POINTS

To address the types of distress identified previously, there are several common repair types that are used for stone masonry mass



Figure 18. Small spill on a stone tread; no consequential damage is likely if left unrepaired.

wall systems and older or historic structures. Many of these repairs also can be applied to more modern stone assemblies, such as stone cladding systems, though that is not the focus of this document. Each of these repairs seems relatively straightforward, but requires several critical decisions to be made to confirm the repairs are appropriate for the application and to optimize their implementation.

No Repair

One "repair" option that should always be considered is to do nothing. This is the benchmark by which all other repair options should be evaluated. Doing nothing has the advantage of no risk of damage to the remaining structural fabric, no initial cost, no maintenance, and no replacement cost (Fig. 18). For small-scale, isolated damage that does not draw attention, there is no reason to execute a repair. If structural stability is a concern, if a lack of repair will accelerate deterioration of the remaining structure fabric, or if the appearance of the damage is unacceptable (Fig. 19), then doing nothing may not be a wise option.

Dutchman

A dutchman is a piece of salvaged or new stone that is carefully cut and fitted precisely into a carved opening within an existing stone unit to replace a damaged section. It is important to understand that by the nature of excavating the damaged



Figure 19. Small incipient spall near joints that will contribute to water infiltration if left unrepaired.

portion of the stone, the load path no longer travels through the damaged section and will not load the dutchman.

Before proceeding with dutchman repairs, it is important to assess the potential sources of stone for use as the dutchman. New stone of the same variety as is being repaired will frequently appear significantly different from the original stone due to variations in weathering, quarrying, and material source (Fig. 20). Often, newly quarried stone of varieties with more color variation tends to blend better with the original stone. It is also possible to improve

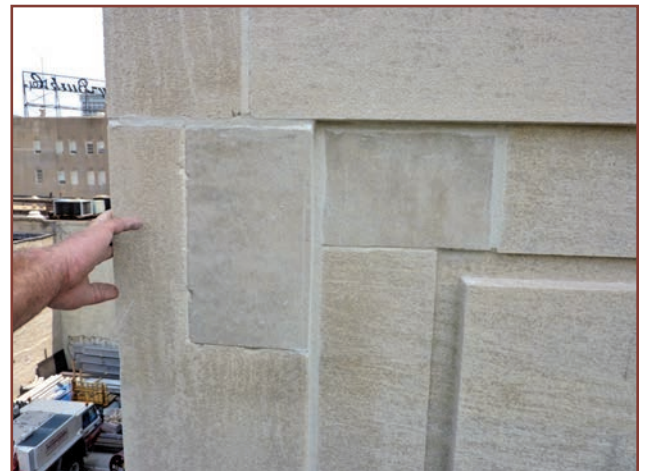


Figure 20. New limestone used as a dutchman.



Figure 21. Salvaged granite used as a dutchman, then microabraded to simulate weathering.

the blending of new stone with the old by artificially weathering the surface to better match the texture of the original weathered stone (Fig. 21).

One of the best options for dutchman stock is salvaged stone from the structure; salvaged stone comes from the same source, has typically been in service for the same period of time, and has experienced similar weathering patterns. Often it is better to remove stone for use as a dutchman from locations on the structure that are less visible (for example, backs of parapets, roof structures, and interior sides of columns) to use at more prominently located repair locations. The areas where the salvaged stone is removed can be repaired with newer and perhaps less-well-matched stone. It is important to determine whether the repair appearance is important enough to warrant the increased expense of removing and the salvaged stone and repairing the source location.

Dutchman repairs rely on initial bond of the joint material and shear friction facilitated by completely filling the perimeter joints. To maximize shear friction, the excavation made to fit the dutchman should be rectilinear and have sharp edges perpendicular to the stone surfaces. If the sides are sloped inward, the perimeter shear friction is reduced, so stability relies on the bond of the joining material. To address the potential variabilities with installation that can affect stability, it is recommended to include mechanical engagement of the dutchman to the substrate. Using dowels or postinstalled anchors across the dutchman/substrate bond interface reduces reliance solely on the joint material as a binder and joint filler.

The size of a dutchman repair is determined primarily by the size of the stone area that is damaged, but practical limits to the size of the dutchman must also be evaluated.

A dutchman excavation that is significantly larger than the damaged stone area is economically wasteful and removes more of the original stone fabric than is necessary. Alternatively, a dutchman excavation that is too small may not allow enough room for the tools necessary to precisely trim the original damaged stone to receive the new dutchman. The dutchman itself must also be large enough to accommodate mechanical anchors to secure it into place. Sometimes postinstalling anchors is a better option than increasing the size of the dutchman sufficiently to accommodate concealed anchors (Fig. 22).

When determining the size of the dutchman and how much of the original stone to excavate, one should also consider the joints and how best to conceal the seams between the dutchman and the original stone. It is preferable for the dutchman edges

to coincide with existing joints, thereby reducing the visible edges of the dutchman. It is also critical to ensure any existing joints are maintained through a repair area and are not interrupted by the dutchman. Cracking can occur in the dutchman if the existing joints are not allowed to continue in their original configuration, which may require two dutchmen to be installed instead of a single dutchman (Fig. 23).

There are options and preferences regarding dutchman perimeter joint treatment. Traditionally, stone epoxy is used to bond the dutchman to the substrate. Using epoxy enables the joints to be narrow at the surface, helping to conceal the repair. However, the joint must be wide enough to facilitate full contact of the epoxy with the substrate and the dutchman. If the joints are too narrow, the adhesive may not spread, causing poor bond and voids that can retain water. If the joints are too wide, shrinkage during cure can reduce bond. Selecting the correct epoxy for the appli-

cation is also critical, as some products are sensitive to ultraviolet (UV) light, which can affect the surface color and integrity. Stability of the dutchman relies on the epoxy for adhesion and also to facilitate shear friction with the substrate. Over time, epoxies undergo shrinkage and lose adhesion, but a joint properly filled with epoxy will maintain shear friction between the dutchman and the substrate.

Some practitioners choose to use mortar at the dutchman perimeter joints instead of epoxy. Setting the dutchman with mortar like a masonry unit requires a more visible joint that must be packed from the exterior, but enables maintenance in the future by repointing. The stability of a dutchman set with mortar relies almost entirely on shear friction because the initial bond is minimal and it is subject to early drying shrinkage.

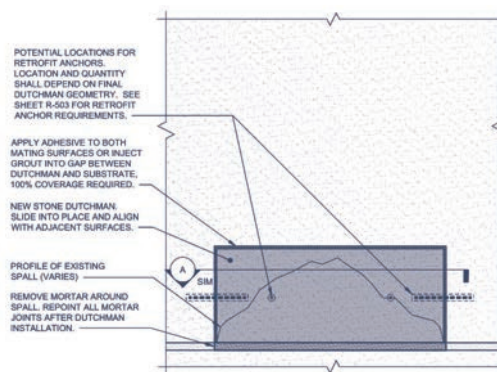


Figure 22. Schematic design for dutchman repair.

Fragment Reattachment

If a stone unit cracks and the stone fragment is recoverable, often the least invasive repair is to reattach it. It eliminates the need to match the stone, and often the fracture plane is sufficiently tight that the

repair is hardly visible. Reattaching a fragment is an option if the condition that caused the damage can be removed, the fragment is large enough to be removed and reattached intact, and the fragment surface is relatively undamaged along the fracture plane. Otherwise, a dutchman may be the better choice.

Because the fracture plane of a stone fragment is often oriented toward the outer surface

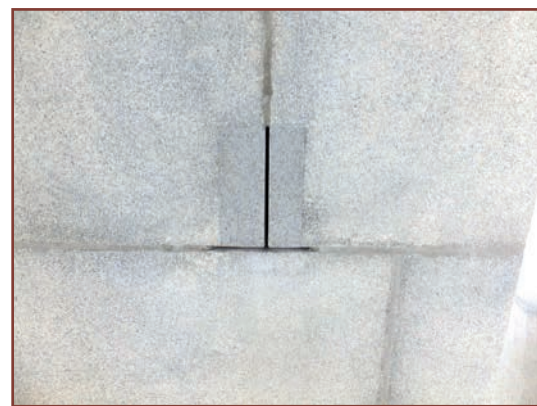


Figure 23. A dutchman repair that straddles an existing joint.



Figure 24. Reattached stone fragment.

of the stone or a joint (Fig. 24), shear friction cannot be relied upon to hold the fragment in place, and stone adhesive will lose bond over time, mechanical anchorage is critical to long-term repair durability. Larger fragments can be removed and reinstalled with anchors positioned across the crack plane. If the fragment is too oddly shaped or too small to preinstall anchors, the fragment can be first bonded into position and then small-diameter through-face anchors used to provide redundant attachment back to the parent stone unit (Fig. 25). If the fragment cracked away cleanly and remained intact, then a thin layer of stone adhesive is all that is needed at the stone mating surfaces. The “crack” at the stone surface will often not require any additional repairs for concealment, but if so, then it can be routed and pointed with a repair mortar that matches the stone.

Crack Grouting/Injection

Not all cracks require repair. There are really only two reasons to repair cracks: structural instability or excessive water penetration into or through the stone masonry. If neither of these conditions is of concern, then the risk of damaging the original stone during repair, the

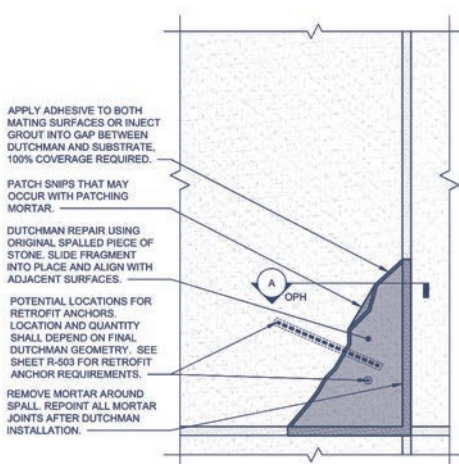


Figure 25. Optional anchorage placement for reattaching a stone fragment.

increased maintenance, or the diminished appearance may not be worth the marginal reduction in water permeance achieved by repairing the crack. One way to think of a crack is as another joint in the stone

assembly, and to determine what, if any, impact an additional few feet of joint will have on the performance of the stone masonry structure.

The primary task when evaluating cracks is to determine

their cause. Cracks can be considered either structural or nonstructural and each type needs to be evaluated differently. If cracks result from a failure of a load path, compromise the load-carrying capacity of the stone masonry, or enable fragments or whole stone units to become disengaged from the structure, they should be considered structural in nature and should command an immediate repair response. Most often the best repair approach is to grout the cracks solid. By grouting the separation, the ability to transfer compression through bearing and shear loads through aggregate interlock is re-established (Fig. 26 and 27).

It is always better to first consider re-establishing an existing load path than to attempt to rationalize an alternative load path because the as-built material characteristics of older stone masonry assemblies cannot always be well defined (Fig. 28 and 29). Using



Figure 26. Stone crack prior to grout injection.



Figure 27. Stone crack after grout injection.

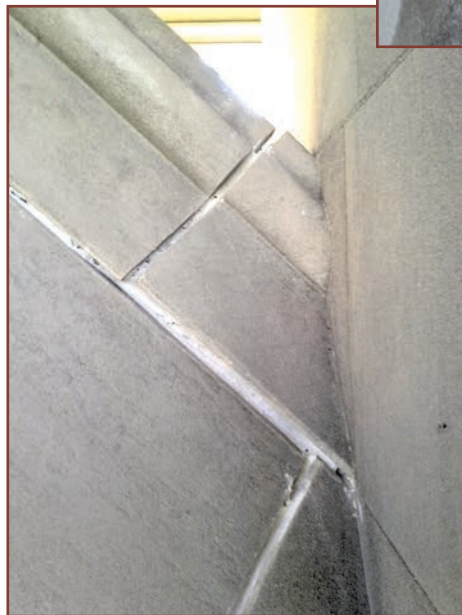


Figure 29. Grout has re-established load transfer across a previously open crack.

Figure 28. A critically damaged load-carrying stone element.





Figure 30. Craftsmen gravity feeding cementitious grout into a cracked joint.

cementitious and resin grouts with a high modulus of elasticity and compressive strength in excess of the stone masonry assembly being repaired is not recommended because the stiffer grout can concentrate localized stresses in the substrate stone. Unless the applied loads are increased and the original assembly was structurally inadequate, supplemental reinforcement is not necessary to increase system capacity and can be detrimental by increasing stiffness, concentrating load, and inducing localized cracking.

Gravity-feed and injection grouts are highly susceptible to mixing errors and our experience suggests that their actual physical properties often do not match the published values for strength, air content, and bond strength. If grouting is being relied upon for structural reasons or is being used in a challenging environment, then mock-ups and field sampling for quality assurance testing are strongly encouraged to ensure the selected materials are appropriate for use.

Also challenging with grout installations are monitoring and verification of flow. Depending on the complexity of the masonry system, the crack width, and the grout viscosity, the grout may not reach the desired depth in the assemblies or may flow excessively and wind up where it is not desired (**Fig. 30** and **31**). Monitoring the volume of the grout being used is critical and establishing volume expectations through trial repairs or mock-ups is essential to confirm volume estimates.

Cracks in stone masonry that are caused by restraint, minor cyclic movements, or a lack of accommodation of volume change, but that have no



Figure 31. Craftsman injecting resin grout into a crack.

significant impact on the load path or masonry stability, are considered nonstructural. Nonstructural cracks need not be repaired unless they are thought to be contributing to excessive water penetration.

Crack Pointing/Sealing

If the appearance of a crack (whether structural or nonstructural) at the surface of the stone is objectionable, the crack surface can be routed and filled with a patching mortar colored to match the stone. Joint mortar



Figure 32. Routed crack pointed with repair mortar.

should be avoided because it rarely is close to the original stone color and may not bond well to the routed edges. The width of the routed crack surface can be as narrow as feasible to minimize its appearance but still be wide enough to enable compaction of the patching mortar, preferably in lifts, to enhance mortar-stone bond (**Fig. 32**).

If increased resistance to water penetration at the crack surface is desired, elastomeric sealant and an appropriate backer can be used instead of patching mortar (**Fig. 33**). Patching mortar is usually less noticeable and more durable, but will typically crack along the bondline with the stone substrate due to shrinkage and differential movements caused by thermal changes. Sealant is more forgiving of substrate movement but has a more pronounced appearance and is often less durable due to loss of

adhesion with the substrate over time. Where cracks are expected to move significantly, sealant should be used to accommodate the crack width changes.

Joint Repointing

Repointing is the process of removing deteriorated mortar at the surface of masonry joints and replacing it with compacted lifts of new mortar. Similar to cracks, there are two main reasons to repoint stone masonry joints: loss of stone unit stability or excessive water penetration through the stone assembly. Repointing of stone masonry joints carries great risk of damage to the substrate stone from tools used by the masons to remove the existing mortar. The principal purpose of joint mortar is to enable stone masonry units to be set plumb and level. Because the mating



Figure 33. Routed crack filled with sealant.

surfaces of two stacked stone units will never be completely smooth, surface irregularities must be accommodated and the voids filled to reduce air and water penetration.

Stone masonry joints are often narrower ($\frac{1}{8}$ in.) than other unit masonry systems, which can make removal of mortar without damaging the stone extremely difficult. Stone is also often set with a higher-compressive-strength mortar, then pointed with a lower-strength mortar. An overly strong pointing mortar can create stress concentrations at the stone face and lead to damage or mortar failure (Fig. 34). The pointing mortar should also be designed with an appropriate aggregate gradation for the joint widths to facilitate compression and bond with minimal shrinkage. Material property testing such as that specified in ASTM C856¹ and ASTM C1342² is recommended at multiple locations to help estimate the compressive strength, as well as identify the binders and other constituents of the original mortar.

When mortar joints are exposed on horizontal surfaces, they are more susceptible to water penetration and deterioration. Often, sealant or lead joint fillers can be used at skyward-facing joints to reduce water entry into the joints and improve durability (Fig. 35). It should be noted that sealant requires periodic replacement to remain watertight and that lead joint fillers are not completely watertight, so avoiding the exposed mortar joints by flashing over them can sometimes be the best solution if the design can tolerate the visual changes.

Patching

One of the most cost-effective repairs available for stone masonry is patching with repair mortar. Patching is the process of applying a mortar with a proprietary blend of aggregates and binders into an excavated repair area. The patch material is then formed to the original surface profile, where it cures and hardens. Key to performance of the patches is the compatibility between the patching mortar and the stone substrate with respect to absorption and compressive strength, the ability to achieve and

maintain bond in spite of inherent shrinkage, and substrate preparation to promote bond and shear friction for stability. There is general consensus in the industry that patches should be of a minimum thickness, have rectilinear perimeters, and have sides that are perpendicular to the stone surfaces for developing shear friction (Fig. 36).

Because performance of patches is tied closely to substrate preparation, the minimum size of patches should provide enough space to achieve the preferred excavation parameters. However, if the patches are too large, material shrinkage can have a significant impact on bond, cracking, and ultimately stability of the patch. To reduce the risk of patch bond failure over time, adding mechanical anchorage across the bond interface is strongly encouraged so that if the bond fails, the patch can remain secured to the substrate until it can be replaced. Avoiding patches over areas where failure would pose a high risk or life safety concern is also recommended (Fig. 37).

Although patching can be cost-effective when compared

Figure 34. Failed joint repointing and widened joint.



Figure 35. Sealant installed at a skyward-facing joint. Note that the mortar is installed in the joint below.



with other repair methods, even the best patches may not meet owner expectations. Patches can change in appearance due to UV light exposure and variations in moisture content, experience plastic drying shrinkage (cracking), debond from the substrate, and ultimately require replacement sooner than other repair options.

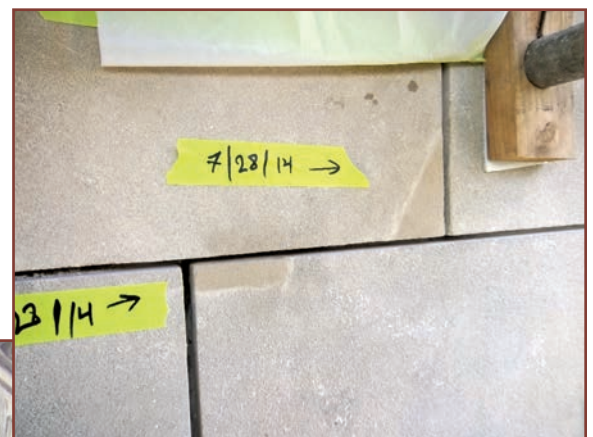


Figure 36. Properly installed stone patches.



Figure 37. Poorly installed and placed patch.

CONCLUSION

There are a number of critical decisions regarding appropriate selection and design of stone repair options that may not be readily apparent to design practitioners or craftsmen who execute stone repairs. All too often, stone repairs are performed without appropriate context, resulting in increased life-cycle cost for stone masonry assemblies. Carefully considering various stone repair options and the project-specific conditions affecting their implementation will result in improved repair service life, lower risk of future damage, and reduced life-cycle cost. 

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Small Unmanned Aerial System Applications in the Building Enclosure Industry: Using Thermal Imaging to Assess Building Performance

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ABSTRACT

In the architecture, engineering, and construction (AEC) industry, several disciplines have seen how small unmanned aircraft systems (sUAS) or drones can make critical, and sometimes dangerous, tasks more efficient, precise, and accessible. For example, drones can be used to perform thermal imaging scans to detect air, moisture, and heat leakage from a building enclosure—the glass, concrete, insulation, and other materials separating the inside and outside environments. Leaky buildings can be costly and dangerous, leading to damaged finishes, increased energy costs, and mold growth within walls and roofs. Infrared thermography is a relatively cost-effective, easy-to-use, non-destructive tool for these types of conditions, but the results require expert interpretation. By using drone technology correctly, AEC professionals can get detailed results to make informed recommendations that address underlying building concerns.

In this paper, we will explore how the AEC industry has implemented drone use to conduct thermal imaging scans of buildings, address some of the nuances of using drones around building enclosures, and discuss the differences of sUAS methods compared to handheld scanning techniques. We will review industry standards and guidelines and share common project challenges and opportunities through a series of case studies.

SPEAKERS



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Christopher N. Grey, PE, joined Simpson Gumpertz & Heger in 2011 and is a senior project manager in SGH's building technology group in Boston. His experience includes investigating, rehabilitating, and designing building enclosure systems on a wide range of project types, from historic buildings to contemporary high-rise structures. He specializes in the design, integration, construction administration, and in-situ testing of complex building enclosure systems with a focus on design efficiency, constructability, and performance. He works directly with architects, owners, contractors, and manufacturers in both the field and office through all project phases. Grey has performed many partial- and

whole-building infrared scans, assists with managing SGH's internal sUAS/drone usage and standards, is a certified sUAS Level I Thermographer, and is a contributing member of the American Architectural Manufacturer Association, serving on several industry standard task groups.



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Kelsey A. Dunn, PE, joined Simpson Gumpertz & Heger in September 2013 and is a senior staff engineer in SGH's building technology group in Boston. Dunn has been involved in a variety of projects involving investigation, design, and construction administration for existing building repair projects, rehabilitation of historic buildings, and new-construction building-enclosure consulting. She has performed many partial- and whole-building infrared scans using both the handheld and sUAS/drones while at SGH.



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Small Unmanned Aerial System Applications in the Building Enclosure Industry: Using Thermal Imaging to Assess Building Performance

Today's building enclosure systems are more complex than ever before, and, according to a study performed by ASHRAE, more than 84% of all construction-related claims, defects, and warranty callbacks are related to building enclosure (69%) and mechanical system (15%) design and/or installation issues.¹ Water infiltration, moisture accumulation, air leakage, and thermal bridging are among the most common and costly failures encountered in building enclosure construction, which can lead to damaged interior finishes, increased energy consumption, and mold growth within the walls.

Infrared thermography, or thermal imaging, which is often used to detect and determine the extent of water leakage into roofs and air leakage through the building enclosure, can also be used to detect thermal bridging, missing wall insulation, insulated glass unit failures, and concrete delamination.

Infrared thermography uses an infrared camera to identify differential apparent surface temperatures that can result from wet roofing materials, air leakage, missing insulation, or delamination. The thermal images display apparent surface temperatures, which are calculated in the infrared camera based on the relationship between emitted radiation intensity and a material's emissivity; therefore, the camera does not directly measure the temperature or moisture content of building materials. The interpretation of thermal images involves identifying patterns to differentiate between possible building enclosure leaks and thermal anomalies caused by other sources (e.g., variations in membrane thickness, penetrations, variations in concealed construction).

Historically, the architecture, engineering, and construction (AEC) industry has used thermal imaging as a tool to diagnose known building enclosure leakage issues in existing buildings. Building

owners and developers have become more cognizant of building enclosure performance and the risks associated with building enclosure leakage, and the industry is experiencing an increased demand for thermal imaging as a preventive quality control field test during the construction of new buildings. Many new construction and large-scale renovation projects now require thermal imaging to be performed on the roofing and exterior wall assemblies prior to project closeout. The new standard for building enclosure commissioning, ASTM E2813-18, *Standard Practice for Building Enclosure Commissioning*,² requires thermal imaging of the roofing assembly to achieve enhanced commissioning status and lists thermal imaging of the exterior wall assemblies as an optional test.

The AEC industry has used handheld infrared cameras to assess building enclosure

performance for many years; however, developments in small unmanned aerial system (sUAS or drone) technology have made thermal imaging safer, more cost-effective, and more accessible; have improved data clarity; and have expanded the range of thermal imaging applications in the AEC industry. Infrared scans that would have normally taken many hours to perform can now be performed in minutes while providing better quality, more comprehensive infrared images of the building enclosures (Fig. 1). Obstacles encountered when performing infrared scans using a handheld camera are minimized when using an sUAS; however, challenges and limitations still exist, and, as with any new technologies, sUAS use should be pursued with some level of caution. Successful sUAS implementation on projects requires training, experience, and certification in both sUAS piloting and infrared technology.

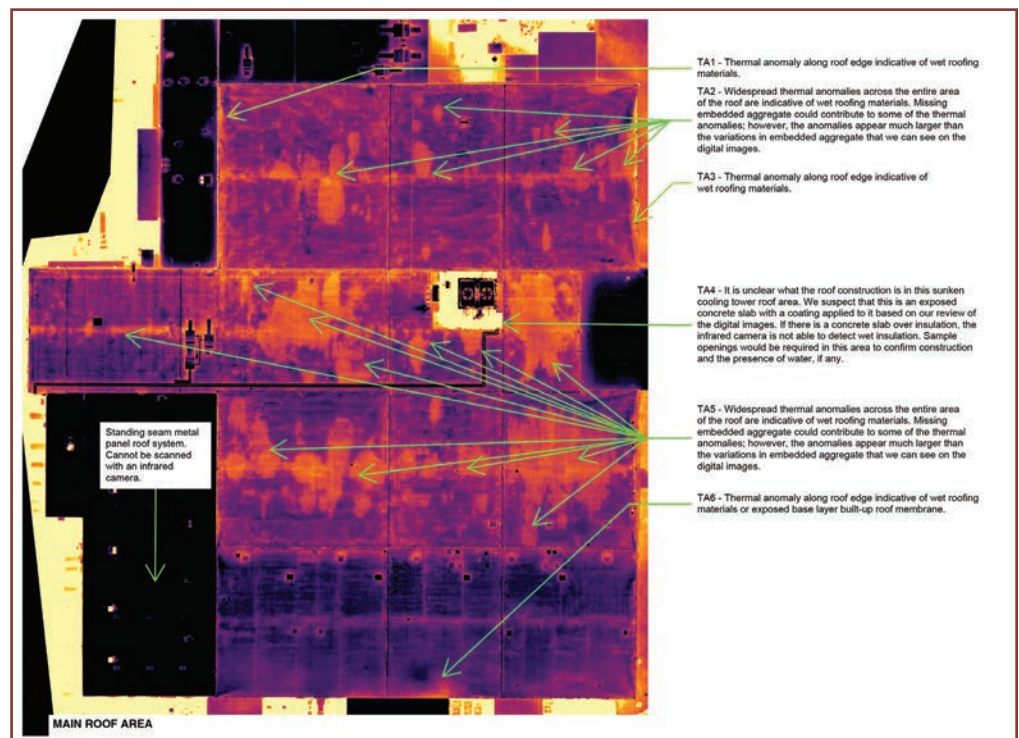


Figure 1. Infrared image of a roof composed of many images digitally stitched together.

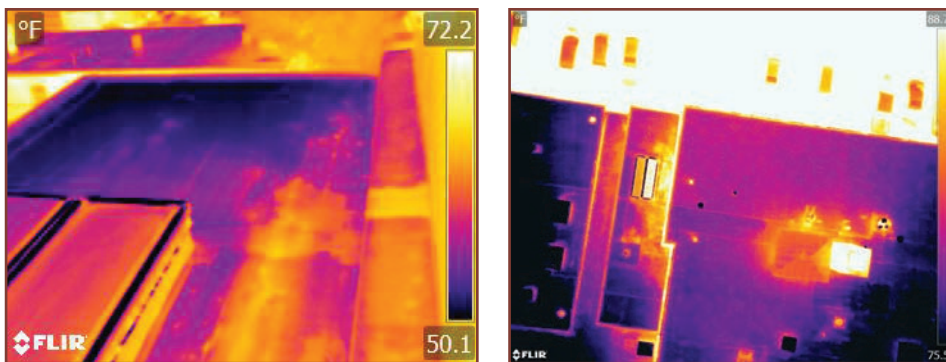


Figure 2. Infrared images from a handheld camera (left) and an sUAS-mounted camera (right).

ASTM STANDARDS

The two most common ASTM standards for test procedures involving infrared technology that we use on new and existing buildings are ASTM C1153, *Standard Practice for Location of Wet Insulation in Roofing Systems Using Infrared Imaging*³ and ASTM E1186, *Standard Practices for Air Leakage Site Detection in Building Envelopes and Air Barrier Systems*.⁴ Brief summaries follow. Refer to Grey and Wartman⁵ for additional discussion of the theory and challenges associated with these standards, as well as case studies.

ASTM C1153

ASTM C1153 outlines the necessary conditions and techniques employed to determine the location of wet insulation in roofing systems. This standard also addresses the criteria for infrared equipment, weather parameters, types of applicable roof construction, operating procedures, and invasive openings. It does not include determination of the cause of moisture or point of entry into the roofing system.

The scan relies primarily on solar exposure and the heat capacity differences between different building materials. During the day, roofing materials absorb heat, primarily due to solar exposure. At night, as solar exposure ceases and air temperatures drop, the roofing materials release the heat absorbed during the day. Water has a high heat storage capacity; therefore, materials that have absorbed moisture, such as insulation or cover boards that have been saturated by water infiltration, will cool at a slower rate than adjacent dry materials. As a result, the roof apparent surface temperatures above wet insulation will remain higher than surfaces above dry materials, until the roof surfaces reach equilibrium several hours after sunset. The concept behind infrared roof surveys is that visualizing these “warm areas,” or thermal anomalies, on the roof will identify approximate locations of potentially wet roofing materials.

ASTM E1186

ASTM E1186 covers the procedure for qualitatively locating air leakage in building enclosure and air barrier systems. The standardized practice does not determine the quantitative rate of air leakage but provides seven different methods for detecting an air leakage site, one of which is through the use of infrared technology. Air-leakage locations are identified by performing an infrared scan from the interior or exterior in conjunction with either pressurizing or depressurizing the building.

To detect air leakage using infrared scanning equipment, ASTM recommends that the indoor-outdoor temperature difference be at least 5°C (9°F). Air is moved through the building enclosure by depressurizing or pressurizing the building interior. As the infiltrating air enters or exits the building, infrared images will detect local interior or exterior apparent surface temperature changes. The larger the difference between interior and exterior temperatures, the easier it is to detect the thermal anomalies on surfaces associated with air leakage. The thermal anomalies resulting from air leakage are different from those associated with varied levels of thermal conductance in the enclosure, allowing air leakage sites to be identified.

BENEFITS OF USING SUAS

As thermal imaging has gained traction, sUAS technology has improved and become more accessible. Many industries, including the AEC industry, are finding new applications for sUAS that provide cost and time savings while also providing higher quality end products. Using sUAS to perform infrared scans of building enclosures has diminished the severity of many of the challenges associated with using infrared thermography to assess building enclosure performance. In the following sections, we discuss several of the common challenges and how sUAS technology has improved the process and results.

Time and Cost Efficiencies

Infrared scans of roofing assemblies using handheld cameras are commonly performed from the roof level, often from a ladder, which is moved around the roof to allow capture of thermal images from various locations at slightly elevated vantage points. This process is time consuming and requires building access, and there are inherent safety concerns as the scans are generally performed at night.

It typically takes several hours to perform an infrared scan of a roof using a handheld camera, whereas an sUAS-mounted camera can capture the same roof area in minutes due to the field of vision in the infrared camera, which is 15 degrees wide on a standard infrared camera. With this field of vision, the camera can capture approximately a 2.6 ft × 2.6 ft area of the roof surface at a distance of 10 ft (the approximate distance atop a ladder) when the camera is oriented directly perpendicular to the roof surface. However, the same camera can capture an approximately 26.7 ft × 26.7 ft area of the roof when mounted to an sUAS and flown 100 ft above the roof surface. Figure 2 shows an infrared image of a thermal anomaly at a roof leak taken with a handheld camera from a ladder and an infrared image of the same location taken from an sUAS.

Similarly, using an sUAS to perform infrared scans of the exterior walls greatly decreases the amount of time necessary to perform the scan, as the sUAS can fly around the building capturing images at regular intervals without requiring the thermographer to walk the entire building perimeter and reposition for each photograph. These time savings in the field provide moderate cost savings to the owner compared to a traditional infrared scan, as additional office time is often required to process and review the hundreds of images captured during an infrared sUAS scan.

Environmental Parameters

The effectiveness of the scan depends on several environmental parameters that can cause significant changes in apparent surface temperatures, which can reduce the thermal pattern intensity. ASTM C1153 provides guidelines for these parameters, including minimum inside-to-outside temperature difference, minimum daytime-to-nighttime temperature swings, limitations of cloud cover, maximum wind speed, roof conditions, and precipitation limitations within 24 hours leading up to the scan. This list of guidelines can make scheduling infrared scans difficult, as these environmental conditions can be hard to

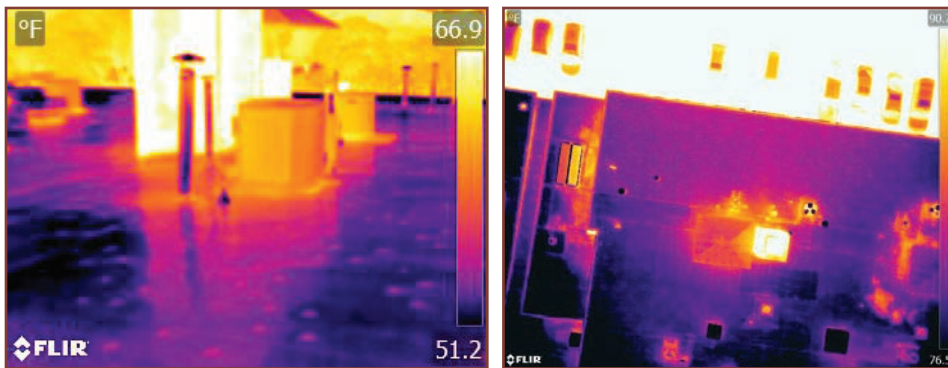


Figure 3. Infrared images of a roof taken by a handheld camera (left) and an sUAS-mounted camera (right). In the image from the handheld camera, the white arrow points to reflections cast onto roof; the white arrow in the sUAS camera image points to approximately same location but does not show reflections.

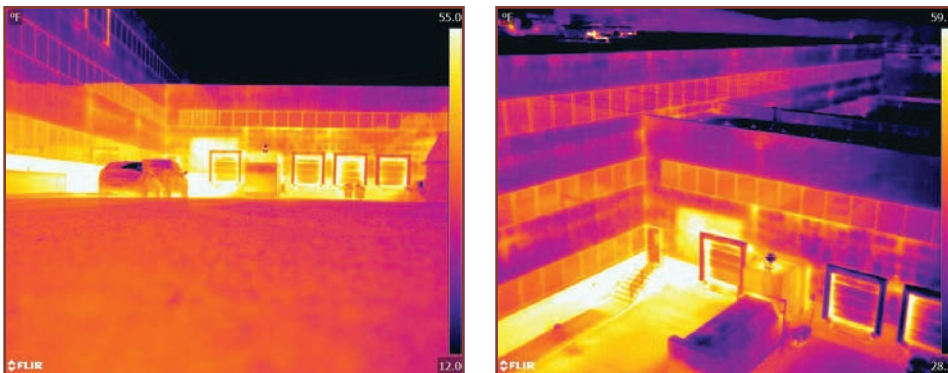


Figure 4. Infrared image from a handheld camera of an exterior wall showing reflections (left), and infrared image of the same wall, without reflections, from an sUAS camera (right).

predict accurately in advance.

The ASTM environmental guidelines must be followed more stringently when performing handheld infrared scans than when an sUAS is used. The infrared camera captures apparent surface temperature differences relative to extents of the camera's field of vision. When the infrared camera is mounted to an sUAS, the field of vision becomes much wider and the apparent surface temperatures are shown relative to adjacent materials over a larger area, which minimizes the effect of minor apparent surface temperature differences due to outside factors and reveals more widespread thermal anomalies associated with wet roofing materials or air leakage. This allows for the infrared scans to be performed during a wider range of conditions. In these scenarios, the ASTM environmental requirements are used as guidelines, with more emphasis on the thermographer's experience.

Reflections

Infrared images are most accurate when taken from a 90-degree angle looking directly perpendicular to the surface being scanned (reflective surfaces require a skew angle vary-

ing slightly from 90 degrees). Unfortunately, due to building geometry and limited access, achieving the ideal angle often is not possible, especially when using a handheld infrared camera. When images are taken from other vantage points, adjacent surfaces often cast reflections, or "thermal shadowing," onto the surface that is being scanned. These reflections can mask thermal anomalies associated with water or air leakage or result in false positives if the thermographer is not experienced with these types of scans. Scanning around reflections is common, and simply adjusting the camera angle can generally help determine whether the anomaly is a reflection or indicative of water or air leakage.

Compared with a handheld camera, an sUAS-mounted camera offers greater flexibility to take photographs from various distances and angles, thereby minimizing challenges

associated with reflections. **Figure 3** shows an angled infrared image taken from a ladder on the roof with thermal shadowing from a head-house on the roofing membrane, and an image of the same location taken from an sUAS at a 90-degree angle from the roof. The thermal shadowing does not appear in the image taken from the sUAS, and it is clear that there are no thermal anomalies potentially associated with wet roofing materials or air leakage at this location.

Similarly, **Fig. 4** compares an infrared image of an exterior wall taken with a handheld camera near grade and an infrared image of the same exterior wall taken with an sUAS-mounted camera. The first image shows reflections on the cladding from the adjacent wall, whereas the image taken from the sUAS minimizes the thermal shadowing on the cladding, even though the location has complicated building geometry.

Aggregate Ballast Roof Systems

Infrared surveys are useful for locating wet insulation in most membrane roof systems containing rigid insulation boards located below the roofing membrane. It becomes difficult to locate wet insulation when there is aggregate ballast over the roof membrane, as the ballast stores heat and inhibits the thermal anomalies on the surface of the roof. It is difficult to produce useful thermal images of ballasted roofing assemblies using a handheld camera unless significant water infiltration into the roof assembly exists, because thermal images may display thermal anomalies due to

Using sUAS to perform infrared scans of building enclosures has diminished the severity of many of the challenges associated with using infrared thermography to assess building enclosure performance.

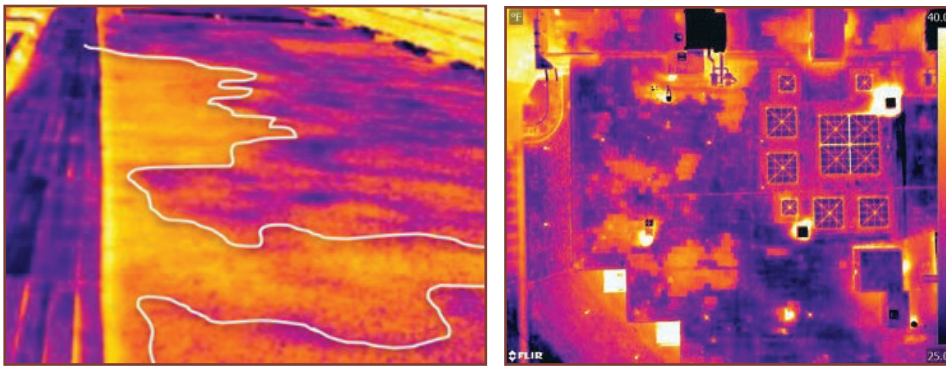


Figure 5. Infrared images of a ballasted roof from a handheld camera (left) and an sUAS-mounted camera (right).

variations in the aggregate ballast thickness or moisture content of the aggregate ballast instead of the apparent surface temperature of the roofing assembly below the aggregate ballast. The thermal patterns associated with aggregate ballast are often indistinguishable from “hot spots” associated with small, localized areas of wet insulation. Relatively new leaks are more difficult to discern from aggregate patterns than older leaks that have large, significantly wet areas.

Using an sUAS, each image typically shows a larger area than a handheld camera, which results in muting of the thermal anomalies associated with local variations in the ballast and reveals the more widespread thermal anomalies associated with wet roofing materials below. **Figure 5** shows thermal images of ballasted roofing assemblies taken with a handheld infrared camera and an sUAS-mounted infrared camera. The image from the handheld camera shows thermal anomalies associated with variations in the ballast, making the exact extent of the wet roofing materials difficult to determine. The infrared image from the sUAS was taken from approximately 150 ft above the roof surface, which muted the localized thermal anomalies associated with the ballast; thus, this image shows only the more widespread thermal anomalies associated with wet roofing materials.

The use of the sUAS allows the infrared scans to be performed on ballasted roofing assemblies where handheld infrared scans were previously not effective. It is important that building owners and clients be aware that even with the use of sUAS on aggregate ballasted roofs, only large, more significant issues will likely be visible, and that an infrared scan may not provide useful information, especially if there are areas of ponded water on top of the roof membrane. When surveying aggregate ballasted roofs, it is also critical that thermographers perform the scan under the best

environmental conditions possible, be able to differentiate between aggregate thickness and thermal anomalies, and potentially be able to adjust their camera angles to help mute aggregate variations.

Quality of Data/Ease of Analysis

In our experience, the quality of the data and deliverables provided by an sUAS infrared scan is superior to the quality of those provided by handheld infrared scans. Capturing larger areas of the roof in individual or stitched images allows design professionals to see a holistic infrared view of the roof that can be easily analyzed to identify larger patterns,

which are more difficult to discern when reviewing the many individual images typically provided using a handheld camera. This is due to the consistency of the images and the software available to aid in processing the data. Images taken with a handheld camera are disparate, as they are taken from different angles and sometimes different heights, depending on the available vantage points. Typically, the thermographer must review images from a handheld camera in real time and mentally process the data while on site performing the scan to determine if and where additional images are required at localized areas to identify larger thermal anomalies and patterns.

When using an sUAS, the thermographer typically has a mapped flight plan to ensure that the images are taken from the same height and angle from the roof. The mapped flight takes hundreds of images that overlap by 75% to 90%. Then the individual images can be stitched together in postprocessing to show the entire roof surface in one image. This allows the thermographer to review the building from a holistic view and identify leakage patterns and areas that require further review.

Based on our experience, we recommend that the thermographer provide a combination of stitched digital and infrared images with

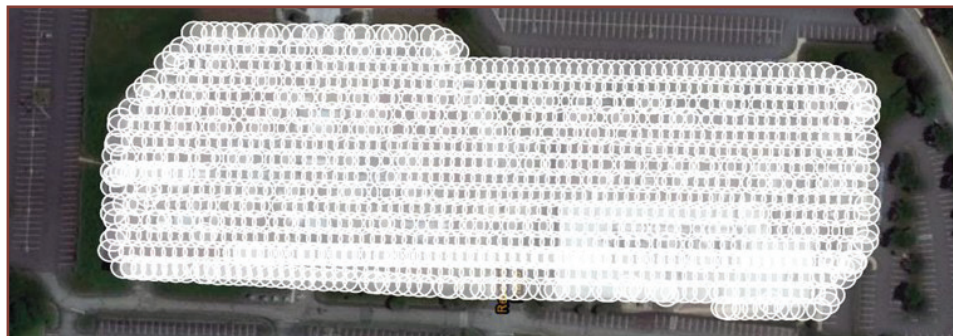


Figure 6. Image showing every photo taken during the mapping of a roof. Each white circle is one photo.

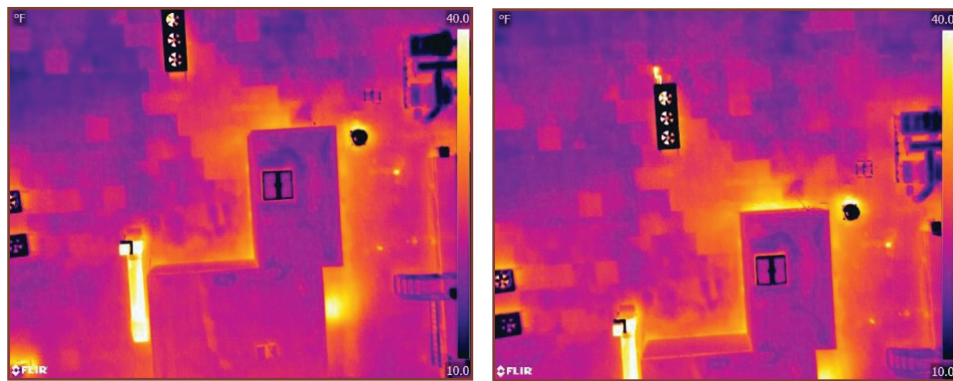


Figure 7. Sequence of infrared images in one area 50 ft above the same roof shown in Fig. 6, showing the extent of overlap required to create a stitched infrared image.

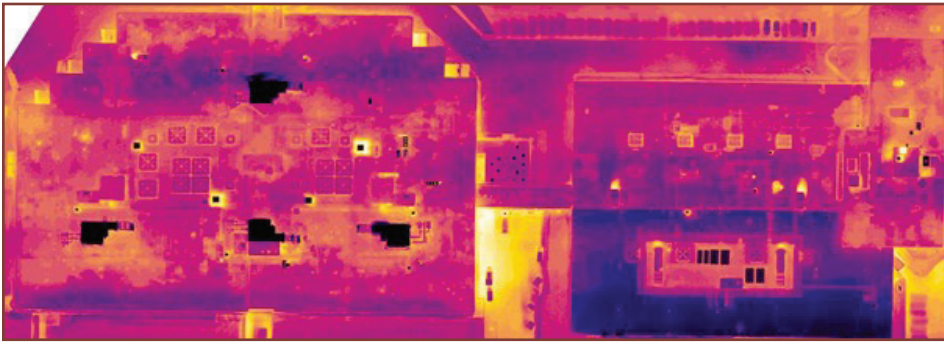


Figure 8. Fully stitched digital infrared image of the roof. The white box indicates the location where the three 50-ft images in Fig. 7 were taken.



Figure 9. Fully stitched digital image of the roof.

additional close-up images at problem locations, which allows the client or end user to compare the images and locate the observed thermal anomalies on the roof more easily. In addition, smaller thermal anomalies may appear more distinct in enlarged close-up images compared to the overall stitched roof images.

Figures 6 through 9 are representative of a typical deliverable from an infrared sUAS scan of a roof and include the mapping sequence. Figure 6, contains over 1000 close-up overlapped individual images (every white circle is an image). Figures 7, 8, and 9 show an individual image, a stitched infrared image, and a stitched digital image, respectively. These images collectively provide a visual representation of the extent of leakage within the roofing assembly. The stitched infrared image in Fig. 8 shows an existing roofing assembly with numerous large thermal anomalies (lighter yellow areas) associated with roof leakage. The image makes it clear that the water leakage is pervasive and that much of the leakage originates around mechanical units and other penetrations through the roof.

One challenge with stitching infrared images into one complete building image is that there is limited software available that can effectively stitch infrared images, which contain embedded complex data. Compared to a typical digital photo where each pixel contains

colors, each pixel of an infrared image contains measurable temperature data. As the infrared scan is performed, the roof is cooling at a rapid rate and, depending on the size of the roof, the thermographer may capture infrared images across the roof with varying temperature ranges. When comparing individual images, this is not an issue because the thermographer is focused on identifying and analyzing patterns rather than the temperature data. However, temperature variations from progressive cooling can result in thermal contrasts in different areas of the roof in the final stitched images, which makes analyzing and identifying thermal anomalies more difficult. For example, the stitched infrared image in Fig. 8 shows thermal contrast in areas where thermal anomalies are not present.

CHALLENGES

Many of the obstacles encountered when performing infrared scans using a handheld camera are minimized when using an sUAS; however, challenges and limitations still exist, and successful implementation of sUAS systems on projects requires training, experience, and certification in both sUAS piloting and infrared technology. The following challenges and obstacles affect how and when sUAS can be used. In some cases, performing a handheld infrared scan cannot be avoided.

Initial Requirements

All commercial sUAS operations are regulated by the Federal Aviation Administration (FAA) and require a certified operator to perform the work. Prior to September 2016, commercial operations required a Section 333 exemption, which required that the operator hold a pilot's license. In September 2016, the FAA enacted Part 107 of the Federal Aviation Regulations for non-hobbyist sUAS operations. The required Part 107 certification is acquired by paying a fee of \$150 and scoring a 70% or better on a 60-question multiple-choice test. Upon completion, the certificate holder is immediately authorized to perform commercial work in Class G airspace without additional permissions. Most infrared scans are performed at night and require a 107.29 Daylight Operation Waiver. This is obtained by submitting a request via the FAA's Drone Zone website (faadronezone.faa.gov) and providing a work plan with all relevant steps that the applicant will take to perform the work in a safe manner. Individuals with Part 107 certification must recertify every 24 months, a process that entails a similar multiple-choice test as the original certification. The Part 107 rules have simplified the path to licensure, which is why sUAS pilots are becoming more common in the AEC industry.

Building Location Challenges

The most important consideration when proposing an sUAS operation is the airspace restrictions at the project site. The FAA provides an ArcGIS UAS Map that outlines the most current airspace restrictions, including maximum allowable altitude above ground level. If a project is within proximity to an airport, some additional authorization may be required. Several airports participate in Low Altitude Authorization and Notification Capability (LAANC), which allows for instant authorization assuming that the flight will remain at or below the published altitude limit in the FAA's ArcGIS UAS Map and will be happening during daylight hours. If it is necessary to operate the sUAS at a higher altitude than the published limit, the operator will be required to submit a request through one of the LAANC providers, identifying the location of the operation and the reason for requesting to fly higher than the posted maximum. Depending on the region, the LAANC providers typically respond between two and seven days. Applicants who need to operate outside of daylight hours must have an approved 107.29 waiver and must submit an

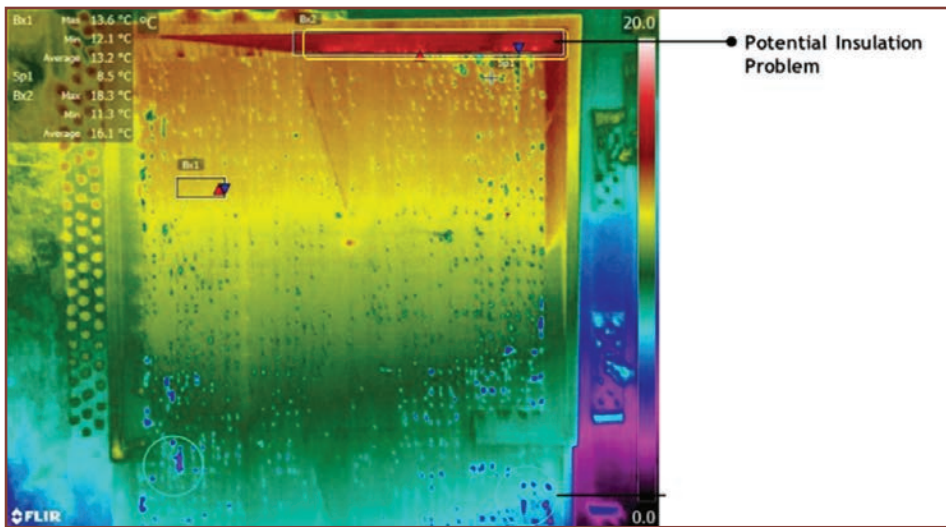


Figure 10. Infrared image taken under incorrect environmental conditions with an anomaly/insulation problem marked on a parapet wall.

airspace authorization request through FAA's Drone Zone portal, attaching the approved waiver. Because the response time for these applications will vary, it is important to submit applications as promptly as possible to ensure approval before the operation date.

Lack of Education and Certification

Some sUAS pilots performing infrared thermography services are experienced sUAS operators but lack knowledge about infrared technology. If they are unaware of the ASTM standards mentioned in this paper or lack an understanding of the fundamentals and theory of infrared scanning, their scans may be performed under incorrect environmental conditions or with an ineffective methodology, and the deliverables are not useful. **Figure 10** is an example of an infrared scan image from a report that indicates a deficiency at the parapet wall. A review of the data showed that the scan was performed at the wrong time of day: The warming of the parapet walls was not indicative of an insulation problem, as noted in the report. Rather, it was due to the early morning sunrise.

The Infrared Training Center (ITC) provides infrared certification courses with multiple levels of expertise. ITC certification focuses on understanding the science and fundamentals behind infrared technology so that it can be applied to a wide variety of services. ITC offers industry-specific training courses in addition to the basic infrared fundamental courses; however, these courses are not a substitute for having intimate knowledge of how building enclosures and structures are designed and constructed when one is aiming to diagnose thermal anomalies observed during an infrared scan. In most cases, a trained

infrared thermographer who has background knowledge in building enclosures can review thermal anomalies and differentiate air leakage or moisture issues from expected construction occurrences such as thermal bridging (e.g., cladding attachment systems that extend through the insulation layer). This background knowledge and ability to interpret the infrared data allows for a comprehensive report with clear recommendations for the owner's use.

Data Collection and Processing

As mentioned previously, performing handheld scans allows for real-time data processing. This provides an opportunity for the thermographer to mark the location of the thermal anomaly on the roof so that it is easily located. In most cases where an sUAS is used, the data processing and analysis are performed in office after the images are downloaded. This is not ideal because the thermographer misses

the opportunity to take additional infrared images and to survey the location of the thermal anomaly in person to review existing conditions, confirm that the thermal anomaly is indeed associated with building defects or deterioration, and then mark the thermal anomaly directly on the roof.

To permit real-time data processing using an sUAS, two controllers can be used, allowing the thermographer to monitor the sUAS infrared images in real time while the pilot focuses on flying. If the thermographer identifies a thermal anomaly, they can alert the pilot and take additional photos and perform a hands-on review of the anomaly.

If this is not done, infrared data should be captured several times to provide enough data to analyze during postprocessing. This includes performing a mapped scan (taken at roughly 50 ft above the roof) so that the images can be stitched, higher-up images that can be processed quickly in office to identify major thermal anomalies, and angled shots to help resolve any issues with reflections.

Another challenge with using sUAS to perform infrared scans is determining the appropriate elevation for capturing data. Industry standards do not provide guidance on the elevation at which the data should be collected. Similar to digital photography, the quality of the image is based on camera resolution and the distance at which the photo is taken. Entire roofs can be captured by operating the sUAS at 400 ft; however, because camera resolution is a fixed parameter, the quality of the infrared image is reduced. Flying lower results in substantially more and higher quality images to process. This can be critical for smaller thermal anomalies in the roof that may be missed if the pilot is flying too high. **Figure 11** shows

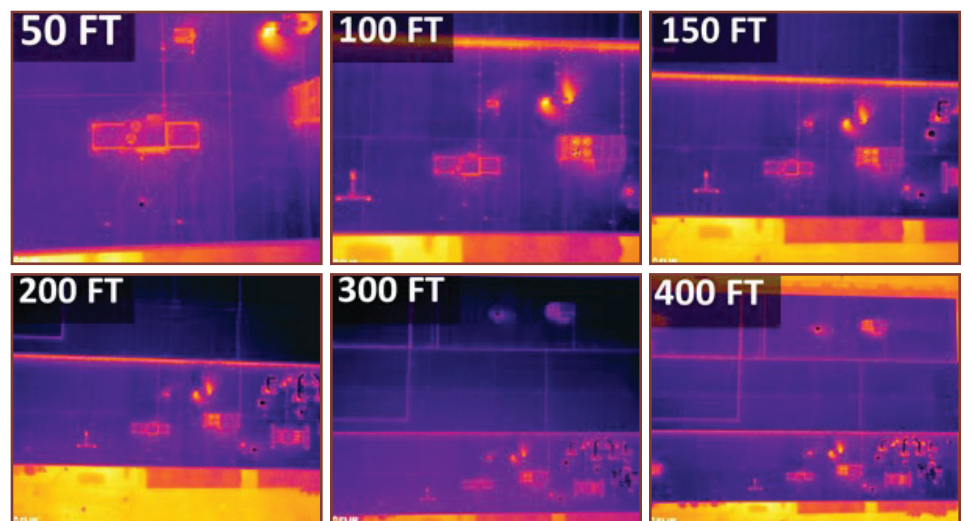


Figure 11. Infrared images of one roof taken at different elevations.

images taken 50 ft and 400 ft above a roof surface. In the image captured at 50 ft above the roof surface, thermal bridging is evident at individual fasteners; however, this is not visible in the image captured from 400 ft.

PROJECT CASE STUDIES

Quality Assurance/Control for New Construction of a Full Enclosure (ASTM E1186)

We performed an infrared scan of the exterior walls of a recently completed building enclosure using an infrared camera mounted on an sUAS as part of the commissioning closeout process. The owner required enhanced building enclosure commissioning on the project; therefore, an infrared scan of the roof was required. The owner also wanted an infrared scan of the exterior walls for additional quality control. The building is a steel-framed structure with a fiber-cement panel rainscreen cladding assembly, aluminum-framed windows, aluminum-framed curtain wall, and a single-ply polyvinyl chloride (PVC) membrane roofing assembly.

ASTM E1186 recommends that the pressure (positive or negative) across the enclosure be, at minimum, between 10 Pa and 50 Pa (0.20 lb/ft² and 1.04 lb/ft²) and that the temperature difference between the interior and exterior be at least 5°C (9°F). We performed a scan of the walls and roofing assembly under no pressure to obtain baseline images for comparison. To reduce setup time, we used the building's mechanical systems to positively pressurize and heat the building, allowing the mechanical systems to pressurize the building to a differential pressure of 174 Pa (3.63 lb/ft²) throughout most of the building. The scan was performed during winter with a 22°C (40°F) temperature difference between the interior and the exterior.

We performed both scans (pressurized and nonpressurized) of the exterior walls and the roof scan in four hours, including the time to pressurize the building between wall scans. By using an sUAS-mounted camera instead of a handheld camera, we greatly reduced the time it took to perform the scans and achieved better results, as we were able to capture images of the building from a variety of angles and heights. During the scan, we observed 44 thermal anomalies indicative of performance deficiencies. When we compared the images from the nonpressurized scan with the images from the pressurized scan, we observed areas with increased apparent surface temperatures

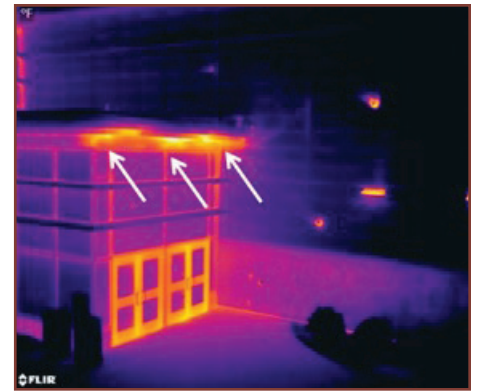


Figure 12A. Comparison of a nonpressurized infrared image of an exterior wall (left) and a pressurized image of the same exterior wall (right).

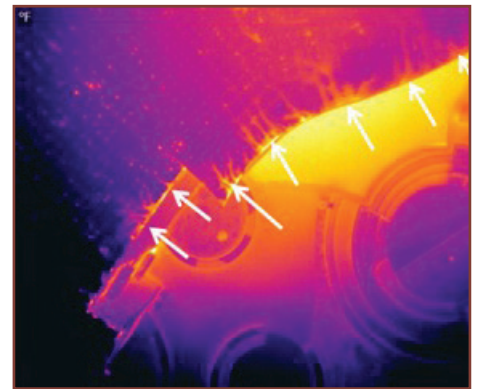
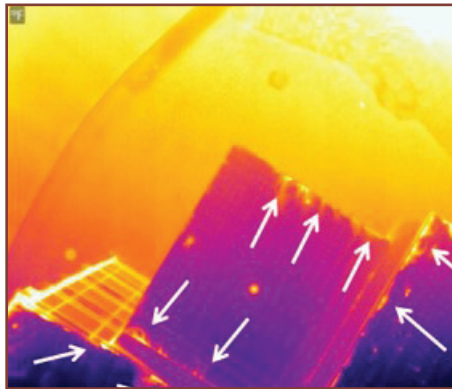


Figure 12B. Pressurized infrared images of a roof edge.

at transitions between the curtain wall and exterior wall assemblies and at the wall-to-roof transitions (Fig. 12A). Images from the infrared scan of the roof also showed air leakage from the wall-to-roof transitions (Fig. 12B), which indicates discontinuities in the air barrier and that the airflow through these locations increased when the building was pressurized. The increase of warm, conditioned air flowing through these discontinuities warmed the cladding materials adjacent to the discontinuity, leading to elevated apparent surface temperatures captured by the infrared scan. Although the owner elected not to remove existing cladding materials to investigate the apparent leakage, it is likely that the air barrier was not properly detailed at these transitions. Ongoing air leakage at these conditions may result in increased energy consumption and accelerated deterioration of the cladding and roofing materials due to condensation and trapped moisture.

Quality Assurance/Control for New Construction of a Roof Replacement (ASTM C1153)

On a new construction project where we were providing building enclosure consulting services, we performed an infrared scan

of a newly completed single-ply PVC roofing assembly. During previous site visits to review ongoing construction, we observed that the temporary tie-ins at the roof perimeter on a bridge connecting the new building to an existing building were not well secured. The owner reported leakage through the new roofing assembly before the building was completed. We performed an sUAS infrared scan of the roofing assembly to provide a quality control check and determine if water were present within the bridge roof where leakage had been observed.

We performed the scan of the entire building between 5:30 p.m. and 7:30 p.m., starting approximately one hour after sunset. The ASTM standard does not provide a minimum temperature differential between daytime weather and when the scan is performed; however, our firm generally uses 5.5°C (10°F) as a minimum. During the day, the weather had been clear and sunny with a maximum temperature of 2°C (36°F); however, the temperature during the scan was -2°C (28°F). Although we did not achieve our desired temperature difference, we were confident that we would be able to identify thermal anomalies due to the amount of solar radiation during the day and the relative height of the sUAS

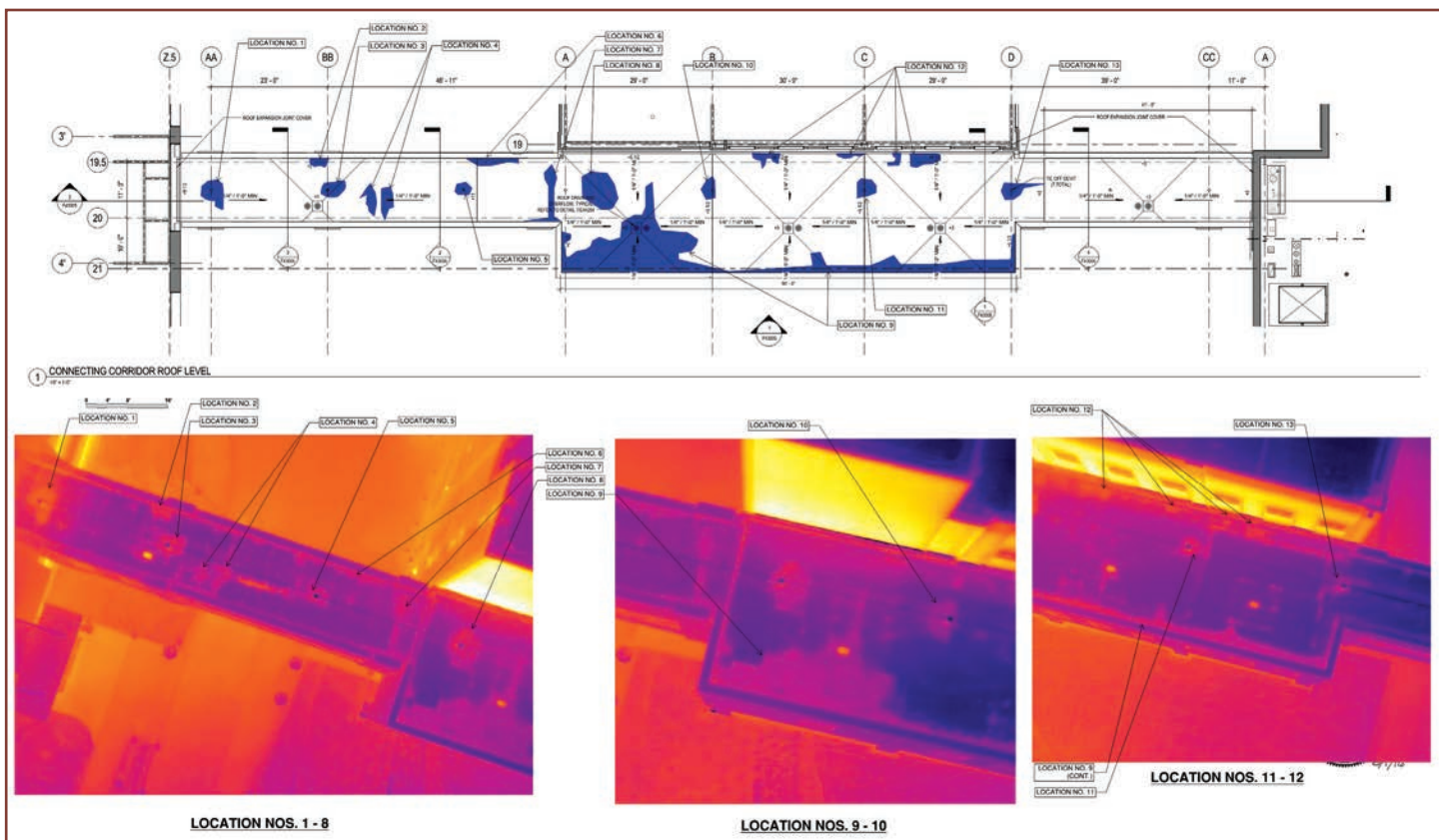


Figure 13. Marked-up roof plan with identified thermal anomalies (top), and three representative infrared images of thermal anomalies (bottom).

above the roofing assemblies. We discussed these conditions with the building owner, who elected to proceed with the scan.

The images from the scan showed thermal anomalies potentially indicative of wet roofing materials over a significant portion of the bridge roof (Fig. 13). The height of the sUAS and the 90-degree angle to the roof surface allowed us to take overall images of the roof that clearly indicated the extent of the anomalies. The project specifications required that after the scan, the roofing contractor had to return to the site, make openings at all identified thermal anomalies, remove all wet roofing materials, and repair the roofing assembly. If this had not been addressed, the moisture would have remained trapped in the roofing assembly and would have resulted in accelerated deterioration of the roofing materials and potential leakage into the building.

Existing Construction Investigation of Roof Water Leakage (ASTM C1153)

We were hired to design the roof replacement for a large apartment complex consisting of 46 high-rise buildings. Prior to our firm being engaged, a firm offering infrared thermography services performed infrared scans of all 46 buildings using a handheld camera and made recommendations to the owner

to replace all 46 roofs due to apparent water within the roofing system. The firm's reports contained minimal infrared data, stated that the roofs were wet without indicating that any follow-up confirmation was performed via test cuts (as required by the ASTM standards), and did not provide sufficient information regarding potential sources of water infiltration or the extent to which the roof was considered wet. The owner chose to replace all 46 roofs based on these reports. The roof replacement was intended to be phased over several years, with an intention to start with the roofs in the worst condition and end with the roofs in best condition.

However, we were not able to categorize the roofs according to severity using the reports

prepared by others based on images from a handheld infrared camera; therefore, we recommended that the owner perform new infrared scans.

The complex is located in a highly populated city area with a "no sUAS" policy, is within the vicinity of a major airport, and is in an FAA no-fly zone. Initially, we assumed that flying an sUAS above the roofs would not

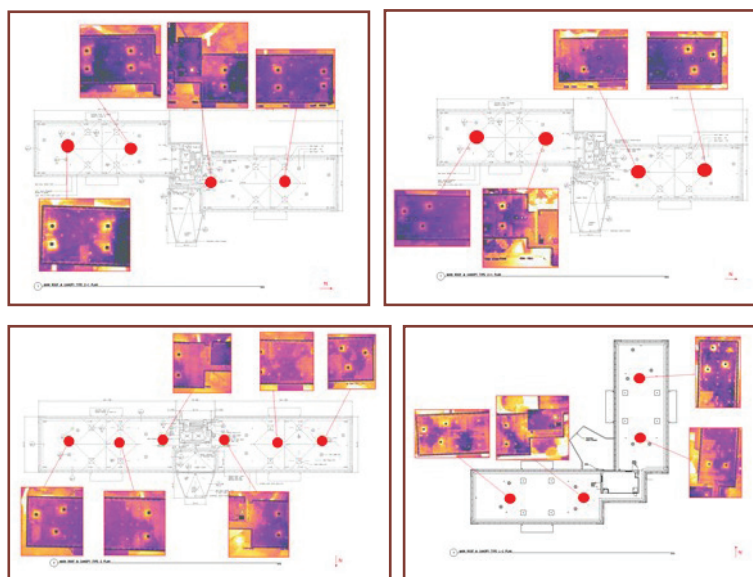


Figure 14. Representative infrared report images for 4 of 46 high-rise buildings investigated for roof water leakage.

be possible given the site's proximity to the airport; however, scanning all 46 roofs with a handheld camera would have required up to 15 nights (approximately three to four roofs per night) with weather conditions acceptable to scan aggregate-ballasted roofs. We contacted the local authorities and airports and determined that the runway that made this area an FAA no-fly zone was under construction and was thus not in use. This provided us a limited window of time to use sUAS to scan the 46 buildings, which we completed in two nights.

The roof area on each building was relatively small; therefore, we opted to capture images from approximately 100 ft above the roof level to expedite the capturing and analysis process. This resulted in four to six infrared images per roof, which could be processed quickly to provide a comprehensive understanding of the extent of the moisture within the roofing assemblies (Fig. 14). Our results were consistent with the handheld scans, which concluded that all the roofs contained wet insulation; however, by reviewing infrared data for the full roof area, we were able to more accurately quantify the area of wet roofing per roof (25%, 50%, 75%, etc.). Organizing the data in this way allowed us to rate the roofs based on the extent of apparent water leakage on an area basis and use that information to propose a phased approach for replacement.

The ability to rate enclosures or roofs based on condition is valuable for owners of multiple buildings, such as big-box retailers or universities. Since this project, we have used infrared to assess multibuilding campuses and inform capital planning efforts to help owners prioritize future expenditures for roof replacements and facade repairs.

CONCLUSION

Infrared thermography is a useful tool for cost-effective evaluations of various building enclosure systems. Owners can use infrared thermography as a quality control process on new buildings, to detect air or water leakage in building enclosures, to help diagnose known leakage issues, and to evaluate the efficacy of repairs, among many other applications. Depending on the application and scale, it may be prudent to consider use an sUAS, which eliminates many of the disadvantages associated with using a handheld infrared camera. Using an sUAS-mounted camera to take thermal images significantly reduces the time and cost of data capture, eliminates issues related to access and safety that are present when using a handheld camera at night, allows for scans to be performed during a wider range of environmental conditions, and improves the overall quality of images that are captured, resulting in a better end product for the client.

Though there are many advantages, the decision to employ an sUAS to perform an infrared scan must be carefully considered. It is critical to confirm that the sUAS operator is certified, trained, and educated on the applicable ASTM standards and understands the nuances associated with infrared thermography of building enclosures, and it is essential that the data can be collected in a way that it will provide the most useful deliverable for the specific project goals.

With any method of infrared thermography, proper verification is necessary for successful use. It is important for thermographers to understand the building enclosure components and environmental factors for scans to be successful and produce accurate informa-

tion. Test cuts should always be performed to verify both the results of the scans and the construction of concealed conditions. Infrared thermography is a powerful tool to aid in the evaluation of building enclosure performance, but it must be accompanied by additional verification and engineering judgment. 

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Roof-to-Wall Connections

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ABSTRACT

Many people feel that a roof assembly is automatically a roof air barrier assembly. A roof can be watertight but not airtight. The difference is the connections. If the roofing material has been connected to all penetrations and terminations, then the result may be a roof air barrier assembly. Places such as pipe penetration, curbs for equipment, and any other hole in the roof can be properly flashed but may also have gaps between the roofing material and the penetration, which can have huge air leaks.

The roof-to-wall connection, which is really a roof membrane-to-air barrier connection, is one of the most critical junction points in today's construction. Done correctly, it is a wonderful thing; done incorrectly, problems with air infiltration/exfiltration will occur. Moisture vapor transport resulting in condensation problems may ensue. A great deal of consideration must be given to how these two product technologies come together. The number of roof membranes, air barriers, and insulations that must come together properly can become overwhelming when divining the correct methods, materials, and sequence of construction. Chemical compatibility is a major concern, as is the correct way to tie-in the edge of the roof-to-wall connections. This paper addresses some of these questions and to provide some general guidance to the construction industry.

SPEAKER



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Roof-to-Wall Connections

As more states, jurisdictions, and design communities require air barriers, the issue of connecting the wall air barrier assembly to other building assemblies, such as below-grade waterproofing, window systems, and roof membranes, must be completely understood to design and construct a functioning building enclosure.

One of the most often missed or poorly executed details is the connection between the air barrier in the wall assembly and the air barrier in the roof assembly (Fig. 1). With a myriad of roofing systems and wall configurations and the growing number of wall air barrier materials, it can be difficult to navigate the process of determining which air barrier systems work best with each other and the chemical compatibility of these systems.

This paper will focus on design considerations as well as practical approaches to ensuring a robust connection is constructed and executed.

THE BUILDING SCIENCE

To understand why the roof-to-wall connection is important, we need to start with the basics. The construction industry and building owners are starting to understand the importance of incorporating an air barrier into the building enclosure. An air barrier is important to manage moisture and reduce energy costs, and to act as a barrier to pollen, allergens, noise, smells, insects, pollutants, and the list goes on. The number one reason to put an air barrier in your building is for moisture management; the most critical climate is hot and humid. We always consider moisture in a building that leaks into the building assemblies to be critical in a cold climate. However, if you calculate the amount of moisture transport for the same amount of air leakage in a warm, moist climate, you will get a greater amount of moisture transported. The amount of moisture in the interior air of a building in a cold climate at 70°F (21°C) and 35% relative humidity (RH) is significantly less than the amount of moisture in the exterior air when



Figure 1. Roof-to-wall transition “done incorrectly” with noncompatible materials and numerous voids.

the temperature is 98°F (37°C) and 95% RH.

The Air Barrier Association of America (ABAA) website¹ provides an energy savings and moisture transport calculator. Looking at three cities and three archetypes out of all those available, you can see the difference between water vapor transmission through a material

(referred to as perms) and the amount of water vapor that would go through a 1 in. (25 mm) square hole. Many design professionals want to use a high-permeance material to allow the building to dry. There is nothing wrong with this approach, but there are two problems with only looking at the permeance of a single material to determine whether water vapor could cause a problem in the building enclosure.

First, we must recognize the amount of water vapor diffusion we are talking about. Testing according to the code-required ASTM E96² desiccant test method shows the amount of water that will diffuse through a 10 perm material will be 16.6 oz (491 mL) per year. The desiccant test method uses a dish that must be at least 4.65 in.² (3000 mm²). The dish has a

desiccant in the bottom, creating 0% RH, and the material being tested covers and is sealed to the top of the dish so that any water vapor must go through the material. The dish is then placed in an oven that has a steady-state temperature of 73.4°F (23°C). This means that the material has 0% RH on one side and 50% RH on the other side, which is considered equal to 25% RH atmosphere.

Second, we need to understand that most water problems are not caused by the water vapor transmission rate of the material. Stopping liquid water from leaking into the building is the first line of defense. The second line of defense is to stop moist air from leaking through the building enclosure, which can change to liquid water.

WATER VAPOR TRANSPORTED BY AIR LEAKAGE

The ABAA calculator (Fig. 2) shows the amount of water transported by air leakage through the holes and cracks in a building over the period of one year. I randomly chose three different locations and a different archetype (reference building types) for each location (Table 1). The materials and construction specified for the U.S. Department of Energy’s reference building types are used to determine energy savings for building codes.³

The screenshot shows the ABAA website's calculator page. At the top is the ABAA logo and a navigation bar with links: Home, QAP, About ABAA, Newsletters, Join ABAA, Events, Education, Technical Information, Search Members, and Conference. The main heading is 'Energy Savings and Moisture Transport Calculator' with a subtext 'See how much you could be saving with an airtight building'. Below this is a section titled 'ABAA Energy Savings and Moisture Transport Calculator' which contains text stating: 'The Air Barrier Association of America, in conjunction with Oak Ridge National Laboratory (ORNL) and the National Institute of Standards and Technology (NIST) have completed the creation of a web based energy saving calculator for building airtightness. This new tool is available to everyone and is free!'. A large blue button labeled 'Use The Calculator' is centered. At the bottom, a small text block says: 'We are very excited to provide this resource to the industry to help quantify energy savings based on the use of air barriers and increasing the airtightness of buildings.'

Figure 2. Air Barrier Association of America energy savings and moisture transport calculator.

Location	Building type	Water vapor moved by air transport through a 1 in. ² hole per year, gal.
Tampa, Fla.	Secondary school	77.41
Bismarck, N.D.	Hospital	45.29
Fort Worth, Tex.	Large hotel	340.69

Note: 1 in.² = 645.2 mm²; 1 gal. = 3.785 L.

Table 1. Moisture movement by air transport

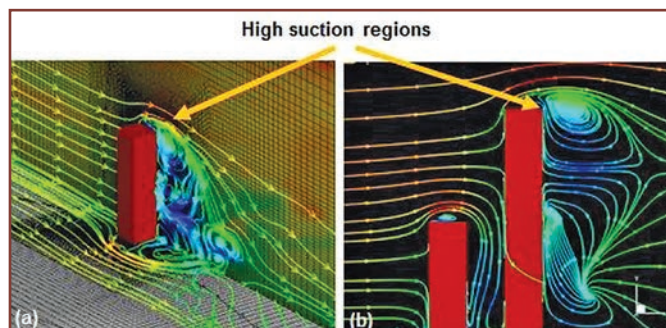


Figure 3. High-suction regions around buildings.



Figure 4. The author's house on the Gulf of Mexico.

Maximum building height above grade, m	Wind	Sustained 1 in 50 hourly wind pressure differences, Pa					
		450	550	650	750	850	1000
12	Cyclic	660	800	950	1090	1240	1460
	Gust	980	1200	1410	1630	1850	2180
20	Cyclic	720	880	1050	1210	1370	1610
	Gust	1080	1320	1570	1810	2050	2410
40	Cyclic	1340	1630	1930	2220	2520	2970
	Gust	2000	2440	2880	3320	3770	4430
60	Cyclic	1440	1770	2090	2420	2740	3220
	Gust	2160	2640	3120	3610	4090	4810
80	Cyclic	1530	1870	2220	2560	2900	3410
	Gust	2290	2800	3310	3820	4330	5090
100	Cyclic	1610	1960	2320	2670	3030	3560
	Gust	2400	2930	3460	3990	4530	5320
120	Cyclic	1630	2030	2400	2770	3450	3700
	Gust	2480	3040	3590	4140	4700	5520

Note: 1 m = 3.281 ft; 1 Pa = 0.021 psf.

Table 2. Sustained, cyclic, and gust wind pressure differences

People do not attribute the amount of water that is transported by air leakage to a building. They see liquid water and assume it is due to a leak or that it has been caused by water vapor transmission through the material.

WIND LOADS BY HEIGHT

If we go back to the physics, we know a hole and a pressure difference are required to move air through a building enclosure. Pressure differences are caused by the wind effect, stack

effect, and mechanical effect. On any given day, these three forces could be cumulative, or they may cancel each other out. As the wind, temperature, and how a building is operated can change by the hour, the amount of air leakage changes with the change in atmospheres.

The wind engineer who provided the calculations for the loading schedule for ASTM E2357⁴ also calculated the loads on a building based on its height (**Table 2**). The table references the 1 year in 50 year wind pressure differences. The work was done for the *National Building Code of Canada*⁵ and is included in its Appendix C.

The pressure difference at the top of a 394 ft (120 m) building is more than five and one-half times the pressure difference at grade. The taller the building, the greater the pressure difference and the greater the air flow through the holes and cracks. The greatest pressure differences on walls are at the top of the building, on the leeward side, and at the corners (**Fig. 3**).

Roof assemblies have different pressure profiles depending on their shape and construction. On the leeward side, the wind tends to pull the material off the building and at the same time, if there is air leaking into the building, that air also tends to push the material off the building. These two forces can not only compromise the air barrier system but also take roofs off buildings.

My Gulf of Mexico coastal house (**Fig. 4**) has weathered direct hits by Hurricane Harvey and Tropical Storm Beta with no damage and no water infiltration, as it has a robust

air barrier that can withstand both loads. Because it was properly constructed to my specifications, which exceeded those of the code, with a properly designed and installed air barrier system on both the roof and walls, my home can withstand high windstorms caused by hurricanes without any damage to the building.

THERE IS AN AIR BARRIER ON THE BUILDING

If a robust air barrier can remain intact even during hurricane conditions, why are we concerned about roof-to-wall connections? Experience from 2000 has shown this is the largest leakage area in the air barrier system.

Table 3 shows the calculation of the total number of component material combinations for wall air barriers. In addition, the ABAA evaluates the materials produced

Wall components	Types of material	Calculation
Three types of back-up walls	Concrete masonry units, oriented strand board, gypsum-based exterior sheathing	3
Seven types of air barriers*	Self-adhered sheet membranes, fluid-applied membranes, medium density closed cell polyurethane foam, mechanically fastened building wrap, boardstock—rigid cellular thermal insulation board, factory-bonded membrane to sheathing, adhesive-backed commercial building wrap	$3 \times 7 = 21$
Four types of insulation	Mineral wool, polyisocyanurate, medium density closed cell spray polyurethane foam, expanded and extruded polystyrene	$3 \times 7 \times 4 = 84$
Four types of cladding	Brick, metal panel, exterior insulation and finish system, cement board	$3 \times 7 \times 4 \times 4 = 336$
Total number of combinations		336

* According to the Air Barrier Association of America, airbarrier.org.

Table 3. Wall air barriers components and materials

by 43 manufacturers. Most manufacturers do not make every type of air barrier listed in Table 3, but there are 25 companies that make a type of fluid-applied air barrier material. The point is that we are dealing with a large group of materials that may not be compatible with one another, and this is just the wall air barrier materials.

As we move to the roof, roofing material may or may not be designated as part of the air barrier system (Fig. 5). Many wall air barrier materials can be used as the roof air barrier, then the roof membrane material can be installed over it. There are many different types of roofing materials; the most common ones are:

- single-ply: polyvinyl chloride (PVC), ketone ethylene ester, thermoplastic polyolefin, and ethylene propylene diene terpolymer;
- fluid-applied: inverted roof membrane assembly and polymer modified asphalt;
- polymer modified bitumen;
- steep slope (metal panels, shingles).

MATERIAL COMPATIBILITY

Roof-to-wall tie-ins have been somewhat problematic since air barriers became a code requirement. Chemical compatibility issues have been present in roof membrane-to-air barrier tie-ins since that time. These issues have been accelerated by the code-mandated use of continuous insulation, which in many instances alleviates the compatibility issue. As

air barrier systems came into use, I had a long conversation with a through-wall manufacturer of copper, stainless-steel, and synthetic flashings regarding this topic. This conversation evolved to become a full-fledged ABAA Technical Committee that is working on a chemical compatibility chart to provide guidance to design professionals. The chemical compatibility issue is a concern with all tie-ins; material suppliers should always provide letters of chemical compatibility of their material to adjacent materials.



Figure 5. Thermoplastic polyolefin membrane functioning as an air barrier in a hot climate zone.

ADDRESS THE PROBLEM HEAD ON

An example is the difference between the front side of the building and the rear side of a parapet on an administrative office building of a Fortune 100 company. The exterior walls are construction with light-gauge steel studs with R-13 batt insulation between the studs, 5/8 in. (16 mm) exterior gypsum sheathing, an ABAA-evaluated liquid-applied air barrier material, 1 in. (25 mm) of an ABAA-evaluated foil-faced polyisocyanurate insulation, and a metal panel façade. This assembly has an effective R-value greater than 13, which exceeds the energy code in the region where it is being built. It is also an ABAA-evaluated air barrier assembly and completely compliant with the code-mandated fire requirement of NFPA 285.⁶ The same manufacturer provided the air barrier and insulation and pro-

vided evidence that chemical compatibility issues are not a concern.

All is well on the front of the building. Unfortunately, all is not well on the back side of the parapet.

The construction detailing of the interior side of the parapet illustrates steel studs, R-13 batts, and 5/8 in. (16 mm) exterior gypsum sheathing, for an effective R-value of 6.6. Undoubtedly, this area is going to be highly energy inefficient. When there are cold exterior temperatures, the materials on the interior side of the parapet will have a colder surface temperature than the front of the parapet, which will cool the air that comes in contact with that surface. If the air is cooled enough, the temperature of the air surrounding the back side of the parapet can be lowered to the dew point—the temperature at which the air is cooled and becomes saturated with water vapor. When warmer, moist air leaks into the parapet and the dew point occurs, condensation will form on the materials and liquid water can work its way into the conditioned space, possibly causing mold and mildew. The

Roof-to-wall tie-ins have been somewhat problematic since air barriers became a code requirement.

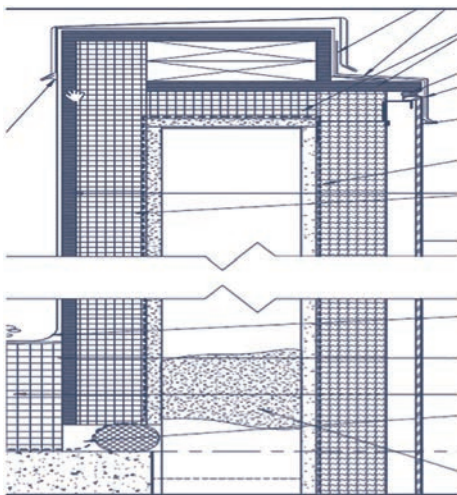


Figure 6. Insulation on both sides of the parapet.

liquid water may cause a stain on the interior finish, leading to reports of a “roof or window leak.”

This fix is a relatively easy design modification. Place 1 in. (25 mm) of the specified continuous insulation over the top and interior side of the parapet and now the entire building has the same thermal enclosure, with the same dew point profile on both sides of the building (Fig. 6).

The wall construction included a polymeric modified asphalt air barrier, which was to be directly connected to the PVC roof membrane. By adding the 1 in. of foil-faced polyisocyanurate insulation, the material can physically separate the asphalt-based air barrier from the PVC roof membrane, avoiding any possible incompatibility problems or premature failure.

LET’S TALK BEFORE STARTING WORK

The roof-to-wall connection at the top of the building is the biggest leakage area in most buildings. This is because 1) there is a high pressure difference, 2) there can be chemical compatibility issues with materials, and 3) this area is seen as the responsibility of “others,” meaning no one has been identified as responsible for doing the work properly.

We cannot change the pressure difference, as we have no control over the environment in which we build our buildings. We have no control, as a contractor, over the height of the building. However, our hands are not tied: we can start a conversation on the proper materials to use in the construction. We can discuss who is responsible for the roof-to-wall connection and what is the proper sequence for construction.

Preconstruction meetings are critical and

should be mandatory. This is where important questions can be identified and resolved, such as compatibility issues, the construction sequence for the project, which trade is responsible for the connection, and what other trades will impact performing the construction. It is much easier to deal with these issues “on paper” and clarify the issues before construction starts rather than having to redo areas after they have been constructed. The use of an ABAA Certified Air Barrier Specialist will go a long way toward ensuring the proper sequencing and details.

ROOFS CAN BE WATERTIGHT BUT NOT AIRTIGHT

Many assume that a roof is automatically an air barrier assembly. The roof must simply drain water. It is not intended to be a swimming pool and it does not have to be airtight; water just needs to be shed or drained off the building. Roof connections to penetrations in the roof are sometimes designed to shed water with flashing but have an opening for the penetration that is larger than the penetration allowing air leakage. These openings include the parapet, equipment curbs, expansion joints, and penetrations. A larger hole through the roof allows some movement of the penetration to properly align with the equipment being installed (Fig. 7).

Each detail must be evaluated for both airtightness and watertightness. There are basic details for these areas, but the actual site conditions will probably be different for each project, requiring a special detail for that building. If you apply the basics for an air barrier design, you can work through the issues and produce a detail that will work.

SOLVING THE PROBLEM

Everyone must be involved in the solution. Manufacturers of air barrier materials and roofing materials must provide the trade contractors with details on how to make the

air barrier part continuous using their materials. Design professionals must be clear on what material is to be a roofing material and if that material is also intended to be the air barrier material. The design team must also provide detailed drawings for the complicated details, preferably in three dimensions. The specification writer must provide detailed specifications as to who does what and what materials

to use where. The general contractor(s) must understand how complex an air barrier system can be and the importance that the air barrier is continuous on all six sides. The air barrier contractor must obtain all possible information and guidance from their supplier and understand the functioning of the air barrier system and location of the critical details. The installers need to have had a comprehensive training course on the type of air barriers that they will be install-

ing. Their knowledge, skills and abilities must be confirmed through an ISO 17024-accredited certification.⁷ The industries representing the air barrier industry and the roofing industry must work together to bring their collective knowledge together to produce materials that will educate and grow the air barrier industry. Figure 8 summarizes the main points to keep in mind.

CONCLUSION

This paper focused on roof-to-wall connections, as this is the largest leakage area in existing buildings. The physics applies to all building assemblies and all climate zones. Even within a single climate zone, there can be



Figure 7. Details for penetrations must be evaluated to ensure that they are airtight and watertight.



Figure 8. Things to remember.

cold winters and hot summers. In warm, moist climates, moisture-laden air is outside and leaks into the building, whereas in cold, dry climates, the moisture-laden air is inside. In both cases, moisture that gets into the building assembly and condenses causes the problem.

A building's mechanical system can add to or reduce the problem. In a warm, moist climate, if all the air is brought into the building through the mechanical system, cooled, and stripped of water, and the building pressurized, the mechanical system is helping to keep the building dry. In the same climate, if the mechanical system causes negative pressure inside the building, the warm, moist air is drawn into the building assemblies and causes the problems of mold, mildew, rot, and corrosion.

In cold, dry climates, the mechanical system has the same effects. If cold, dry air is drawn in through building assemblies and then heated, this air leakage helps keep the building dry. However, if the building is pressurized, warm, moist air is pushed into the building assemblies, where condensation can occur.

There is no single straightforward answer here. Building assemblies have to be properly designed to have the appropriate thermal performance, water vapor transmission rates, and no air or water leaks. The result is a building that performs as intended and does not run into unexpected maintenance and expensive repair costs. In other words, a building you would want to own or be a tenant in. 

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Thermal Bridging Analysis as Part of an Integrated Project Delivery

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ABSTRACT

There have been significant developments in methods to quantitatively evaluate building enclosure thermal bridging. As project teams are incorporating target value design and Lean principles through integrated project delivery, a thermal bridging analysis can add value to the project. An effective analysis quantitatively identifies thermal performance and condensation risk, while helping the project team determine the most cost-effective approach to meet project goals. The thermal analysis can be reconciled with the code requirements, owner's project requirements, energy modeling, and HVAC design to realize the full value. However, it is apparent that many project teams do not know how to efficiently incorporate thermal bridging analysis as part of project design. This presentation will summarize the technical aspects of thermal bridging and use case studies to show how the process is used effectively to achieve maximum value.

SPEAKERS



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Rick Ziegler, RRC, RRO, PE, is a professional engineer with over a decade of experience in the design, construction, and rehabilitation of building enclosures. His technical expertise is broad and includes thermal bridging analysis, energy code compliance, and roofing/waterproofing. Rick has consulted on existing buildings and new-construction projects across all market sectors throughout North America, Europe, Asia, and South America.



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Elisa Cheung, PE, is a building science consultant and professional engineer with an education from one of Canada's top universities. She has over four years of technical experience working on a variety of projects in the building design and construction industry. Her building enclosure project experience includes condition assessments, nondestructive and exploratory investigation, remedial design and construction administration, diagnostic water testing, and consulting on new construction projects. Cheung is passionate about her projects and loves problem solving to help her clients meet project performance goals.

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Stéphane Hoffman currently holds the positions of vice president and senior building science specialist at Morrison Hershfield. With master's studies in historic restoration that combines structural engineering, building science, and architecture, Hoffman brings a well-balanced consulting approach to the conservation of the building enclosure; blending scientific analysis with an understanding of aesthetic considerations. As a key technical leader, she has worked on projects throughout North America and led the expansion of Morrison Hershfield's building science practice in the United States.

Thermal Bridging Analysis as Part of an Integrated Project Delivery

For many years, predicting building enclosure performance has been qualitative. Building enclosure design and construction was largely based on experience. The design professional and construction team relied on standard materials they knew would work based on previous experience. Thanks to recent advances in the industry related to computer modeling and simulations, project teams are now able, more than ever, to quantify performance through computer simulations. Some tools, such as energy modeling, have made their way into codes and are now being used to demonstrate energy code compliance. Other tools, such as hygrothermal, computational fluid dynamics, and thermal modeling, are beginning to be used on a more regular basis to predict performance. This movement is expected to continue for two reasons: new quantitative methods using simulation tools to evaluate performance are equally accurate as and more cost-effective than empirical testing, and building owners want to know more about the value received for the money they spend on building enclosure construction, including maintenance issues such as anticipated performance, maintenance requirements, and useful service life.

This paper discusses maximizing value through integrated project team concepts related to building enclosure thermal performance and whole-building energy modeling based on recent advances in predicting quantitative performance. Effectively mitigating heat transfer across the building enclosure is beneficial for heating, ventilation, and air-conditioning (HVAC) performance, occupant comfort, operational efficiency, and condensation resistance. It has long been understood that to effectively condition an interior space, there must be sufficient resistance to heat flow across the building enclosure. Modern building enclosure construction often results in conductive materials that bypass the insulation layers and create thermal bridging, which can significantly decrease the effectiveness of the insulation. In practice, the nominal thermal performance of the multiple layers with thermal resistance must be reduced to an effective value. Commonly accepted reduction factors based on empirical testing

for typical construction, such as insulation within the clear field of a steel-stud cavity, have been available in the building code for some time; however, these reduction factors do not reflect most building enclosure construction at three-dimensional interfaces. The result of this disconnect, in the authors' experience, is overestimating thermal performance by 20% to 50% and increasing initial construction costs due to added insulation and wall assembly thickness with diminishing effects. Uncertainty regarding the actual building enclosure thermal performance can contribute to inaccuracy of energy models, oversizing of HVAC equipment, and/or inefficient designs. In addition to the lack of three-dimensional consideration within the current reduction factors, energy consultants often use incorrect assumptions for thermal performance, which can result in inaccurate life-cycle cost comparison. Additionally, mechanical engineers have historically applied significant safety factors to their design to account for unknown performance characteristics such as air leakage and thermal performance. This uncertainty is not the fault of energy consultants or mechanical engineers, but largely due to a lack of knowledge regarding thermal bridging and coordination between consultants during the project design phase.

While these advancements in quantitative evaluation using computer simulations have been beneficial for the industry, in the authors' experience, many project teams continue to wrestle with the process for effectively incorporating a thermal performance evaluation. Effectively incorporating available thermal performance guidelines and tools is key to maximizing value for the project. The authors acknowledge that the existing level of implementation and coordination of these tools are largely based on project complexity and local project team practices. This paper presents a flexible approach for thermal

performance evaluation that can be implemented on all types of projects, regardless of the project delivery method or performance goals ranging from code minimum to net zero. The approach can be especially beneficial to project teams that are incorporating target value design and lean principles through an integrated project delivery approach.

An effective thermal analysis should both quantitatively identify thermal performance and condensation risk, while providing the flexibility for the project team to determine the most cost-effective approach to meet project goals. The thermal analysis described herein should be reconciled with the owner's project requirements, energy modeling, code compliance, and HVAC design to recognize maximum value. Additionally, this paper provides an overview of thermal performance requirements in building codes and associated limitations, discusses useful thermal modeling tools and available industry guidelines, and summarizes the technical aspects of thermal bridging while using case studies to demonstrate how the proposed approach can be used effectively to achieve maximum value on any project.

An effective thermal analysis should both quantitatively identify thermal performance and condensation risk, while providing the flexibility for the project team to determine the most cost-effective approach to meet project goals.

OVERVIEW OF THERMAL PERFORMANCE REQUIREMENTS WITHIN CURRENT ENERGY CODES

It is important to begin with an understanding of current code requirements related to thermal performance and how energy code compliance is demonstrated. By understanding the options allowed by codes, project teams can incorporate the method to demonstrate code compliance with other project goals.

Thermal performance is generally measured with R -value (resistance to heat flow) or the inverse, U -factor (heat flow). Most building products, especially those intended for thermal performance such as insulation materials, will identify the R -value as determined typically through guarded hot-box testing per ASTM C518, *Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus*,¹ performed in a laboratory. Guarded hot-box testing generally consists of a box with warm temperature on one side of a test specimen with a cold box on the opposite side. The heat flow is measured across the specimen by dividing the heat flow rate through the specimen by the area times the temperature difference.

Many states currently require compliance with the 2015 *International Energy Conservation Code* (IECC)² or the 2018 IECC,³ with some states following older versions of the code. These codes provide the following three options to achieving code compliance for thermal performance ranging from prescriptive approach to whole-building energy modeling, which differ in flexibility for design options.



Figure 1. Photograph of exterior insulation with continuous metal Z girts installed through insulation.

Option 1: Prescriptive (Section C402.1)

The prescriptive path requires that each building enclosure system meet the minimum code-specified performance criteria as identified in the 2015 IECC or ANSI/ASHRAE/IES Standard 90.1-2013.⁴ Since the 2012 IECC and ASHRAE 90.1-2010, continuous insulation has been required for all eight North American climate zones if the project team demonstrates code compliance with the prescriptive method. The R -value method in the prescriptive path provides specific assemblies that are based on continuous insulation as defined by the code. Other methods to demonstrate code compliance do not specifically require continuous insulation for these assemblies. The most recent versions of IECC define continuous insulation (ci) as “insulating material that is continuous across all structural members without thermal bridges other than fasteners and service openings. It is installed on the interior or exterior or is integral to any opaque surface of the building envelope.”⁵

For assemblies such as walls and roofs, Option 1 allows for a component R -value method or the U -factor method:

- Component R -value method (C402.1.3): If using the R -value method to demonstrate code compliance, the assembly must meet the specified R -values for the assembly described. For example, this approach would require R -7.5 continuous insulation (ci) and R -13 insulation in the steel-framed wall cavity for climate zones 3 to 8. In the authors’ experience, using the prescriptive R -value approach is often challenging as achieving continuous insulation can limit options for supporting the exterior cladding (e.g., nonthermally broken, conductive continuous Z girts cannot be used). The component R -value method is the only section of the code that requires continuous insulation. If using any of the following methods, while exterior insulation is likely needed to meet thermal performance, it may not need to be truly continuous insulation. For example, assemblies that use continuous exterior metal

girts that bypass the exterior insulation would not meet the prescriptive definition of continuous insulation but may be acceptable per other methods that use a U -factor calculation (**Fig. 1**).

- U -factor method (C402.1.4): The assembly must meet the maximum specified U -factor. Current codes do not provide much guidance on how the U -factor is calculated, nor to what extent thermal bridging must be accounted for beyond typical clear field thermal bridging such as insulation placed within steel-stud framing. Most practitioners rely on the *ASHRAE Handbook – Fundamentals*⁵ and the information provided therein that describes the parallel path method, the isothermal-planes method, and the zone/modified zone method. The authors have largely interpreted the U -factor method to require a calculation to show how the U -factor has been determined, including reductions in the effective thermal performance due to thermal bridging. The methods given in the ASHRAE fundamentals handbook do not account for additional heat loss at interfaces between systems. There is generally more flexibility with the U -factor method; however, each individual assembly must comply with the maximum U -factor (e.g., a lower-performing wall cannot be traded off against a higher-performing one).
- To assist in quantifying thermal bridging impacts, in the recent versions of IECC, Table C402.1.4.1 provides reduction factors and effective R -values for insulation placed within steel-stud wall cavities for Option 1. However, this does not account for the majority of thermal bridging conditions in a typical building, such as cladding attachments and/or supports, window perimeters, and parapets.
- While the prescriptive option appears to be relatively straightforward to implement after initial review, it is the authors’ experience that this method provides the least flexibility for building enclosure assembly options. The main disadvantage of the prescriptive path is that one must comply with all the prescriptive requirements of the code and therefore it lends itself only to simple, straightforward building assemblies and components.

Option 2: Component Performance Alternative (Section C402.1.5)

In this approach, the performance of the proposed building is evaluated against a code-compliant baseline building. The building enclosure component performance alternative method (also commonly referred to as “trade-off method”) allows higher-performing assemblies to make up for lower-performing assemblies (referred to as trade-offs). For example, if the area-weighted opaque wall thermal performance is worse than the prescriptive requirement, this may be acceptable provided that the area-weighted thermal performance of other assemblies, such as the roof and windows, are better than the corresponding prescriptive requirements. This method only allows trade-offs within the building enclosure systems (for example, a lower-performing building enclosure cannot be offset by a higher-performing mechanical system).

- Section C402.1.5 of the IECC outlines a weighted average approach that incorporates fenestration and opaque areas in the thermal performance calculations and prescribes maximum allowable fenestration areas within wall and roof assemblies. Glazing ratio is also in the prescriptive path, but within Option 2 it can be changed to accommodate the design.
- Many states and jurisdictions allow use of a spreadsheet or other tool to demonstrate compliance using the trade-off method. In the authors’ experience, this method is the commonly used approach to demonstrate code compliance for relatively straightforward building enclosure assemblies. When using these tools, the design team can input thermal performance for building enclosure systems using *R*-values or *U*-factors, similar to the prescriptive option. Using *U*-factors usually allows more flexibility in design options (and assembly thermal bridging is accounted for as required by code) compared to *R*-values, as the *R*-value method requires continuous insulation for opaque walls and roofs.

Option 3: Total Building Performance (Section C407)

For more complex buildings that do not meet one or more prescriptive requirements that cannot be offset with other systems within the performance category to meet the baseline building performance, a whole-building

energy model can be used to demonstrate compliance, provided that the energy used is equal to or less than the baseline code minimum performance. Performance-based compliance requires demonstrating that the annual energy cost of the proposed building is less than or equal to the annual energy cost of the standard design (baseline). The performance-based method requires the development of an energy model. It allows enhanced HVAC and lighting systems to be traded off against lower-performing enclosure components (or vice versa) and is the most flexible of the three options summarized.

SIMULATIONS OF THERMAL PERFORMANCE

Regardless of the method selected to demonstrate code compliance for thermal performance, it is widely accepted that using *U*-factors will provide more design flexibility as truly continuous insulation may not be required (for most projects where continuous insulation would be required per the prescriptive *R*-value method, some level of exterior insulation is usually still required). Using *U*-factors requires performing a calculation for the assembly that accounts for thermal bridging. The IECC, ASHRAE 90.1, and ASHRAE fundamentals handbook provide basic guidelines and methodologies to account for thermal bridging, as previously discussed; however, the information available is limited and typically oversimplified.

The two main limitations to the options available within existing ASHRAE and IECC requirements are limited quantitative methods to account for thermal bridging and the approach in Option 2 that cannot account for thermal bridging elements without areas and does not fully account for lateral heat flow, which often underestimates total heat flow (Fig. 2).

Around 2010, industry leaders recognized these limitations. Research resulted in the publication of ASHRAE 1365-RP, *Thermal Performance*

of Building Envelope Details for Mid and High-Rise Buildings.⁶ Per ASHRAE 1365-RP, “The goal of the project was to develop procedures and a catalogue that will allow designers quick and straightforward access to information with sufficient complexity and accuracy to reduce uncertainty in the thermal performance of building envelope components.” The heat transfer modeling was performed using a three-dimensional finite element analysis. Multiple simulations were compared with a variety of guarded hot-box testing results; the deviations were within $\pm 8\%$, with most simulations falling within $\pm 3\%$ deviance. The simulations were deemed sufficiently accurate for calculations on buildings.

ASHRAE 1365-RP refers to thermal bridging as thermal transmittances and groups them into three categories: clear field, linear, and point. The methodology is different from the area-weighted average approach used historically in North America due to the limitations noted. Clear field transmittances are assemblies with an area that account for consistent thermal bridging that occurs throughout. An example of a clear field transmittance is steel studs or girts used to support a cladding away from any interfaces. Linear transmittances are thermal bridging elements typically at interfaces with a length, such as masonry shelf angles, parapets, and window perimeters. Point transmittances consist of a single location of heat transfer without an area or length,

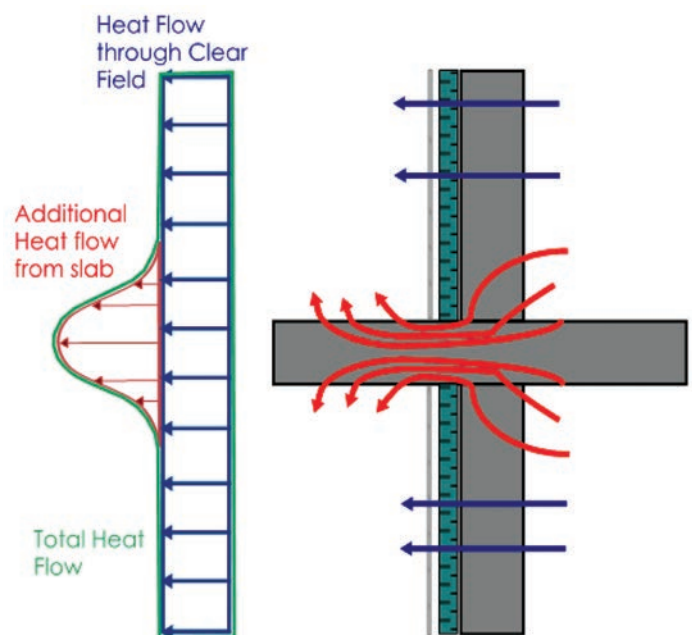


Figure 2. Graphical representation of lateral heat flow through a thermal bridge. Source: Morrison Hershfield, *Building Envelope Thermal Bridging Guide* (2020), page 10.

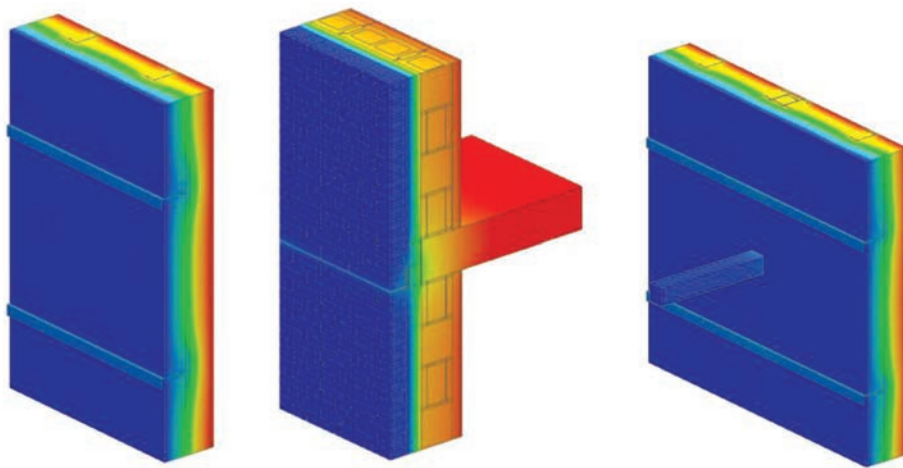


Figure 3. Graphic demonstrating clear field transmittance (typical Z girt), linear transmittance (masonry shelf angle directly connected to slab edge), and point transmittance (square steel structural penetration). Source: Morrison Hershfield, *Building Envelope Thermal Bridging Guide* (2020), page 11.

such as a beam penetration. By classifying the thermal bridge by the type and identifying a similar modeled condition, project teams can now predict actual thermal performance more accurately (Fig. 3).⁷

Several guides or industry resources have become available for design teams to reference, including, but not limited to:

- ASHRAE Research Project Report RP-1365⁶
- ISO 10211:2017, *Thermal Bridges in Building Construction – Heat Flows and Surface Temperatures – Detailed Calculations*⁸
- ISO 14683:2017, *Thermal Bridges in Building Construction – Linear Thermal Transmittance – Simplified Methods and Default Values*⁹
- *Building Envelope Thermal Bridging Guide* by Morrison Hershfield⁷
- Testing or modeling information from manufacturers, especially cladding attachment manufacturers and thermal break manufacturers

After working on multiple projects using these guides and resources to determine effective thermal performance in the United States, the authors have experienced the following issues:

- Some project teams are still electing to use the trade-off method to demonstrate code compliance. Within the trade-off method, design professionals typically prefer the component *R*-values; this is likely due to perceived simplicity of entering *R*-values for the insulation used within the assembly.

- The *R*-value method often provides less flexibility for assemblies, specifically anchoring or attachment of components within opaque walls and roofs as continuous insulation is often required. Sometimes there are viable options to provide continuous insulation, but it may be less cost-effective than other options. A *U*-factor calculation of an assembly that accounts for clear field thermal bridging as required by code often provides more flexibility.
- Actual building thermal performance is overestimated by at least 50%. This is consistent with the 20% to 70% range provided in the *Building Envelope Thermal Bridging Guide*.⁷
- There is a disconnect within the design team between the architect, mechanical engineer, and energy consultant. The mechanical engineer's design assumptions for heat loss and other building enclosure performance metrics are often not accurately reflected in the architectural design or reconciled with the energy model.

These issues can exist within many project types but will create magnified obstacles for high-performance buildings with stringent performance requirements. Information that is readily available to project teams can demonstrate assembly *U*-factors with a method to calculate total building heat loss. Now that the information is readily available to project teams to calculate these values, project implementation is critical.

MAXIMIZING VALUE THROUGH ENERGY MODELING

More and more projects are using techniques and concepts from the integrated project delivery method and lean principles. Some building owners and developers have recognized that spending time throughout a thoughtful design process can save money and maximize value. In the authors' experience, ongoing coordination can be helpful, but a life-cycle cost analysis performed within the context of the owner's project requirements is where owners can make real-time decisions on where money is spent while understanding the performance impact. Certainly, the length of time the owner will hold onto the building will impact how the life-cycle cost analysis is performed.

Energy modeling is the primary tool for a comparative energy performance analysis for various building systems. Energy modeling can be used to identify the building energy consumption and cost along with other outcomes that are based on various key building systems. This tool can be leveraged to inform building owners and design teams about how best to save money and time while still meeting project energy and sustainability goals. The tool is especially helpful when used early in design. One downside of traditional energy modeling is the time it takes for the energy engineer to simulate various building options. Many project teams have expressed disappointment when learning that an option would have had a significant benefit to the project when this information was learned too late in the design process to make changes. In addition to the length of time and timing of when modeling is performed, performing a limited number of select simulations has an impact. These limited simulations make it difficult to gain a deep understand of the interaction between systems. Energy consultants now use energy mapping tools that provide all options to be considered by the project team and can be adjusted in real time with project-specific performance outcomes. Only parametric analysis capable of contrasting hundreds of different simulations can provide this clarity. However, many of these are of limited value because they do not leverage enough variables. The most sophisticated applications include all significant mechanical, electrical, and building enclosure systems so that various options can be compared in real time using a graphic interface. Outcomes generally include energy usage, level above or below baseline code performance, annual energy cost, and sustainability

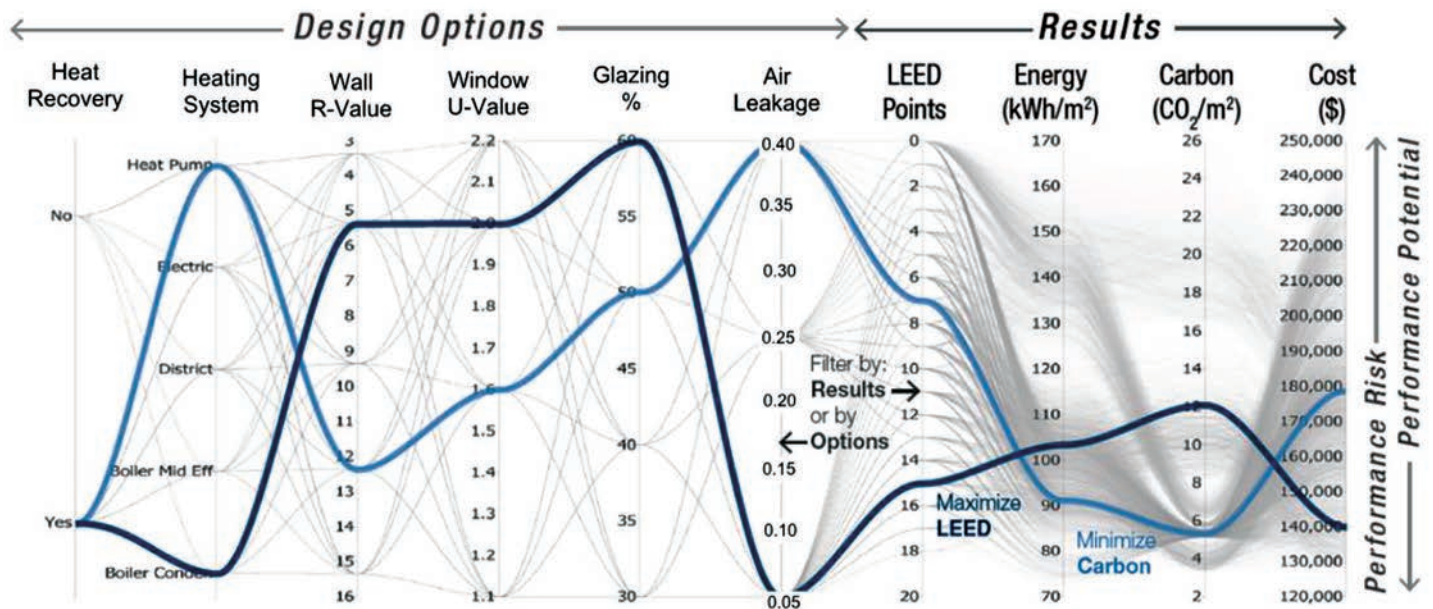


Figure 4. Example of energy optimization tool with design options and results.

targets such as LEED points.

A few key benefits of early energy modeling with advanced mapping capabilities include the following¹⁰:

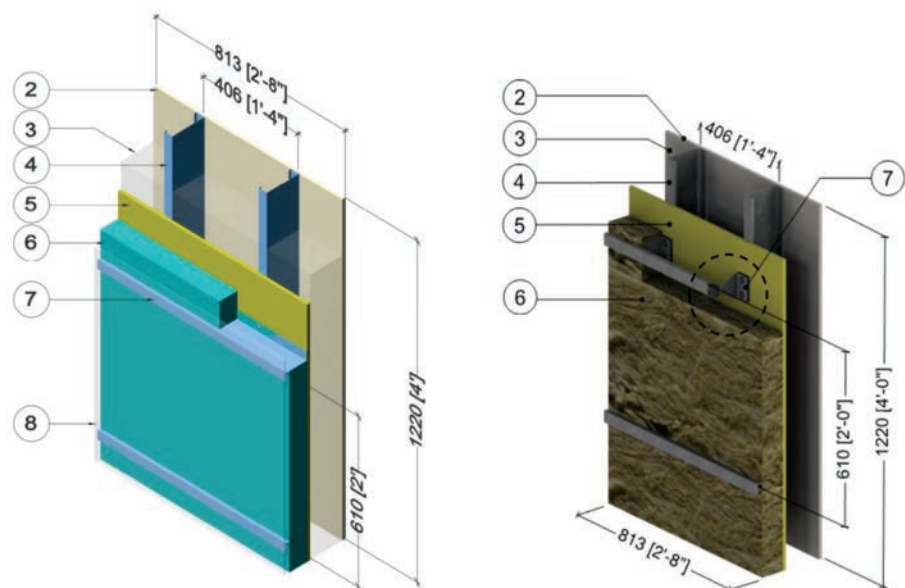
- Key building design option inputs and outputs are customized, providing the project stakeholders with focused priorities.
- Teams meet energy cost saving and environmental goals by identifying the critical design parameters early.
- Project design delays are decreased as risk is managed through reducing redesign at later stages. This is especially important for projects using integrated delivery methods or target value design.
- Different design decisions, combinations of systems, and multiple performance criteria can be weighted to provide a complete list of options that meet targets and goals.
- Results of system trade-offs can be instantaneously simulated, allowing component comparison targeting building goals saving the owner time and money.

The options can be compared to initial cost and operational cost to determine the most cost-effective options that meet the project goals using life-cycle cost analysis (Fig. 4).

Once the overall project energy performance goals are identified, either as code minimum prescriptively or through energy modeling, the building enclosure assemblies, and linear/point transmittances can be reviewed,

compared, and prioritize to meet the project goals. A comparative tool can be used to input building enclosure assemblies and thermal

bridging to identify where improvements can be made—typically to the conditions with the largest relative amount of heat loss. Figure 5



Wall Option #1¹⁰:

Interior Film: R-0.7
 Interior Gypsum Wall Board: R-0.5
 Air in Stud Cavity: R-0.9
 Exterior Sheathing: R-0.5
 4" Exterior Insulation: R-20
 18 Gauge Horizontal Z-Girts
 Exterior Film: R-0.7
Total Nominal R-Value: R-23.2
Total Effective R-Value: R-13.1

Wall Option #2¹⁰:

Interior Film: R-0.7
 Interior Gypsum Wall Board: R-0.5
 Air in Stud Cavity: R-0.9
 Exterior Sheathing: R-0.5
 3" Exterior Insulation: R-12.6
 Thermally Broken Brackets
 Exterior Film: R-0.7
Total Nominal R-Value: R-15.8
Total Effective R-Value: R-14.1

Figure 5. Comparison of two metal-panel-clad wall options. Source: Morrison Hershfield, *Building Envelope Thermal Bridging Guide* (2020), pages A.5.14 and A.5.21.

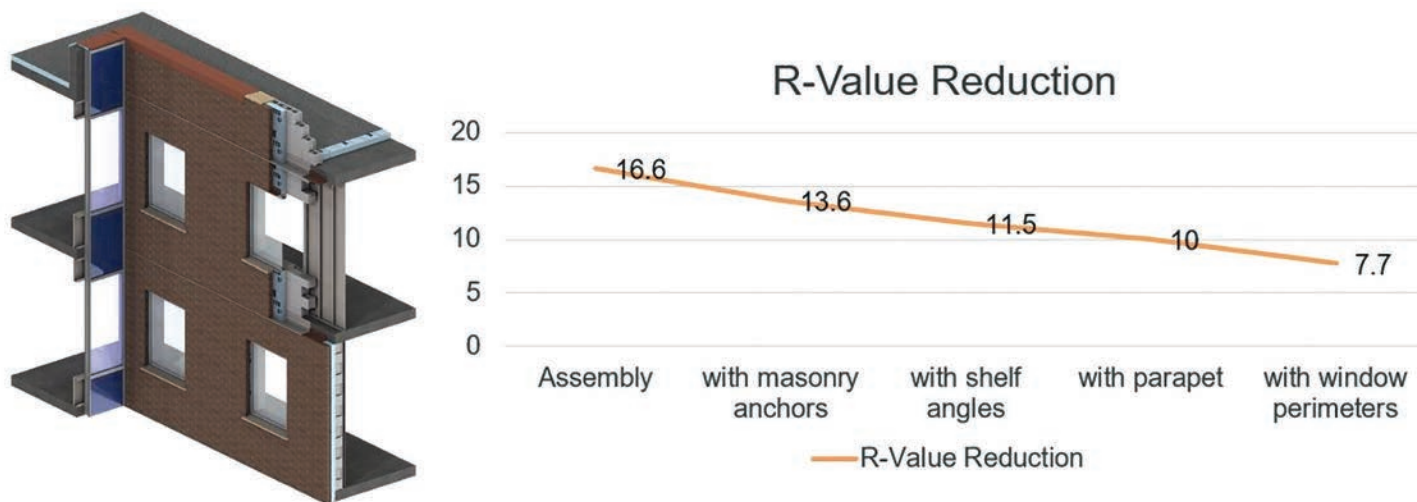


Figure 6. Typical masonry wall R-value reductions due to various thermal bridging conditions. Source: Morrison Hershfield, *Building Envelope Thermal Bridging Guide* (2020), page 12.

summarizes two metal-panel-clad wall options that were considered on a recent project with corresponding wall layers from interior to exterior and corresponding nominal R-values for each component.

The main difference between the two wall assemblies is the girt system used to support the metal-panel cladding. The continuous metal Z girts through the insulation significantly decrease the effective thermal performance compared to the thermally broken clips (56% reduction vs. 89% reduction). The intent of the comparison is not to convince the project team to select one option over the other; it is to compare the assembly including the cost comparison of the following:

- continuous metal Z girts versus thermally broken clips
- 4 in. of exterior insulation versus 3 in. of exterior insulation
- simple break shape metal versus proprietary clips

By looking at the broader impact of the options beyond the way the cladding is attached, one may determine that reducing the thickness of the exterior insulation more than offsets a potentially higher-cost metal-panel girt system. The two options considered represent a small percentage of the total possible options. The two options reviewed for the project were narrowed down from around 10 assembly options based on other performance

factors and familiarity with products and constructability among the project team.

Not only should individual assemblies be compared, the entire building enclosure can be reviewed to further understand options and where to focus mitigating thermal bridging efforts. A masonry-clad wall assembly was used on a recent project with thermal performance within the field of wall calculated to be R-16.6 nominal (Fig. 6).

Like the metal-panel wall assembly comparison, owners and project teams must remember that it is not the goal of the consultant to design a building that exceeds the thermal performance goals. The efforts of the consultant must focus on analyzing the impact

of thermal bridging to identify where improvements can be made to have the largest impact at the lowest initial cost. For the preceding masonry wall assembly example, if addressing only thermal bridging, the order of importance of improvements would be: masonry anchors, window perimeters, shelf angles, and parapet.

Some improvements do not have a cost. Mitigating a thermal bridge without added cost, regardless of the impact, is often the first step. While the previous example identifies masonry anchors as the largest thermal bridge, improving the type or material of masonry anchor will likely have a cost. Depending on the configuration, improving the window perimeters may not have a cost impact;

	Performance Category	Description and Examples	Linear Transmittance	
			$\frac{\text{Btu}}{\text{hr ft}^2 \text{ F}}$	$\frac{\text{W}}{\text{m}^2 \text{ K}}$
GLAZING TRANSITIONS	Efficient	Well aligned glazing without conductive bypasses Examples: wall insulation is aligned with the glazing thermal break. Flashing does not bypass the thermal break.	0.12	0.2
	Regular	Misaligned glazing and minor conductive bypasses Examples: wall insulation is not continuous to thermal break and framing bypasses the thermal insulation at glazing interface.	0.20	0.35
	Poor	Un-insulated and conductive bypasses Examples: metal closures connected to structural framing. Un-insulated concrete opening (wall insulation ends at edge of opening).	0.29	0.5

Table 1. Thermal comparisons of three glazing transitions (details)

therefore, details like window perimeters can typically be improved first. By aligning the window frame thermal break and insulating glass unit with the adjacent insulation, thermal bridging is minimized compared to designs with large offsets between the window and adjacent insulation. By detailing with alignment of the thermal barriers, the linear transmittance and condensation risk is decreased. **Table 1** compares three types of glazing transitions categorized from efficient to poor, each with a corresponding linear transmittance value. With lower transmittance there is less heat flow and therefore greater efficiency.

PROPOSED PROJECT APPROACH

Prediction of effective thermal performance is of little value to the project when not properly reconciled with the project performance goals, initial cost, and operational costs. Even if the owner/developer desires to sell the building after completion, understanding how building enclosure design impacts initial costs can be important. As project owners look for methods to meet performance goals within budgetary constraints, project teams are incorporating lean principles and integrated project delivery (IPD) concepts. Even projects using more traditional delivery methods, such as design-bid-build and design-build, are using techniques from the IPD method. Overall, in the authors' experience, these principles can be helpful provided that the project team is organized and understands the project goals and the process to achieve these goals. While individual projects tend to be substantially different based on project type and location, there are key takeaways in the process identified that can be used, perhaps to varying extents, on all projects.

The following proposed project approach provides a robust methodology to understanding, reconciling, and achieving owner's project requirements (**Fig. 7**). This approach is intended to be flexible so that all projects can benefit from some level of this process.

The Team: Owner to contract required project team members early in design. While the designer of record is usually the first technical member engaged, other consultants, such as the building enclosure consultant, commissioning agent, and energy consultants,

are unfortunately added too late. For cost estimating and design assist, the construction manager/general contractor (CM/GC) along with design-assist subcontractors can also be engaged early in the process.

Owner's Project Requirements: Project team to begin the process to understand the project goals. Without performance goals, the project team will unfortunately be lost in ambiguity. Good consultants form the basis of their recommendations on the project goals with quantitative and/or empirical data to support the technical advice. Due to the complexity of modern building enclosure construction and more compressed schedules, having a clear understanding of the project goals is more critical than ever. Working hard to develop and refine the owner's project requirements (OPR) and refining throughout design is, in the authors' experience, unfortunately one of the most overlooked aspects of design. The commissioning process used on projects has been helpful to engage projects teams in the OPR development, but an OPR can be used and applied effectively to projects that aren't using commissioning. Some typical performance categories for an OPR can include the following:

- applicable codes and standards
- overall energy or sustainability goals
- building enclosure performance requirements related to acoustics, durability, maintenance, water-penetration resistance, thermal performance, air leakage, condensation resistance, etc.

Many of the specific quantitative performance goals within the OPR will be developed

and refined throughout early design and ideally are informed by the energy model reconciled with initial costs, maintenance costs, and ongoing energy costs.

Energy Mapping: Evaluate the building systems options by comparing initial versus long-term operational costs. Advanced modeling techniques that allow real-time comparison are critical for effectively using the energy model during the design phase. It is important to understand the outputs of the energy model for each potential building option. For many projects, energy modeling would allow the thermal performance of the building enclosure to be less than the prescriptive requirements. Some project teams and standards address a building enclosure threshold value. If the project team elects to set building enclosure thermal targets less than the prescriptive values, the team must analyze peripheral impacts of less insulation, such as occupant comfort. On a recent project where less than prescriptive insulation was considered, the team used ANSI/ASHRAE Standard 55-2013, *Thermal Environmental Conditions for Human Occupancy*,¹¹ to help understand the potential impact to occupant comfort.

Enclosure Performance Metrics and Energy Modeling: The code/energy analysis to be reconciled with HVAC design to determine building enclosure performance metrics. The method to demonstrate energy code compliance should be fully vetted and confirmed. The project team must identify to what extent energy modeling will be performed on the project. If energy modeling is going to be used to demonstrate code compliance, the project team should consider two energy models:

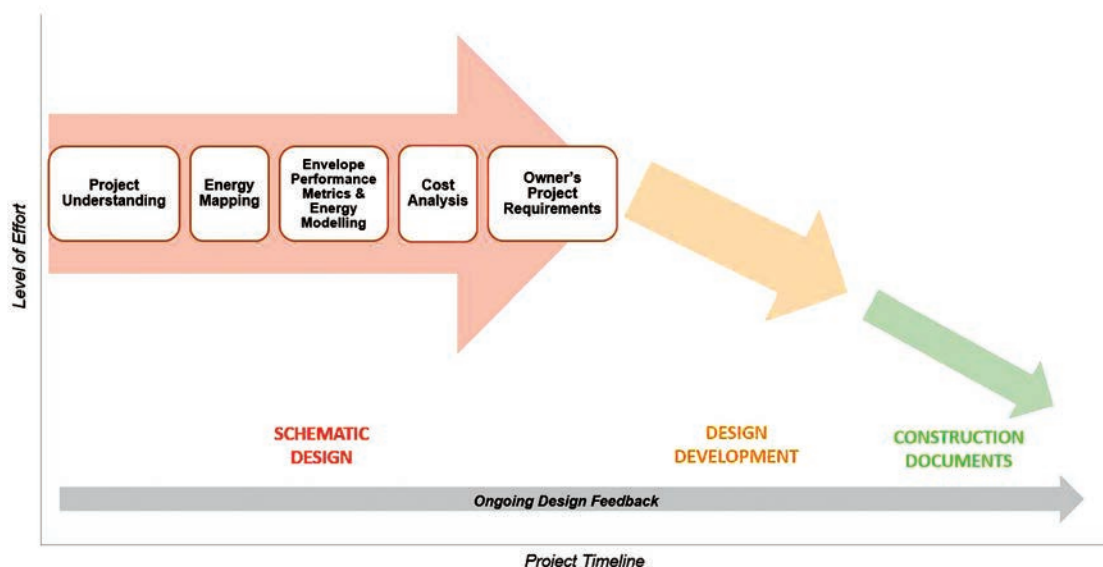
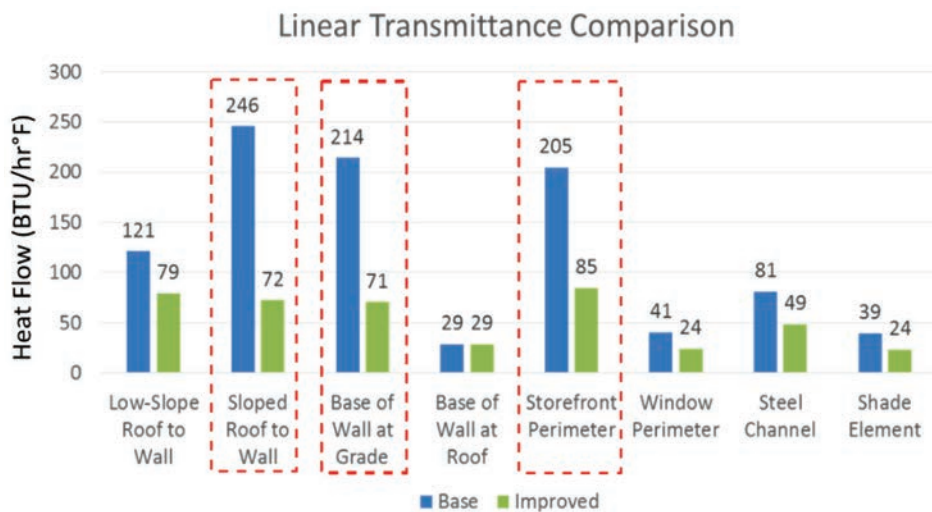


Figure 7. Proposed project approach demonstrating early schematic design phase effort to maximize value.



Base: Accounting for thermal bridging: R-7.3

Improved Linear Transmittances: R-11.3 (> R-11 Goal)

Figure 8. Comparison of linear transmittances with the largest contributors to thermal bridging that were improved through thermal bridging mitigation and detailing outlined in red.

- An energy model used for code compliance that accounts for clear field thermal bridging of opaque assemblies only. If all thermal bridging was properly accounted for, the proposed design could never surpass the baseline building because the latter does not account for thermal bridging at interfaces.
- An energy model that is used for more realistic analysis and life-cycle cost analysis. This model would accurately incorporate thermal bridging conditions and realistically reflect actual building enclosure performance. For example, a spandrel within an aluminum-framed fenestration is categorized as an opaque wall with maximum U-factor requirements per ASHRAE 90.1 (U-0.064 or R-15.6 for many United States climate zones). Many designs incorporate 4 in. of insulation within a spandrel; however, the realistic expectation for thermal performance (while dependent on specific design and area of spandrel) is often greater than U-0.1 (less than R-10). When comparing higher-performing glazing such as vacuum insulated glazing to an overestimated base condition, the return on initial investment appears to be lower when comparing to the nominal spandrel performance. A realistic comparison may allow new and higher-performing technologies to gain entrance into the market.

Cost Analysis: Determine and confirm the most cost-effective approach to meeting the project goals. After understanding the overall performance impact of individual systems through modeling, the project team can begin to prioritize the systems contributing to the most energy usage and consider which systems can be improved for the lowest initial and operational cost. This can be performed in greater detail within building enclosure systems. For example, on a recent project there was an overall effective thermal performance goal of R-11. After addressing the clear field thermal bridging and improving the overall thermal performance to R-7.3, the project team evaluated the linear thermal bridges. Using the thermal bridging guide,¹² the team was able to identify the largest contributors to thermal bridging, improve them, and increase the overall effective R-value to R-11.3, meeting the project goal (Fig. 8).

Ongoing Design Feedback: Ensure the design accurately represents the approach, including architectural design and mechanical calculations. At this point, several important components of the process need to be considered:

1. The architectural design needs to accurately reflect systems, products, and assemblies that can meet the OPR. These considerations often include thermal performance, durability, airtightness, water-penetration resistance, and more.
2. The architectural design and speci-

fications should not only reflect the thermal performance requirements for each system but provide a basis of design that can achieve those values. Detailed building enclosure assembly details within the drawings along with the calculation/reference is an easy way to clearly demonstrate the thermal performance requirements as well as the basis of design system to achieve that goal.

3. The building enclosure details should be developed in a way that demonstrates the level of mitigation of thermal bridging as required to meet the overall building enclosure thermal performance target. While references such as the *Building Envelope Thermal Bridging Guide* demonstrate the placement and location of insulation and systems, the details must also demonstrate continuity of other control layers, such as the water-resistive barriers, air barriers, and vapor barriers, which are critical to identify and locate in the correct position based on the project-specific climate. The details should also be developed in a way that is constructible, which is where the CM/GC and design-assist contractors can be helpful to determine installation methods and sequencing.
4. The mechanical engineer must use the actual performance of the building enclosure when calculating loads and sizing equipment. Improper building enclosure assumptions and unreasonably high safety factors can not only diminish the value of performance and the process but can inadvertently create performance problems.
5. The project specifications need to clearly identify a project-specific mock-up and testing plan to effectively and efficiently verify the OPR. The level of verification should be balanced against the project budget, owner's tolerance for risk, and stringency of performance goals. In the authors' experience, using a stand-alone specification for mock-ups and performance testing can help to clearly demonstrate the project-specific mock-ups, testing requirements, and performance criteria.

Construction Verification: Verification of construction is the final step in achieving the OPR. Building enclosure mock-ups, either

stand-alone (often laboratory or on-site) or in-situ can be used to evaluate and verify the initial installation. Enhanced coordinating between the CM/GC and the project team can be very helpful for the proper timing of mock-up review. A stand-alone mock-up allows many building enclosure systems and details to be evaluated and tested before construction on the building. Ongoing construction observations and testing by the building enclosure consultant and project team provide ongoing feedback and some level of OPR verification.

NEXT STEPS

While there are significant advances within the industry to help predict building performance, there are still large gaps to be filled. Some next steps that could be helpful include the following:

- Advancements to the energy codes and institutional requirements to provide additional information to help clearly identify the extent to which thermal bridging must be accounted for and to provide additional resources on how to calculate to that extent. For accurate thermal bridging calculations, some entities, or institutional owners such as the State of Utah, are considering a requirement that any thermal bridge that accounts for greater than 10% of the assembly heat loss must be accounted for.
- Project teams to start considering project performance metrics beyond direct cost and energy usage and to consider more sustainable energy sources.
- Improvements to energy modeling metrics that separate the combined cost of conditioning the space from other occupancy-driven energy use in the building such as plug loads and hot water. This acknowledges that traditional modeling based on overall energy use undervalues the impact of the enclosure and results in buildings that are much less resilient. Codes and institutions to consider increasing requirements for building enclosure threshold values. Some entities are beginning to require that the building enclosure thermal performance cannot allow more than 20% less heat flow than a baseline building insulated per the prescriptive requirements. Guides that address this threshold include Passive House standards¹³ and the *Guide to Low Thermal Energy Demand*

for Large Buildings (TEDI) published by the BC Housing Research Centre.¹⁴ In Canada, the British Columbia Step Code and the City of Toronto have instituted a TEDI metric as part of the code compliance requirements.

- Improvements to energy models to accurately reflect building enclosure thermal performance and accurately compare new technologies against existing with performance that is usually overestimated.
- Energy modeling to continue to decrease the performance gap between modeled and actual performance. In the authors' opinion, the gap could be decreased by incorporating a thermal bridging evaluation and better predicting occupant behavior.

CONCLUSION

Assuming building design and construction continue to increase in complexity, it is critical for design professionals and consultants to focus on increasing technical knowledge and adapting to projects to best apply innovative technical concepts. Understanding the available tools and process is often a powerful first step. Providing increasing value to building owners and developers through reliable technical advice within the context of the project delivery methods should continue to be the focus of design professionals and consultants. The ongoing pursuit of the next steps identified within this paper can improve how the industry delivers buildings that meet the project goals while enhancing owner value. 

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Manufactured Stone Veneer: Common Pitfalls in Design and Installation

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ABSTRACT

Adhered masonry veneer (often referred to as manufactured stone veneer, or MSV) has been growing in popularity and use throughout North America over the past 20 years. MSV offers the beauty of masonry with the cost efficiency and reduced weight of stucco. In addition to specific manufacturers' instructions, current codes and industry standards that govern its design and installation include ICC-promulgated model building codes, masonry codes (TMS 402 and TMS 602), ASTM standards, and Masonry Veneer Manufacturers Association (MVMA) publications. Simply referencing these published code and industry standard documents in drawing notes, project manuals, or contracts is often insufficient, leading to improper design and installation techniques that ultimately result in failure. This paper presents some of the common design and installation pitfalls associated with MSV to help designers and installers enjoy a more successful, durable application. This presentation is targeted at an intermediate audience of designers, installers, and building owners.

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Manufactured Stone Veneer: Common Pitfalls in Design and Installation

Manufactured stone veneer (MSV) has its roots in portland cement plaster (stucco). As will be discussed in greater detail in this paper, an MSV system is similar to stucco, as both MSV and stucco systems share a base coat (that is, scratch coat and brown coat) behind the finish coat. While adhered tile cladding systems have been in use since ancient Egypt, some of the early concepts of modern MSV can be traced back to the early 1950s via Garden State Brick. Named after New Jersey, where it was innovated and commonly used, Garden State Brick featured the use of a simulated brick template that was stamped into an oversized stucco finish coat, leaving the impression of perfectly laid brick coursing with the economic benefit of plaster. (Garden State Brickface and Siding, formed in 1953, innovated the technique and created the formulations for the proprietary system that is still in use.) In more recent times, cultured (faux) brick or stone or “thin” brick (actual brick units shaved into ¼-in.-thick sections) would ultimately become the finish coat that, applied on top of the base coat, formed the MSV system.

While MSV has been in use for nearly 70 years and was first included in a building code in 1967, it was not until 2009 that a detailed installation guideline was issued.^{1,2} Even currently, the design standards are confusing, as the MSV system is a hybrid of both stucco and masonry. The following sections of this paper discuss the building code requirements and industry standards that govern the application of MSV.

BUILDING CODE REQUIREMENTS

The *International Building Code (IBC)* and *International Residential Code (IRC)* contain general requirements for exterior wall assemblies that apply to MSV assemblies. In particular, the IBC and IRC contain the following as they relate to exterior drainage wall assemblies (direct-applied applications are outside the scope of this paper):^{3,4}

- Exterior drainage walls are to include

at least one layer of a water-resistive barrier (WRB) and flashings located at interruptions in the vertical plane to divert water to the exterior.

- Where plaster (including the base coats for MSV systems) is applied over wood-based sheathing, a performance equivalence of two layers of Grade D paper for residential construction or a WRB meeting ASTM E2556, Type I, for commercial construction is required. Alternatively, one layer of WRB with resistance equal to or greater than Grade D paper (residential construction) or a single layer of WRB meeting ASTM E2556, Type II (commercial construction), can be used if the base coat is separated from the WRB via an intervening non-water-absorbing drainage layer or airspace, such as in a rainscreen system. An additional exception for commercial construction permits a single layer of WRB where a ventilated airspace is provided between the stucco and the WRB for installations in Climate Zones 1A, 2A, and 3A.
- When using multiple layers of WRB, each individual layer of WRB is to be lapped independently.
- The WRB is to lap over the designated drainage screed or flashing.
- Designated drainage screeds are to be located a minimum of 4 in. above earth, 2 in. above paved surfaces, and ½ in. above exterior walking surfaces supported by the same foundation that supports the exterior walls (for example, balconies and patios).

In addition to the general exterior wall requirements highlighted previously, the IBC and IRC also incorporate requirements from other publications through reference. These include references to TMS 402, *Building Code Requirements for Masonry Structures*, and TMS 602, *Specification for Masonry Structures*,

as well as to various standards promulgated by ASTM International (ASTM). These building codes and specifications provide requirements for WRBs, flashing, and weeps as well as structural requirements, such as the accommodation of differential movements, structural support (gravity and lateral loading), and height limitations and considerations. (Manufacturers' requirements specific to proprietary systems may differ from those explicitly prescribed in the model building codes and referenced standards. Such deviations may be permitted through approval by the building official or other authority having jurisdiction under the alternative materials provisions in the code. A discussion of such proprietary systems is outside the scope of this paper.)

Key prescriptive requirements in the masonry codes and standards as they relate to MSV include the following:^{5,6}

- The size of the veneer unit is to have a face area of no greater than 5 ft², a weight no greater than 15 lb/ft², and dimensions that measure no greater than 36 in. in height and length and no greater than 2⅝ in. in thickness.
- The height, length, and wall area are unlimited except as required to accommodate differential movement.
- Backing for MSV can be masonry, concrete, or metal lath and portland cement plaster.
- The adhesion of MSV must have at least 50 psi in shear strength when tested in accordance with ASTM C482. Alternatively, the face units are to be adhered in compliance with Article 3.3C of TMS 602.

The prescriptive requirement to adhere face units in accordance with Article 3.3C of TMS 602 warrants further discussion. This article of the specification refers to model building code provisions for metal lath and portland cement-based plaster. It also refers to ACI 524R, *Guide to Portland Cement Plastering*, for information on lath and acces-

As can be inferred from their titles, ASTM C926 and ASTM C1063 are standards that provide the minimum design and application requirements for stucco systems. It is noteworthy that ASTM C926 and ASTM C1063 are prescriptive standards and not performance-based. The completed system conforming to these prescriptive requirements is therefore deemed to comply with building code requirements.

sories and their installation. Article 3.3C also refers to the model building codes and ACI 524R for recommendations to control cracking. In turn, ACI 524R references stucco standards ASTM C926, *Standard Specification for the Application of Portland Cement-Based Plaster (Stucco)*, and ASTM C1063, *Standard Specification for Lathing and Metal Accessories*.⁷

As can be inferred from their titles, ASTM C926 and ASTM C1063 are standards that provide the minimum design and application requirements for stucco systems. It is noteworthy that ASTM C926 and ASTM C1063 are prescriptive standards and not performance-based. The completed system conforming to these prescriptive requirements is therefore deemed to comply with building code requirements. Examples of key prescriptive requirements found in ASTM C926 and ASTM C1063 that are pertinent to base coats of MSV systems include the following:^{8,9}

- Preparation of the base coat substrate
- Proportioning and mixing requirements for the scratch and brown coats
- Nominal thickness requirements of the scratch and brown coat
- Application and curing requirements
- Lath and accessory material and fabrication requirements
- Lath and accessory fastening requirements
- Lath laps
- Control joint layout requirements as follows:

- Maximum spacing of 18 ft
- Maximum panel size of 144 ft² (for vertical applications—that is, walls)
- Maximum panel length-to-width ratio of 2½ to 1

INDUSTRY STANDARDS

Although not code requirements, several industry standards have been published to provide guidance regarding the design and installation of MSV. In 2009, the Masonry Veneer Manufacturers Association (MVMA) first published a guide that summarized best practices for the WRB, lath and accessory materials and their installation, scratch coats, mortar mixtures, surface preparation, and veneer installation. This guide also included schematic detail drawings for typical conditions at corners, transitions, and terminations.² Since 2009, MVMA has updated and reissued its guide several times, with the two most recent editions (the fourth edition in 2014 and the fifth edition in 2017) issued by MVMA as an affiliate of the National Concrete Masonry Association (NCMA). The title of these last two editions was revised to *Installation Guide and Detailing Options for Compliance with ASTM C1780*, ASTM C1780 being a new consensus-based standard that was first released in 2013.

The most recent revision of ASTM C1780, *Standard Practice for Installation Methods for Cement-Based Adhered Masonry Veneer*, issued in 2020, refers back to the MVMA installa-

tion guide document and reiterates much of the same information but does not include the schematic detail drawings. Guidance is provided for both interior and exterior applications. Important provisions in this ASTM standard for exterior applications include the following:¹⁰

- Two layers of WRB are required over all sheathing except where the local building code permits otherwise.
- Foundation weep screeds and lath are to be installed in accordance with ASTM C1063.
- Stucco scratch and brown coats when used as the MSV scratch coat are to meet ASTM C926 up to the brown coat without the application of the finish coat. MSV scratch coats are required to be a minimum of ½ in. thick, which differs from the ASTM C926 requirement for scratch and brown coats to be a total of ¾ in. thick (nominal) for application over lath.
- Mortar is to be either Type N or Type S in accordance with either the property or the proportion specification of ASTM C270 or ASTM C1714. Mortars meeting ANSI 118.1, 118.4, or 118.15 are also permitted.
- Cement backer board located out-board of the WRB and sheathing is a permissible substrate for MSV installation. Specific surface preparation instructions for this assembly are provided.
- Assemblies incorporating continuous insulation are not addressed within ASTM C1780; however, direction is provided in the referenced MVMA guide.
- Generally, MSV units are to be applied to the scratch coat after the scratch coat is thumbprint hard. The scratch coat is to be damp, but no free water is to be present on its surface.
- Units are to be set in a full setting bed mortar that is either applied directly to the prepared backing surface (for example, scratch coat or cement board) or applied to the unit itself using the “back butter” method. Full coverage of the unit and full contact with the setting bed, unit, and prepared surface are required. The overall thickness of the scratch coat and mortar setting bed is limited to a maximum of 1¼ in.
- Mortar is required between units, even in “tight fit” joint applications, such as

those that are intended to provide the appearance of dry-stack masonry.

- Movement joints (control and expansion joints) are not directly addressed in the standard. However, the standard does refer to other industry standards as follows:
 - The standard references TMS 402, which requires the veneer to be designed and detailed to accommodate differential movement.⁵ TMS 402 does not offer any further guidelines or requirements on how to accommodate the differential movement; rather, that is left to the discretion and judgment of the design professional.
 - Installation of lath and foundation weep screeds is to be performed in accordance with ASTM C1063, which itself provides prescriptive requirements for control joint installation. However, the MSV standard does not mention the term control joint, so it is reasonable to conclude that the *control joint* spacing requirements provided in ASTM C1063 are not necessarily incorporated by reference.
 - The referenced MVMA guide states that “consideration should be given to where differential movement is expected.”¹¹ The current printing refers to NCMA’s website for more information. Previous printings of the current edition of the MVMA guide referred to an article titled “Are Control Joints Needed with Adhered Concrete Masonry Veneer?” that is no longer available from the MVMA/NCMA website;¹² this reference is not included in the current printing of the current version of the guide. The article makes the argument that, unlike stucco, the joints between masonry units in MSV effectively act as control joints. It concludes that control joints at spacings mandated in ASTM C1063 are not justified, although movement joints should be located to coincide with expansion joints in the substrate. The article indicates that study of this issue was ongoing to determine what, if any, practical limits should be implemented for constructing oversized

panels.¹³ The copy of the article the authors were able to locate was dated October 2011; it is unknown whether this subsequent study resulted in a revision to MVMA’s position regarding control joints.

- The annex provides much-needed modifications to the shear bond test method in ASTM C482. The unmodified version is a tile test that uses a standard mortar and substrate to test the bondability of the adhered unit. The modifications in the annex to ASTM C1780 instead test the shear bond of the actual assembly using the masonry unit, mortar, scratch coat, and substrates that the system is to use during field work. However, the samples are still to be prepared and cured under laboratory conditions, which may not reflect actual construction or exposure.

In addition to the consensus-based ASTM C1780 standard and the industry group MVMA guide, other industry associations have provided guidance for material-specific adhered veneers. These include Brick Industry Association (BIA) Technical Note 28C for thin brick; NCMA TEK 3-6C for concrete masonry veneers; *Thin Veneer Installation Guide*, published by the Indiana Limestone Co. (ILC) for Indiana Limestone veneers, and *Adhered Natural Stone Veneer Installation Guide*, published by the Rocky Mountain Masonry Institute (RMMI) for other natural stones. Items of interest within these industry standards include the following:

- Thin brick can be installed via either (1) the thick set method, which employs a scratch coat installed over lath; (2) the thin set method, in which the thin brick unit is adhered directly to the substrate (consisting of either cement board, masonry, or concrete) with a thin (approximately $\frac{1}{8}$ in. thick) layer of adhesive or modified mortar; or (3) as a modular panel or prefabricated panel system.¹⁴ The thick set method is nearly identical to the method described in ASTM C1780.
- ILC provides instructions for installation of thin stone veneer over continuous insulation, while RMMI advocates against such installations, as the rigid insulation does not have enough rigidity to resist crushing under applied loads (such as from a ladder leaned

against the completed veneer). The insufficient rigidity could, in turn, result in cracking of the stones.^{15,16} Neither BIA nor NCMA addresses assemblies with continuous insulation.^{14,17}

- Movement joints are recommended for thin brick and natural stone products, even though RMMI notes that natural stone tends to be relatively dimensionally stable. BIA, ILC, and RMMI provide detailed direction regarding the spacing and construction of movement joints. For thin brick, these recommendations mirror the requirements for control joint spacing given in ASTM C1063.^{9,14} The recommendations for stone vary, but generally include locating movement joints at openings, near building corners, between dissimilar materials, and within large expanses without openings.^{15,16}
- NCMA’s stance on movement joints in adhered concrete masonry veneer is less clear. TEK 3-6C provides information for both anchored and adhered veneers. As a design consideration that is applicable to both types of veneer, it states, “[C]ontrol joints should generally be placed in the veneer at the same locations as those in the backing, although recommended control joint spacing can be adjusted up or down based on local experience, the aesthetic requirements of the project, or as required to prevent excessive cracking.” It refers to another publication for additional information on this topic: TEK 10-4, “Crack Control for Concrete Brick and Other Concrete Masonry Veneers.”¹⁷ While adhered concrete masonry veneer would appear to be one of these “other concrete masonry veneers,” the dimensions of the units described in the publication all exceed the thicknesses permitted by code for adhered units. Assuming that adhered concrete masonry veneers do fall under the umbrella of “other concrete masonry veneers” within the purview of this document, control joints are recommended at locations of stress concentrations with a maximum spacing of 20 ft and a maximum panel ratio for length to height of $1\frac{1}{2}$.¹⁸

Table 1 provides a comparative summary of the industry standard requirements discussed above.

Component	MVMA/ASTM C1780	BIA TN 28C	NCMA TEK 3-6C	ILC	RMMI
Continuous insulation	Not addressed*	Not addressed	Not addressed	Guidance provided	Not recommended
Mortar/base coat	ASTM C270 Type N or S; ASTM C1714 Type N or S; ANSI A118.1, A118.4, A118.15	ASTM C270 Type S (with or without latex or polymer modifier) or ANSI A118.4	Follows TMS 402/TMS 602 requirements	ASTM C270 Type S	Type N or Type S (presumably ASTM C270)
Drainage	Two layers WRB and weep screed per ASTM C1063	References IBC and IRC requirements	References IBC requirements for weep screeds; indicates that backing system must be designed and detailed to resist water penetration	References building code requirements	Single layer of building paper with flashing at base of walls
Setting-bed application	Full setting bed either applied to the scratch coat or "back buttered" to the unit itself	Thick set per ASTM C1780, thin set with ⅜ in. setting bed, or modular/prefab system	Follows TMS 402/TMS 602 requirements	Back buttering of masonry units with reference to ASTM C1242	Full setting bed applied to the scratch coat
Movement joints	No guidance provided	Follows ASTM C1063	20 ft or length-to-height ratio of 1.5:1	At openings, at changes in materials, and where movement is anticipated in backup construction; near outside corners; references ASTM C1242 and The Building Stone Institute for maximum spacing recommendations (15 ft and 30 ft, respectively)	At openings and changes in materials, near corners, and at approximately 35 ft o.c. in walls without openings

* Not addressed in ASTM C1780, but direction is provided in the referenced MVMA guide.

Note: BIA TN 28C = Brick Industry Association (2014); IBC = *International Building Code*; ILC = Indiana Limestone Co. (2016); IRC = *International Residential Code*; MVMA/ASTM C1780 = Masonry Veneer Manufacturers Association (2009); NCMA TEK 3-6C = National Concrete Masonry Association (2012); o.c. = on center; RMMI = Rocky Mountain Masonry Institute (2010); WRB = water-resistive barrier. 1 in. = 25.4 mm; 1 ft = 0.305 m.

Table 1. Comparative summary of industry standard requirements

COMMON DESIGN AND INSTALLATION ISSUES

The following section of the paper provides examples and case histories of common design and installation pitfalls associated with MSV. While this section is not intended to provide a comprehensive examination, it is the authors' intent to raise awareness of these common problems and offer ways to avoid them in practice.

Improper Integration of WRB, Accessories, and Flashings

As is common with any drainage wall assembly, problems with the design and instal-

lation of the WRB, accessories, and flashings can lead to devastating consequences, including water infiltration, microbial growth, curtailed service life of the exterior walls, and occupant discomfort.

The IBC and IRC clearly require flashings in exterior walls at specific locations, such as perimeters of windows and doors; penetrations and terminations; exterior wall intersections with roofs, chimneys, porches, decks, and balconies; and other locations where moisture can enter the wall. Failure to properly integrate the WRB with the flashing can undermine the performance of the flashing to the point that it would be completely useless. The most com-

mon manner in which the WRB is not properly integrated with the flashing is a reverse lap where water is directed behind the flashing. An example of this condition is represented in **Fig. 1**, where reverse laps were observed between the WRB, consisting of a paper-backed metal lath installed over a liquid-applied material, and the base of wall flashing. Often, reverse laps between the WRB and the flashing (or between individual layers of sheet WRB) can also direct water behind the WRB, where it is subject to damaging the surface of the exterior sheathing.

MSV is particularly vulnerable to water damage; although the system itself is relatively

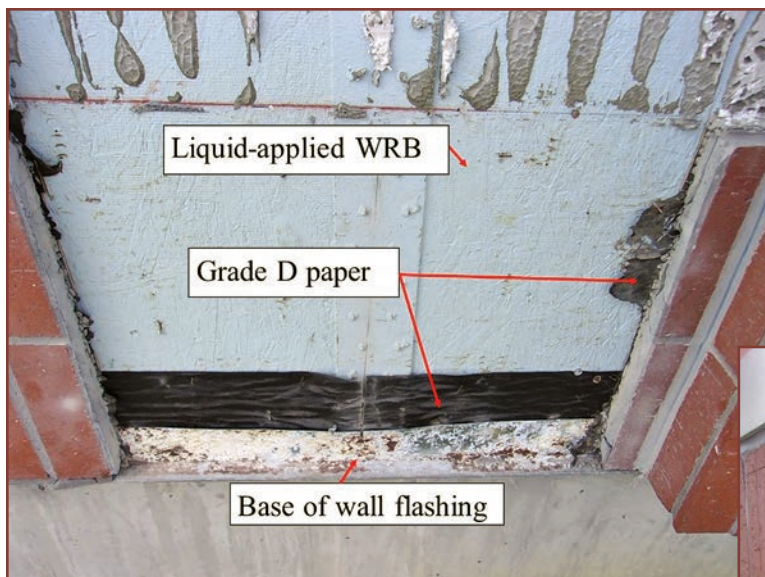


Figure 1. Example of reverse lapped WRB materials in an MSV system. Note: MSV = manufactured stone veneer; WRB = water-resistant barrier.

Figure 2. Poorly integrated/installed water-resistant barrier and flashing behind manufactured stone veneer allowed for significant water intrusion, damage, and swollen substrates.



unaffected by water, when installed over weather-sensitive materials (particularly wood-based sheathing), the associated swelling and volumetric changes of the underlying material(s) can exert forces on the veneer, resulting in cracks, spalls, and pop-offs. Examples of this condition are provided in **Fig. 2**.

In the authors' experience, a rainscreen assembly is the most effective means of collecting and discharging water that penetrates the MSV. Effective drainage design and installation are key to avoiding the detrimental effects of water. To a lesser extent, two layers of WRB properly lapped and integrated with flashings can be used; however, consideration should

be given to the scores of fasteners that will ultimately penetrate the WRB during installation.

Insufficient Embedment of Lath

As discussed previously, MSV is often composed of a cementitious base coat installed on top of lath. Until about 2015, metal was the predominant (and only) material used for lath. (While metal lath is most common, nonmetallic laths are readily available with the development of ASTM C1787 and 1788.) A

common challenge with lath—particularly expanded metal, or diamond, lath—is embedment within the plaster matrix. It is well known that MSV is not waterproof and allows water to penetrate through the veneer to the WRB. As water penetrates

through the veneer, it comes into contact with the metal lath. In conditions where the lath is not protected by the plaster matrix, and especially in brackish and coastal environments, the lath is subject to corrosion. In turn, corroded lath can cause the MSV system to spall, or pop off the wall, because of the expansive forces associated with the corrosion. Examples of this phenomenon are provided in **Fig. 3** and **4**. Moreover, corroded lath can also lead to compromised lath attachment to the backup wall and present a risk of falling debris.

In most instances, improper embedment of the lath is the result of poor workmanship—such as, poor troweling and insufficient base coat thickness.

However, even with the best of application techniques, it is noteworthy that complete embedment of lath is nearly impossible to achieve in the field. Screws, nails, and staples used to fasten the lath to the substrate pinch the lath tightly against the backing material, making it impossible to achieve complete embedment



Figure 3. Poorly embedded lath and associated corrosion.

Figure 4. Poorly embedded metallic lath resulted in corrosion, pop-offs, and compromised anchorage.



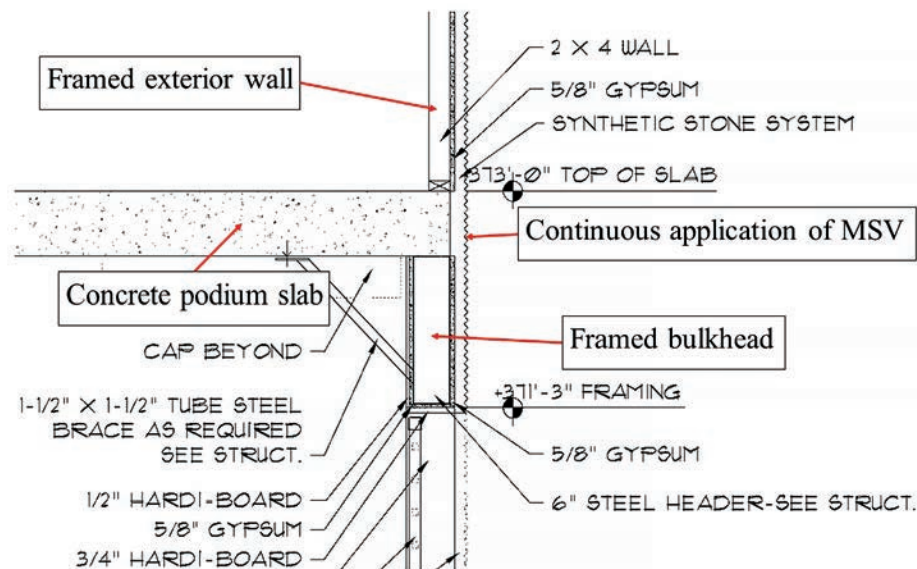


Figure 5. Sample detail indicating continuous application of MSV over dissimilar materials.
Note: MSV = manufactured stone veneer. 1" = 1 in. = 25.4 mm; 1' = 1 ft = 0.305 m.

in all locations. In the authors' opinion, consideration should be given to materials that are not sensitive to corrosion, such as nonmetallic laths and stainless steel, particularly in highly corrosive, brackish environments.

Failure to Account for Anticipated Movements

A common pitfall in the design of MSV is the failure to appropriately account for and accommodate differential movements. This is most commonly found when the MSV is applied over dissimilar backing materials, such

as cast-in-place concrete and wood framing. With the advent and growing popularity of wood-frame over podium-slab construction, this problem has likewise grown in frequency and severity.

An example of this condition is presented in the detail in **Fig. 5**. As can be seen from this detail, a continuous application of MSV was designed over dissimilar backing materials: namely, wood-framed exterior walls and bulkheads and the edge of a concrete podium slab. No means to accommodate differential movement were called out in the detail or provided in the finished construction.

After construction, widespread cracking, bulging, and delamination were noted in this area (**Fig. 6**). Test cuts performed in the existing cladding revealed no provisions for differential movement, discontinuous lath, and poor bond between the MSV base coat and the concrete slab edge (**Fig. 7**). As is well known and documented in the industry, wood-frame construction undergoes considerable shrinkage with time. In the absence of joints to relieve the downward movement of the wood-framed exterior walls, the MSV compressed at the slab edge, leading to the observed cracking, bulging, and delamination.

In addition to the differential movements anticipated between dissimilar substrate materials, the MSV also needs to be designed and constructed with movement joints to accommodate movement within the veneer itself, due to shrinkage (or in the case of thin brick, expansion) of the MSV units, the shrinkage of the underlying cementitious mortar and scratch coats, and thermal cycling. Although ASTM C1780, MVMA's guide, and NCMA's TEKs do not directly address the inclusion of control joints for these purposes, it is the authors' opinion that such joints are necessary, particularly in long expanses of veneer that can occur on commercial buildings. Such joints should be located as directed in ASTM C1063 and summarized earlier in this paper. Failing



Figure 6. Cracking noted in manufactured stone veneer in area that correlated with dissimilar backup materials.

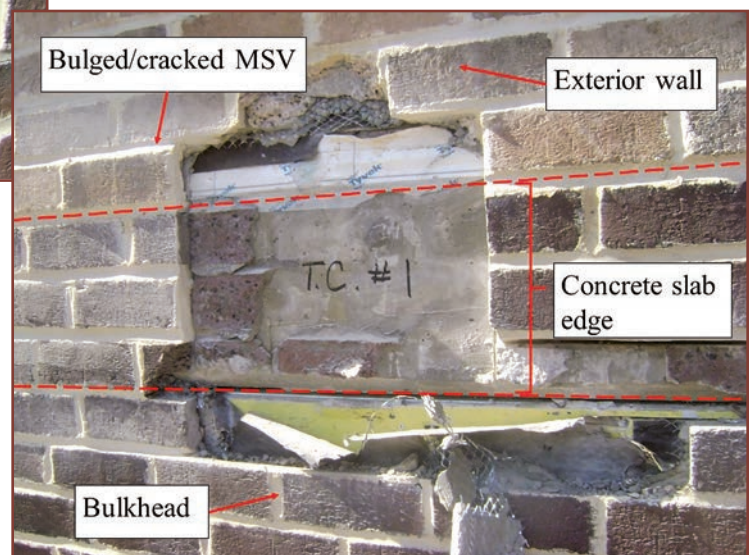
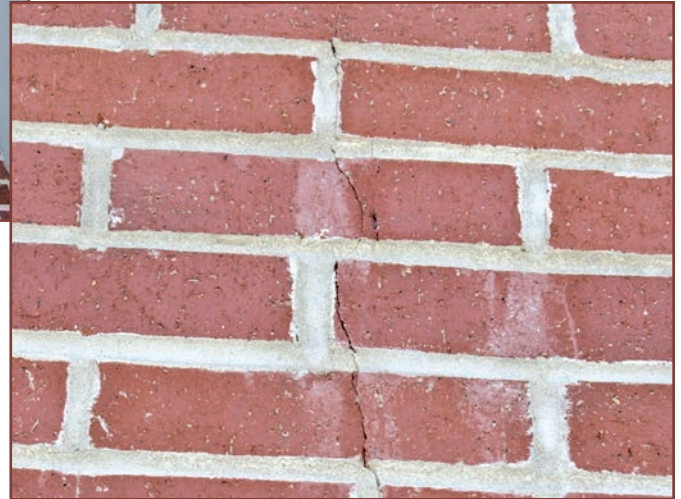


Figure 7. Test cut over bulged and cracked MSV revealed continuous application of MSV without provisions for differential movement between framed exterior walls and concrete podium slab. Note: MSV = manufactured stone veneer.



Figure 8. Large area of manufactured stone veneer without any control joints.

Figure 9. Close-up view of Fig. 8 showing cracked manufactured stone veneer (MSV) likely resulting from the absence of control joints in a large surface area of MSV.



to provide these movement joints can result in cracking, such as that exhibited in **Fig. 8** and **9**.

Insufficient Coverage on Back of Units

As previously discussed, ASTM C1780 requires that MSV units are to be set in a full setting bed mortar that is either applied directly to the backing surface or applied to the unit itself using the “back butter” method. Full coverage of the unit and full contact with the setting bed, unit, and prepared surface are required.

Full coverage is required to provide sufficient adhesion of the finish material to the base coat. Without appropriate adhesion, it is possible the veneer would not have sufficient shear or tensile bond strength to resist applied stresses, putting them at risk of detaching from the substrate. Additionally, voids in the setting bed (**Fig. 10**) can collect water that penetrates the finish coat. Water that remains in these void pockets is subject to freezing and thawing effects that can impart expansive forces on the back side of the adhered veneer and spall it from the wall surface.

CONCLUSION

In summary, MSV can be an economical, attractive, and durable cladding material when properly designed, detailed, and applied. With roots in portland cement plaster, MSV shares many of the same design and application techniques. As a result, the MSV base coat is often governed and specified by stucco standards ASTM C926 and ASTM C1063.

In addition to stucco, MSV also shares common elements with masonry cladding. Masonry codes/specifications (for example, TMS 402 and ASTM C270) and masonry

industry standards (for example, BIA Technical Note 28C, NCMA TEK 6-3c). Proper knowledge and understanding of these requirements and industry standards is key to a proper and successful installation.

Common pitfalls in the design and installation of MSV include improper integration of WRB materials, insufficient lath embedment, improper accommodation for differential movement, and insufficient coverage on the

back side of face units. Awareness of these common mistakes can avoid problems in MSV systems and costly repairs. 



Figure 10. Incomplete setting bed resulted in voids/pockets behind the adhered brick veneer.

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