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2025 BUILDING ENCLOSURE
SYMPOSIUM

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PROCEEDINGS

ST. LOUIS

MISSOURI, OCT 26-28 | 2025

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Tom Smith, RRC, AIA, F.SEI

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The Retrofit Dilemma: Balancing Deep Energy Goals with the Reality of an Existing Building

ABSTRACT

How far can we push the limits of an existing building to achieve significant energy and carbon savings while navigating the constraints of its structure and function? This paper delves into the challenges of pursuing a deep energy retrofit for a high-rise residential building, with the goal of achieving EnerPHit certification, the version of Passive House with slightly relaxed performance targets, designed for existing buildings. We will examine the design decisions, construction challenges, and necessary compromises made throughout the project, highlighting the delicate balance between ambitious energy targets and the practical realities of working with an existing building. By sharing lessons learned, this presentation aims to provide insights for other design professionals facing similar challenges.

LEARNING OBJECTIVES

- » Identify the challenges of balancing extreme energy savings while addressing the needs and experiences of the building residents.
- » Differentiate between the installation details and the requirements of mineral wool versus expanded polystyrene foam (EPS) exterior insulation and finish system (EIFS) assemblies.
- » Discuss common deficiencies in each system, appropriate repair methods, and how these issues are evaluated.
- » Identify common failure points in air/vapour barrier detailing, explore potential causes, and recommend solutions for both pre- and post-cladding installation.
- » Discuss the impact of cost on a project, from the design stage through to construction, particularly in the face of inevitable changes.

SPEAKER



Jennifer Hogan, REWC, RRO, CET, CRE, LEED AP, Certified Passive House Consultant
Project Principal
Pretium Engineering Inc.

Jennifer Hogan is passionate about building sciences and energy performance. She has been a building science consultant for over 17 years and uses her experience and knowledge to help clients achieve their energy and carbon goals as the leader of the Energy and Carbon Reduction team at Pretium. A lifelong learner, Hogan has dedicated herself to furthering her craft by obtaining numerous industry certifications. If you asked what her favorite thing is about her career, she would tell you that it is being able to share her love of the built environment with others.

AUTHOR:

Jennifer Hogan, REWC, RRO, CET, CRE, LEED AP, Certified Passive House Consultant



As humans, we like to push the limit of what's possible—first striving to design things bigger, and now striving to design them better. To hit our lofty targets for reducing our impact on the planet, we are being asked to push those same limits with our existing building stock. But what are the real-world implications of striving for a deep energy retrofit? Where does our desire to achieve peak performance clash with practicality?

In 2018, Raymond Desmarais Manor was a 43-year-old through-the-wall (TTW) brick building that both looked and performed its age. With significant capital expenditures on the horizon to maintain the building (Fig. 1), the owner, Windsor Essex Community Housing Corporation, saw an opportunity to make a change for the better. From that point on, this 20-story, 300-unit high-rise nonprofit housing building began its transformation guided by the EnerPHit standard—the most rigorous energy standard for existing buildings today.¹ EnerPHit is considered the most rigorous energy retrofit standard because it applies the stringent principles of Passive House to existing buildings, with strict performance-based criteria for energy use, airtightness, and thermal comfort, ensuring deep energy savings while accommodating the limitations of retrofit projects. This journey would lead to drastic changes to the interior building systems and, fittingly, a drastic change to the building exterior—worthy of its iconic location on the Detroit River, next to Caesars Palace in Windsor.

Ultimately, the project is modelled as achieving a reduction in energy consumption and greenhouse gas emissions of approximately 65%, which corresponds to an estimated annual

savings of 2,717,000 kWh or 282 tonnes of carbon dioxide equivalent (CO₂e). This equates to taking roughly 200 passenger vehicles off the road, all while saving an estimated \$300,000 annually.² But what did it take to get there?

STUDYING FEASIBILITY

The goal of achieving EnerPHit Certification became the driving force behind every design decision on the project. A feasibility study was done to determine options for each of the systems requiring renovation. Eighteen scenarios were modelled in Passive House Planning Package (PHPP) with changes to the exterior cladding, balconies, roof assembly, floor slab and foundation walls, ventilation design, domestic hot water system, vent stacks, penthouse, and lighting. The design options were narrowed down based on the EnerPHit requirements, impact on the residents, and price until an optimal recommendation was achieved. The main components of this recommended package included a new semi-centralized energy recovery ventilator (ERV) system, new through-



FIGURE 1. 255 Riverside Drive (Raymond Desmarais Manor) before the deep energy retrofit.

wall air conditioning units, below-grade insulation, new Passive House certified windows and doors, and new exterior insulation and finish system (EIFS) overcladding. Given the size and complexity of the scope, and with all 300 units in the building occupied, a phased approach was planned, as shown in Fig. 2.

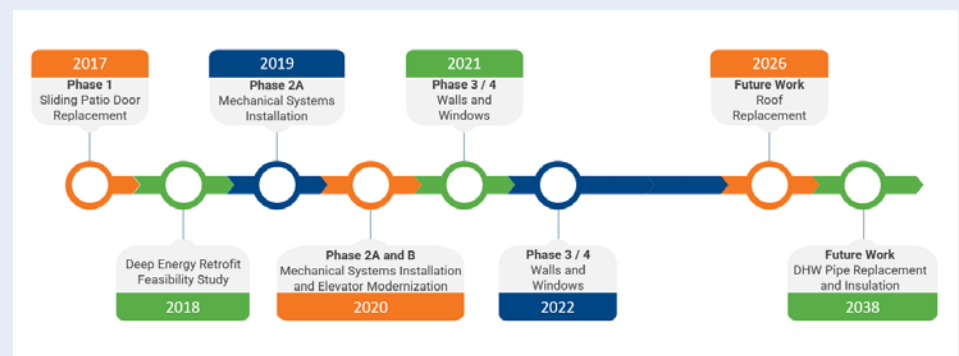


FIGURE 2. 255 Riverside Drive took a phased approach to the deep energy retrofit, targeting Step-Wise Certification through EnerPHit.

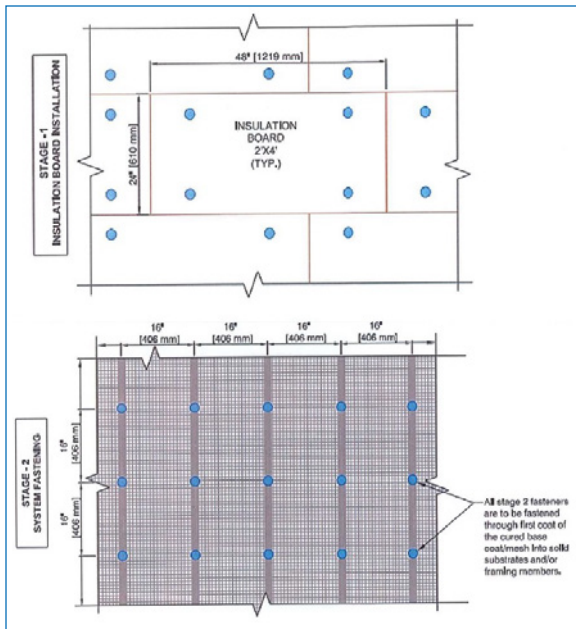


FIGURE 3. Two-stage fasteners for mineral wool exterior insulation and finish system. *Image from shop drawings prepared by Durabond.*

Additional future work was also identified and planned at the roof and domestic hot water system based on their remaining service life.

Throughout both the design and construction phases, the project faced several challenges with detailing that required close collaboration among all parties to balance the energy performance, tenant needs, and budget. The most notable of these include the following:

- » Windows with combustible sashes and frames at the north and south elevations
- » Thermal bridging at the balconies
- » Low-cost, active cooling system
- » Overall airtightness

MINERAL WOOL EIFS

At the time of the initiation of this project, options for Passive House certified windows in North America were limited. So, in advance of the feasibility study, along with the purchase and installation of the balcony doors, the windows were selected from a European supplier and are made of vinyl. This created a small challenge for the over cladding; per the 2012 *Ontario Building Code* requirements, since

the selected windows are combustible, the exterior walls must remain of non-combustible construction, which precluded the use of EIFS using EPS insulation.³ Ultimately, the design settled on a combination of EPS and mineral wool, with 150 mm of expanded polystyrene (EPS) on the end walls and 100 mm of mineral wool on the north and south elevations, which have windows and balconies.

The use of mineral wool insulation for EIFS construction came with some unique challenges fewer contractors have experience applying EIFS using mineral wool and the techniques required to ensure proper surface flatness and desired appearance.

EPS insulation in EIFS is required to be applied using channels of adhesive, which not only secure the insulation to the substrate but also create a drainage gap and plane behind the insulation to manage moisture. In some cases, mechanical fasteners are also used, depending on the type of substrate and its condition. When mineral wool insulation is used in EIFS applications, a two-stage fastening process is recommended. As shown in **Fig. 3**, the first set of fasteners secures the insulation directly to the substrate, while the second set is installed after the application of the base coat and reinforcing mesh to increase wind load resistance. To create the drainage plane

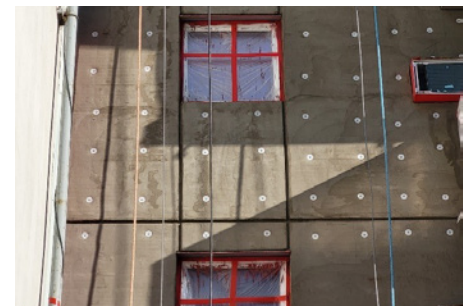
for the mineral wool system, you can either use boards with a pre-notched back face or pre-apply the ribbons of adhesive to the back of the board and allow them to cure prior to installation. Since the mineral wool boards are not being set into wet adhesive and cannot be rasped, which allows some “play” and leveling of the boards during application, additional surface preparation may be required to level the substrate in combination with a thicker base coat to level the surface is often necessary in achieving a visibly “flat” finish.

The quantity and placement of fasteners can significantly affect the thermal performance of a wall assembly by introducing thermal bridging. To mitigate this, a thermally broken anchor system was implemented. In the first stage, fasteners were installed with countersunk plastic sleeves, which were then fully covered with a 25 mm cap of mineral wool insulation to minimize thermal conductivity across the assembly (**Fig. 4**). The second stage employed flush-mounted sleeves, each capped with a small insulating plug positioned directly over the screw head (**Fig. 5**).

A few other key differences between the application procedures for EPS and mineral wool EIFS that had to be monitored on site are shown in **Table 1**.

BALCONY THERMAL BRIDGING

The balcony doors were replaced with Passive House certified doors prior to the full feasibility study. The doors were installed within the existing openings or, in some cases, moved to new openings. In either case, the doors were raised above the finished slab by approximately 294 mm and, in many locations, had



FIGURES 4 & 5. Stage 1 fastener through mineral wool insulation, countersunk to allow for insulation plug and stage 2 fasteners installed over the fully cured base coat.

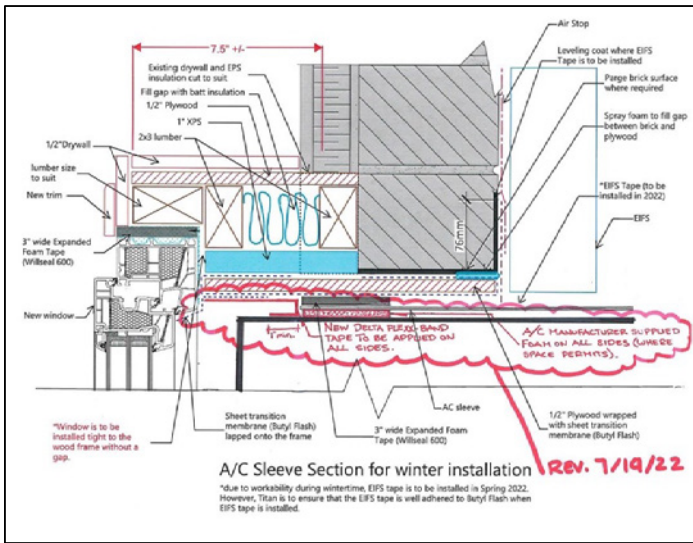


FIGURE 9. Final air-conditioning (A/C) sleeve section detail, including markups for additional insulation and air sealing measures.

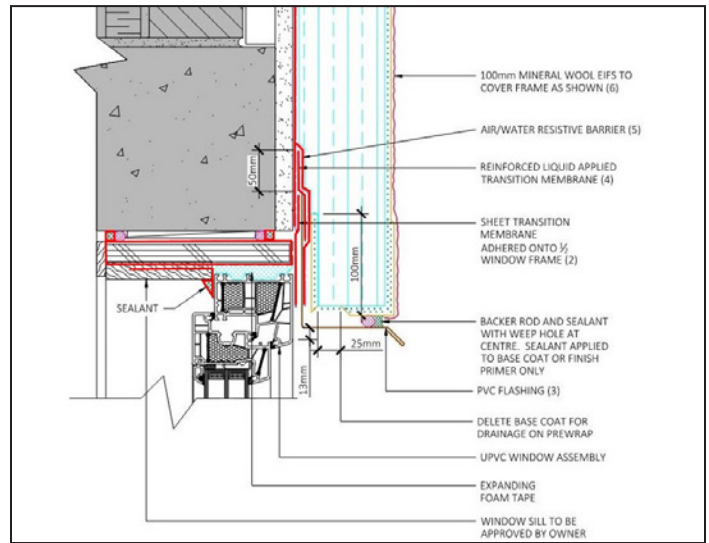


FIGURE 10. Air barrier components at window head highlighted in red.

Fig. 9 includes the final configuration, including insulation within the enclosure, as well as the critical expanding foam and tape air barrier system that was installed around the perimeter of the A/C units, connected to the back face of the new window frames, to achieve continuity of the air barrier.

The final installation, which can be seen in **Fig 11**, is functioning well, with some resident education required to ensure that during the winter months, the unit is disconnected and the window closed and latched. It is interesting that, to ensure that the window cannot be closed while the unit is running, it was decided to leave the electrical connection running through the window opening, in lieu of running it through the base of the new enclosure—a simple but effective failsafe.

AIRTIGHTNESS

Achieving airtightness in existing buildings relies heavily on the precision of detailing rather than just the application of air barrier materials across the wall field. While applying two coats of liquid-applied air barrier to the primary wall surfaces was essential, most observed deficiencies occurred at penetrations and transition areas.

Window perimeters posed a significant risk for air leakage, which was mitigated through a “belt and suspenders” strategy.

A combination of a liquid applied air barrier, transition membranes, air barrier tapes, and sealant was used to create a robust detail, with seals connecting to both the interior and exterior of the window frame, as shown in **Figs. 10 and 12**.

One of the most frequent issues during construction was at the transition membranes, where insufficient pressure rolling prevented full adhesion, and poorly executed cuts (especially at inside and outside corners) left unsealed gaps. These gaps were uncovered during diagnostic airtightness testing, where the building interior was pressurized and tracer gas was released to locate leaks. An example of one such leak is shown in **Fig. 13**.

To achieve either EnerPHit certification, a building must demonstrate that it has

achieved an airtightness of 1.0 ACH at 50 Pa.¹ This is verified by completing a whole-building blower door test in accordance with EN 13829 (Method A). With large, occupied buildings, completing one whole-building air leakage test can be challenging. For this reason, Passive House Certifiers will often allow the building to be tested in sections to reduce the impact on the occupants while still achieving the goal of testing 100% of the exterior enclosure.

The plan at Riverside Drive included testing each floor by guarding the floor above and below, as shown in **Fig. 14**, and moving sequentially either up or down the building. The testing is somewhat invasive for the residents, requiring that they not enter or exit the test floor, that their unit doors and all doors within the unit remain open, and that all exterior doors and



FIGURE 11. Completed window enclosure for the through-the-wall air-conditioning system.



FIGURE 12. Supplemental interior air barrier application at window perimeter.

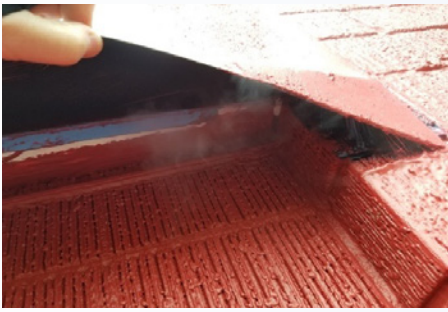


FIGURE 13. Poorly bonded transition membrane, with tracer gas leak during diagnostic airtightness testing.



FIGURE 14. Sample of guarding for a whole-floor test, with the test floor in red and the guards in blue.

windows remain closed and latched for the duration of the test, which can take several hours from setup to completion. It would therefore be necessary to provide security on each floor for the duration of the testing to help mitigate resident concerns

regarding potential unrestricted access to their unit. With the exterior enclosure only recently completed, this testing has not yet been completed, with the client further evaluating the impact and cost associated with this final step toward certification.

A FUTURE CHALLENGE WITH A TOUCH OF OPPORTUNITY

With the roof replacement on deck for 2026, the realities of the congestion on the rooftop are just now setting in. Because the roof is covered with raised penthouses, long runs of cables, wood walkways, and a plethora of antenna and dishes, the work to coordinate with service providers and prepare for the reroofing project will require significant time and attention. However, the roof has also presented an opportunity to increase the performance to an RSI of 7, which will allow the building to make up the performance lost because of the remaining balcony thermal bridge, and at a much lower price point.

CONCLUSION

While achieving ultra-low energy targets is entirely possible with unlimited budgets or in the controlled conditions of new or unoccupied buildings, the reality of retrofitting existing buildings is far more complex and constrained. Pushing for extreme performance standards can sometimes lead to

expensive and impractical details. From an academic perspective, pursuing these targets can be valuable, as it pushes the boundaries of our understanding and forces innovation. However, we must acknowledge the limits imposed by existing structures, budgets, and occupant needs. We should aim for thoughtful, context-sensitive upgrades that significantly improve performance without compromising feasibility.

In the case of Raymond Desmairais Manor, the final decision to certify or not remains to be made. However, with or without it, the seniors who occupy the building can enjoy a significantly improved indoor environment—free from cold exterior walls and drafts and a with noticeable reduction in noise from busy Riverside Drive. Combined with significantly lower utility costs, the final product is one that balances results and reality (Fig. 15).



FIGURE 15. Original to rendering and design to construction completion—the transformation of 255 Riverside Drive East.

REFERENCES

- 1 Passive House Institute. *Criteria for Buildings: Passive House – EnerPHit – PHI Low Energy Building*. Version 10c. Darmstadt, Germany: Passive House Institute, January 2023. Revised January 20, 2023.
- 2 Natural Resources Canada. Greenhouse Gas Equivalencies Calculator. <https://oee.nrcan.gc.ca/corporate/statistics/neud/dpa/calculator/ghg-calculator.cfm>.
- 3 Ontario Ministry of Municipal Affairs and Housing. *Ontario Building Code*. Toronto, ON, Canada: Government of Ontario, 2012. Updated as amended.
- 4 EIFS Council of Canada. *EIFS Practice Manual*. Version 1.0. Richmond Hill, ON: EIFS Council of Canada, 2013.

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Case Study on Insulated Concrete Form Panel Waterproofing Failures

ABSTRACT

Insulated concrete forms (ICFs) are becoming increasingly popular for custom homes and do-it-yourself enthusiasts. However, details can be hard to find, and many trades may be unfamiliar with their unique requirements. This presentation will explore a case study on construction defects in a newly built \$1.3 million home with insulated concrete forms. This session will provide an overview of the process, from the first leak detection all the way through to litigation. We will discuss a review of the different types of testing that took place, such as nondestructive, leak detection, mold, blower door, infrared thermography, and destructive testing. The general contractor, who was new to building with ICF panels, made one major mistake: assuming the panels were effectively airtight and watertight. The significant defects included poorly installed foundation waterproofing, failure to flash the window/door rough openings, failure to install through-wall flashings, and discontinuity between the roof and wall flashings. Generally, the panels failed to create a continuous exterior air and water barrier system at every opportunity. We will review the pros and cons of ICF construction and will identify the necessary waterproofing and flashing requirements. We will also discuss the conflicts between the ICF requirements and those of other trades, including carpentry, masonry, windows, and roofing. We will also review the necessary scope required to remediate the defects in order to give homeowners a safe and dry home. We will then touch on our steps to prepare for a difficult litigation process.

LEARNING OBJECTIVES

- » Discuss the fundamentals of insulated concrete form (ICF) panel construction.
- » Identify appropriate methods in waterproofing ICF foundations.
- » Evaluate the requirements for flashing in ICF construction.
- » Explain how to remediate defects after construction is complete.
- » Assess appropriate documents and preparation for litigation.

SPEAKER



Michael Williams, F-IIBEC, RRC, RWC, RRO, RPA, RCIF, CCMi, BECxP, CxA+BE, CIT 2, UAV
President
Building Envelope Consulting LLC

Michael Williams began his career in the roofing industry by hand-nailing his first shingle roof in the summer of 1980, during the presidency of Jimmy Carter. Since then, he has dedicated his professional life to roofing, waterproofing, and building enclosures. In 1992, he established his own roofing company in Nebraska, focusing on the installation of standing-seam and architectural metal products. In 2000, he sold his company and relocated to the Washington, DC, area, where he took on the role of roofing and waterproofing consultant for a local engineering firm. Over the next decade, he developed expertise in built-up and single-ply roofing systems, as well as in exterior walls, plaza decks, coatings, flashing, air barriers, doors, and windows. In 2006, he founded Building Envelope Consulting and currently serves as its president.

AUTHOR:

Michael Williams, RRC, RWC, RRO, RPA, RCIF, CCMi, BECxP, CxA+BE, CIT 2, UAV



Insulated concrete forms (ICFs) are a revolutionary building material known for efficiency, sustainability, and strength. Popular among custom homeowners, light industrial, and do-it-yourself enthusiasts, ICF construction offers energy efficiency, sound insulation, and disaster resilience benefits. Despite its advantages, ICF construction presents unique challenges. The construction industry is navigating a learning curve regarding the particular requirements. In this case study, we examine a \$1.3 million custom-built home plagued by construction defects resulting from misapplications in ICF installation. This study highlights the critical nature of understanding ICF technology and the impacts of construction missteps on building integrity.

ICF panels are unique because they form the structure, insulation, air/water barriers, and backup walls for the wall claddings. Manufacturers claim there is no need to add any of those components. They are easy to install and modify for penetrations and mechanical, electrical, and plumbing components, but require concrete pump trucks to place the concrete in the cells. ICFs are hollow styrofoam blocks that stack to form a wall, which are then filled with concrete to create a solid, secure structure. Using ICFs enhances the building's thermal insulation, making it ideal for energy-efficient designs. However, the technology comes with specific construction requirements unfamiliar to many builders. Misunderstandings can lead to severe structural issues. Proper training and experience are crucial when working with ICFs to avoid errors such as incorrect concrete pour rates and insufficient reinforcement layout.

The property consisted of a four-story (Fig. 1), 2,800 ft² single-family home located just south of Washington, DC, completed in 2021. The lot exhibits a significant grade descending from rear to front, resulting in surface runoff from the backyard and adjacent properties channeling toward the rear foundation of the residence. The home's lowest level consists of a two-car garage, storage, and living space. The second level is the rear entrance and living areas, including the kitchen and dining area. The third level has bedrooms and a master bedroom with a balcony. The top floor includes a loft, with a bedroom and a walkout rooftop balcony. The exterior walls are constructed with ICF panels; however, the interior framing and top floor are wood-framed. The exterior cladding is a combination of brick, stone, and fiber cement lap siding. The windows are flanged vinyl windows, but many of the doors, including the garage doors, were custom-made on-site. The roofing is a combination of low-sloped single-ply ethylene propylene diene terpolymer (EPDM) membranes and steep-sloped copper standing seam. No air barrier or weather-resistive barrier (WRB) was installed on the ICF walls before cladding. The general contractor (GC) was working on just his second home.

The owner reported water and air intrusion, and Building Envelope Consulting (BEC) was hired to perform multiple investigations. For this paper, we will focus on the water intrusion. Water entered the home through the foundation, some doors, some windows, the rear patio and the terrace roof.

The GC made many assumptions regarding the airtightness and



FIGURE 1. Overall view of the subject property during construction.

watertightness of the ICF panels, leaving the masonry contractor without much direction.

The following major defects were identified:

1. Poorly installed foundation waterproofing, no primer, too short, and no termination bar (Fig. 2).
2. Failure to flash window and door rough openings. Flanged windows were not sealed to the ICF but only to the brick veneer and siding



FIGURE 2. Waterproofing was applied without primer or termination bars.



FIGURE 3. Doors and windows were installed without flashing.

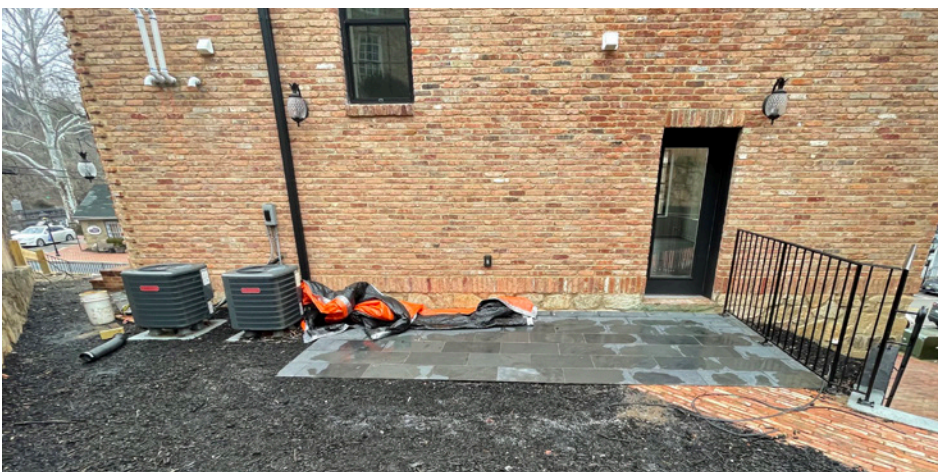


FIGURE 4. The horizontal waterproofing did not turn up the wall.



FIGURE 5. The insulated concrete form panels have continuous insulation.

Failure to create a continuous exterior barrier resulted in massive water intrusion into every level of the home. These faults stemmed from a lack of understanding of ICF requirements and negligence in the detailed execution of standard waterproofing practices.

PROS AND CONS OF ICF CONSTRUCTION

ICF panels offer numerous advantages:

- 1. Energy Efficiency:** ICF panels provide excellent insulation, which reduces energy consumption for heating and cooling. This leads to lower utility bills and a smaller carbon footprint (Fig. 5).
- 2. Thermal Mass:** The concrete core of an ICF panel provides thermal mass, helping to regulate indoor temperatures by absorbing and releasing heat.

- 3. Sound Insulation:** ICF walls have superior sound-dampening qualities compared to traditional framing, creating a quieter indoor environment.
- 4. Speed of Construction:** ICF panels are quick to assemble, reducing labor costs and construction time. They can be erected rapidly, and since they combine both formwork and insulation, there is less need for multiple materials.
- 5. Durability and Resilience:** ICF structures are highly durable and resistant to impacts, termites, mold, and rot. They can withstand severe weather conditions, including high winds and flooding.
- 6. Fire Resistance:** Concrete is non-combustible, which gives ICF buildings enhanced fire resistance compared to traditional wood-framed structures.
- 7. Design Flexibility:** ICF panels can be shaped and modified to accommodate various architectural designs, providing versatility for builders and architects.
- 8. Sustainability:** ICFs can be made from recycled materials, and their energy efficiency contributes to sustainable building practices.
- 9. Reduced Construction Waste:** Since ICF panels are manufactured to specific dimensions, there is often less on-site waste than traditional building methods.
- 10. Long-Term Performance:** ICF buildings often have a longer lifespan due to their sturdy materials and construction methods, leading to lower long-term maintenance costs.

ICF panels come with some disadvantages and challenges:

- 1. Higher Initial Cost:** The up-front cost of ICF construction is higher than traditional building methods due to the materials and technology involved. However, this may be offset by energy savings over time.
- 2. Limited Availability:** Depending on the region, ICF products may not be readily available. This can impact procurement or increase transportation costs.

from the exterior. This resulted in extensive interior damage (Fig. 3).

- 3. Discontinuity in roof-wall flashings and no through-wall flashing:** missing connections in the roof and wall flashings compromised the building envelope (Fig. 4).

- Require Skilled Labor:** ICF construction may require specialized skills and knowledge that not all contractors possess, leading to potential difficulties in finding experienced labor. Most tradespeople are not familiar with ICF construction.
- Plumbing and Electrical Challenges:** Installing plumbing and electrical systems can be more complex, as they need to be routed through or



FIGURE 6. Water leaks appeared immediately.

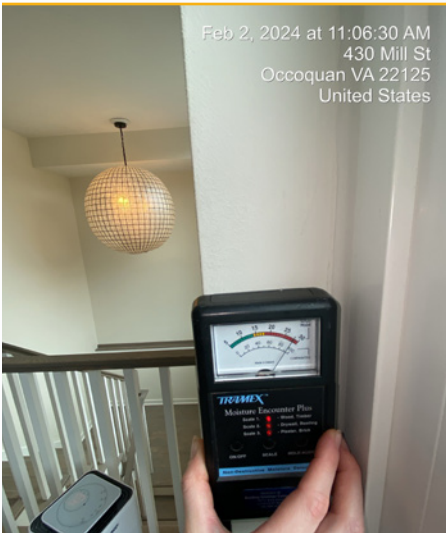


FIGURE 7. Nondestructive testing revealed many wet locations on the walls and floors.

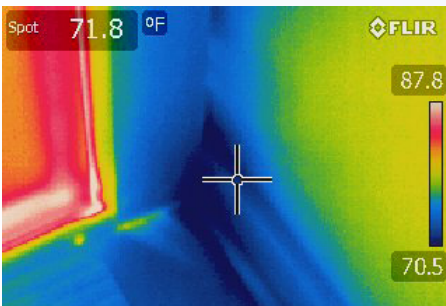


FIGURE 8. Blower door with infrared showed many locations of air infiltration.

around the concrete forms, which may require additional planning. This requires extra training.

- Fire Code Considerations:** While concrete is fire-resistant, any foam insulation used may be more susceptible to fire unless properly rated. Builders must understand and adhere to local building codes related to fire safety.
- Moisture Concerns:** If not properly managed, moisture infiltration can occur, leading to potential issues with mold or mildew within the walls if the ICF is not adequately protected or if the building envelope is not designed correctly.
- Settlement Risks:** Concrete is heavy. In some cases, if the underlying soil is not adequately prepared, concerns may arise about settlement or shifting that could impact the integrity of the ICF structure over time.

These challenges highlight the importance of training and collaboration between trades to ensure the successful integration of mechanical systems in ICF construction projects.

The new owners immediately began to experience water intrusion (Fig. 6). They contacted a building envelope consultant when it became apparent the GC/developer was not going to correct any of the major problems. We were hired in the spring of 2022 by the owner's legal counsel to assist with repairs and possible litigation. The owner was prepared to start making repairs to make the home habitable without the GC's assistance.

NONDESTRUCTIVE TESTING METHODOLOGIES

- Nondestructive testing included document review, visual survey, moisture meter and mold testing. We found water damage and mold on all four floors (Fig. 7).
- Water spray testing proved to be somewhat destructive because water seeped in everywhere we tested.
- We then put water in the yard drains but did not exit the other end of the drain line, so we had a plumber videotape the lines from the house and the exterior yard drains.



FIGURE 9. Destructive testing was performed to document concealed conditions.



FIGURE 10. No flashing or waterproofing was present at the windows, as expected.

- Blower door testing was combined with infrared thermography and smoke pens. Air loss was twice the code limit, and we found several areas that lacked insulation (Fig. 8).

DESTRUCTIVE TESTING

- To document concealed conditions, we removed sections of brick, doors, windows, siding/trim, roofing, and patio tiles with the assistance of a contractor. We excavated the soil to observe the foundation waterproofing and terminations, as well as the subsurface drain tiles (Fig. 9).

FINDINGS

The testing revealed that window/door openings were not flashed or not properly flashed, there was no WRB, there were no sill pans, and there was no attempt to seal the foundation waterproofing or roof-to-wall details. We found little to no effort to install flashing that would keep water out of the building (Fig. 10).



FIGURE 11. The patio waterproofing failed and was not tied into the wall or foundation.



FIGURE 12. The foundation waterproofing did not extend to the top of the foundation walls.

We also found a red shower/tub waterproofing material used to seal the back patio; this material was not tied into the foundation waterproofing or the adjacent walls above (Fig. 11, 12).

Another major contributing factor was that the home was situated on a steep slope, and we discovered that the drain line from the yard and downspouts had been severed during the installation of the front retaining wall, resulting in the foundation wall being under hydrostatic pressure. The foundation waterproofing stopped below the finished grade, lacked the required primer and termination bars, allowing water to easily enter through the foundation, which caused mold and water damage.

RECOMMENDATIONS

Our recommended solution was to remove most of the cladding, install new flashing at the doors, windows, penetrations, and roof-to-wall conditions, and extend and adequately terminate the waterproofing. All custom doors and windows needed to be

replaced with quality new-construction components. Repairs to the foundation and yard drains were also required (Fig. 13, 14).

Repairs will require educating the workforce on the peculiarities of ICFs to prevent future mistakes.

REPAIRS

The homeowner attempted to remediate several water problems by replacing some doors and windows, but replaced the components without adding the necessary flashings in the rough openings, thereby failing to accomplish their intended goal. The door and window contractor simply replaced the doors and windows as directed without addressing the flashing issues (Fig. 15).

The GC made no additional repairs after BEC was involved in the project, and the case settled in 2024.

CONCLUSION

ICF foundations demand distinct waterproofing strategies, focusing on system integration that includes foundation drains, correct membrane applications, and adequate sealing of seams and penetrations. Flashing around openings requires specialized attention, aligning with the ICF panel system to maintain barrier continuity and prevent water ingress. Effective execution and coordination address issues arising from improper flashing installations by the untrained workforce. ICF manufacturers state that ICF walls are air, water, and vapor resistant, and that a weather-resistive barrier is not required; however, proper flashings are undoubtedly necessary. A complete air barrier with integrated flashings is still needed. The designer and/or contractor must understand the limitations of the ICF and pay special attention to penetrations and other potential weak points in the system, and design in redundancy where possible.

ICF construction offers tremendous potential but mandates precise understanding and application. This case exemplifies how missteps propagate significant structural issues, emphasizing the importance of



FIGURE 13. Photo of water “squirting” out of the retaining wall under hydrostatic pressure.



FIGURE 14. The excavation had to be reinforced due to constant water movement below the concrete retaining wall .



FIGURE 15. A window installer replaced the kitchen windows and doors, but did not add flashing and did not eliminate the water intrusion.

training and adherence to guidelines. This comprehensive analysis compels industry stakeholders to integrate thorough education and meticulous procedural adherence in future ICF projects to assure quality and minimize defects. Learning from these failures, we advocate for enhanced industry standards and accountability to safeguard the integrity of ICF structures and advance the construction industry globally.

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Ramova Theatre Renewed: Restoring a “Peaceful Place”

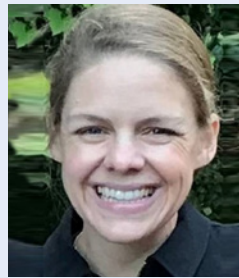
ABSTRACT

Adaptive reuse of existing buildings enhances sustainability and resiliency in the built environment while preserving the sense of place and stimulating economic growth. Recent economic and social shifts have increased the financial attractiveness of these conversions. Design professionals managing adaptive reuse projects must balance various, sometimes opposing factors, including historic preservation standards, code requirements, and client expectations. The Ramova Theatre project exemplifies the benefits and challenges of such endeavors. Originally constructed in 1929, the Ramova Theatre had been vacant since 1986. The comprehensive adaptive reuse project, led by O’Riley Office LLC, transformed the site into a vibrant community hub featuring a live performance theater, restaurant, and brewery within the existing footprint of a historic theater and commercial space. The project encompassed exterior enclosure rehabilitation, including masonry restoration and repairs, roof replacement, window restoration, and interior plaster restoration. The authors discuss their roles in the Ramova project team and illustrate the challenges they faced, such as maintaining authenticity, integrating contemporary regulations and codes into a historic building, and balancing preservation to deliver a successful project to clients. The Ramova Theatre project demonstrates how adaptive reuse can preserve cultural heritage, promote sustainability, and stimulate economic growth.

LEARNING OBJECTIVES

- » Summarize how masonry facade repairs can be successfully implemented within budget and schedule constraints by utilizing a collaborative approach between owner, architect/engineer, and contractor.
- » Discuss the considerations for interfaces of masonry walls with windows, roofs, and balconies.
- » Recognize building enclosure and interior improvements to consider during adaptive reuse, including discussions regarding code compliance requirements.
- » Explain the need for an integrated, multidisciplinary planning approach to the basic adaptive reuse principles that apply to existing building reuse strategies.

SPEAKERS



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Associates Inc. in Chicago, Illinois. She has nearly 20 years of experience related to the investigation and repair of historic building facades. She has performed numerous evaluations, prepared repair documents, and provided construction period observations for many historic masonry (stone, brick, and terra-cotta) facades as a part of adaptive reuse projects. She has authored multiple articles and given numerous presentations related to masonry, adaptive reuse, and historic preservation.



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Principal
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Dan O’Riley is a principal of O’Riley Office LLC, where he leads all projects in the office.

With more than 25 years of experience, he specializes in leading architectural design, with multidisciplinary teams working on programmatically complex projects. As an advocate for collaborative design, he works closely with clients to cultivate strong, meaningful relationships on each project. Prior to founding O’Riley Office, he spent 10 years working for the Chicago, Illinois, office of Skidmore, Owings and Merrill LLP, where he was a studio head. There, he oversaw a 30-person “office within an office” focused on domestic, complex, program-driven, institutional projects, such as hospitals, research laboratories, and university buildings.

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Adaptive reuse is a significant testament to human ingenuity and respect for historical preservation. The Ramova Theatre, an architectural and cultural landmark, holds a narrative deeply intertwined with Chicago's history of resilience and transformation. Its story encompasses rise, decline, and eventual rebirth, illustrating how historic landmarks can adapt to changing times while maintaining their intrinsic character. Over the years, the theater has witnessed shifts in entertainment trends, community dynamics, and economic challenges, serving as a silent symbol of a bygone era.

As urbanization and modernization progress globally, there is a growing necessity to harmonize the new with the old. The Ramova Theatre stands as a notable example of adaptive reuse, highlighting the potential to preserve cultural heritage while integrating contemporary functionality.

HISTORICAL SIGNIFICANCE OF THE RAMOVA THEATRE

The Ramova Theatre, nestled in the heart of Chicago's Bridgeport neighborhood, has long been a cherished cultural landmark. Opened in 1929, it was designed by architect Meyer O. Nathan in the Spanish Revival style, which was widely popular during that era. With its ornate facade, grand interiors, and impressive auditorium, the theater became a beacon of entertainment for the local community. Over the decades, it hosted a myriad of performances, from vaudeville acts to cinematic screenings, leaving an indelible mark on the city's cultural tapestry.

Despite its initial success and popularity, the Ramova Theatre faced challenges



FIGURE 1. Overall view of Ramova Theatre east facade prior to adaptive reuse in 2020.

as the entertainment industry evolved. The advent of television, changes in consumer behavior, and the rise of multiplex cinemas contributed to the gradual decline of single-screen theaters. By the late 1980s, the Ramova Theatre struggled to attract audiences and maintain financial viability. In 1985, the theater closed its doors, leaving behind a vacant building that gradually fell into disrepair (**Fig. 1**).

In 2012, the City of Chicago (City) took ownership of the building as a way of saving the building from demolition but had no plan for redevelopment. While the building sat vacant for nearly 40 years, the community grew nostalgic of an earlier era when theaters served as a center of community and civic engagement.

VISION FOR RAMOVA THEATRE'S REVIVAL

The revival of the Ramova Theatre was driven by a vision to restore its grandeur and repurpose it as a multifunctional space that would once again serve as a cultural hub for the community. In 2017, Tyler Nevius initiated the reimagining, rehabilitation, and adaptive reuse of the project. In 2020, Baum Revision joined Tyler, adding their expertise in adaptive reuse and the historic tax credits process with the Illinois State Historic Preservation Office and the National Park Service. In 2023, McHugh Construction completed the rehabilitation and renovation project.

Initially envisioned by ownership as a live music venue and brewery, the authors were invited to participate in due diligence assessments and planning

along with the general contractor. This collaboration was aimed at developing repair scopes and preliminary budgets for the building's exterior facades, as well as full programming for the proposed new venue. Following due diligence and feasibility studies, ownership and multiple investment partners proceeded with the adaptive reuse plan, obtaining approvals from the City of Chicago amidst the Covid-19 pandemic. O'Riley Office LLC developed a conceptual plan for adaptive reuse of the site, including the Ramova Theatre building, the vacant lot south of the theater, and the commercial building north of the theater, which then led to O'Riley Office LLC and Wiss, Janney, Elstner Associates Inc. (the design team) working collaboratively to provide repair solutions for the exterior enclosure and interior decorative plaster for the new live music venue and brewery.

Sitting unused for nearly 40 years, the Ramova had fallen into significant disrepair due to deferred maintenance

stemming from ownership structure, financial difficulties, site logistics, code regulations, and other challenges. Issues such as material durability, environmental and sustainability concerns, and historic preservation or political influences contributed to vacancy and severe deterioration (Fig. 2, 3). Given its vacancy since the 1980s, a team experienced in adaptive reuse projects was essential to address unforeseen conditions during construction without significant schedule or budget impacts. Ownership, unfamiliar with adaptive reuse projects, faced numerous unexpected conditions that required attention during the restoration of the existing historic building.

UNDERSTANDING ADAPTIVE REUSE

Adaptive reuse of existing buildings is one of the most effective strategies for enhancing sustainability and resilience in the built environment. Recent economic and social shifts have made these

conversions more financially viable. Adaptive reuse involves repurposing old structures for new functions while preserving their historical and architectural integrity. This approach not only prevents demolition but also revitalizes communities by creating spaces that meet contemporary needs.

The adaptive reuse of the Ramova Theatre exemplifies this concept, demonstrating the potential to seamlessly integrate history with modernity. It underscores the necessity for collaboration among an interdisciplinary team of designers, contractors, and ownership to apply best practices for successful adaptive reuse of culturally significant spaces. The project methodology established general repair parameters during the investigation and design phases that were refined throughout construction. Flexibility in repair methods was essential to meet the owner's expectations and financial constraints. Collaboration between



FIGURE 2. View of existing conditions of the east facade elements (terra-cotta, marquee and blade signs, and monumental window) of the Ramova Theatre in spring 2021.

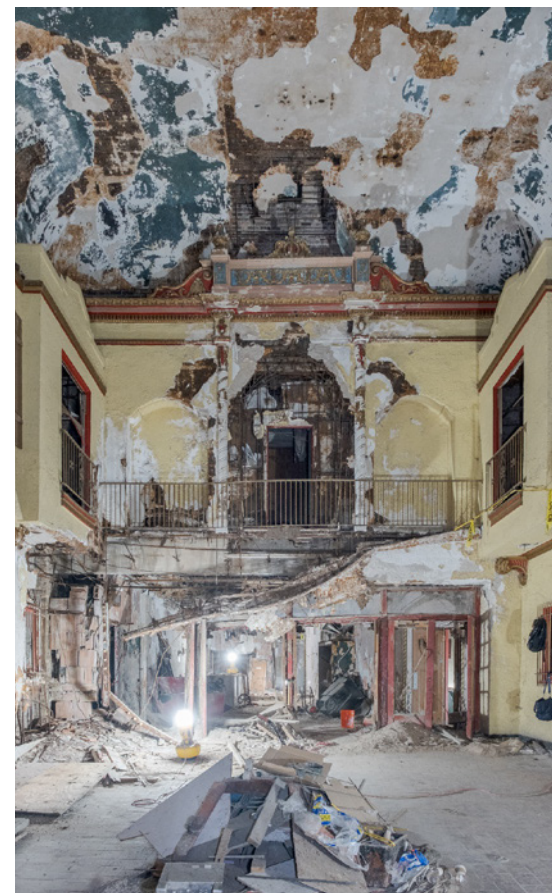


FIGURE 3. Interior view (from main entrance) of the existing plaster conditions of the lobby space.



FIGURE 4. View of restored facade elements (terra-cotta, marquee and blade signs, and monumental window) of the Ramova Theatre in winter 2024. *Photo credit: Eric Laignel.*

the contractor and architect/engineer was crucial to achieving project goals, maintaining the schedule, and adhering to the budget.

ARCHITECTURAL REHABILITATION

Restoring the architectural splendor of the Ramova Theatre’s exterior facades and interior plasterwork required significant attention to detail. The original Spanish Revival elements were carefully preserved and renovated,

ensuring that the building’s historical integrity was maintained. The theater’s iconic marquee was also restored to its former glory, serving as a visual reminder of its storied past.

Exterior Enclosure

The scope of the repairs for the exterior enclosure of the Ramova Theatre aimed to retain its historic charm while ensuring structural integrity and modern functionality. The process commenced with a limited assessment of the facades to identify areas that required intervention, such as deteriorated masonry; damaged architectural details, specifically the terra-cotta arches, finials, window heads, and compromised structural elements for the signage supports; and concealed steel support for the brick and terra-cotta masonry. The repair approach for the exterior enclosure and the interior plaster restoration evolved throughout the project to address unforeseen conditions and interior programming adjustments to meet budgetary constraints and historic preservation tax incentive requirements.

Exterior enclosure preservation efforts focused on the original theater entry facade, featuring a large stained glass and divided-lite window, marquee, and neon building signage as focal points. All but one piece of the original stained glass rosette was reused and set in new lead coming within the larger vision glass window, preserving the window’s appearance and its functional effect of

admitting substantial daylight into the theater’s entry lobby. Ornamental terra-cotta on the entry facade was repaired to the greatest extent possible and replaced only where necessary.

Special emphasis was placed on restoring the theater’s iconic marquee and blade sign. The marquee and blade sign were dismantled, refurbished, and reassembled, and new energy-efficient lighting was used to illuminate the marquee to its original brilliance (**Fig. 4**).

Interior Plaster Restoration

The restoration of the intricate plasterwork was essential to bring the theater back to its original luster. Many interventions to the theater were made to make the space suitable for today’s needs, including the addition of a large balcony for additional patrons, a smaller cantilevered VIP balcony, as well as the retrofitting of existing roofing trusses to support the loads of new theater acoustic and lighting equipment. Creative plaster restoration was also required at these interfaces. The interior plaster restoration aimed to revive the ornate details that had adorned the theater since its inception, while allowing for modern interpretation and adjustment.

Where necessary, missing or damaged ornamental elements were recreated using molds taken from existing, intact sections, ensuring a seamless blend between the original and restored areas (**Fig. 5, 6**). Restoration plaster ornamentation happened in the theater,



FIGURE 5. Interior view (from the stage) of the theater space showing the plaster conditions of the auditorium. *Photo credit: Danielle Campbell.*



FIGURE 6. Interior view of the theater space showing the plaster conditions of the auditorium prior to repairs, highlighting repair scope.



FIGURE 7. View during construction, showing new support steel structure for balcony, including footing repairs and interface with interior plaster.

the lobby, and the concession. This also included the need to adjust the scale of select ornamental components to accommodate elements such as the VIP balcony and the new large-scale balcony (Fig. 7). Additionally, contemporary acoustic requirements and retrofits for the roof trusses for new sound and light equipment required repairs for the plaster ceiling. The restored plasterwork, now

in a contemporary color palette, stands as a testament to the craftsmanship of the past, adding to the theater’s grandeur and elegance (Fig. 8).

MODIFIED DESIGN-BUILD METHODOLOGY

O’Riley and WJE used a modified design-build approach for the exterior and interior restoration, which allowed for an early demolition phase, quicker glass-fiber-reinforced concrete (GFRP) fabrication, and timely facade repairs. This method helped align the scope of work with funding schedules and enabled on-site solutions based on existing conditions. This methodology also proved effective in navigating the challenges of industry-wide material shortages and back orders resulting from the Covid-19 pandemic.

The team created schematic elevation drawings from a limited condition survey to indicate repair locations and types. These drawings, along with a written scope of work, helped subcontractors estimate repair costs and obtain permits from the City of Chicago. This approach required significant field time for the design team while allowing for quick adaptations to field conditions during the construction phase. Once in construction, a communicative

relationship between the design team and the repair subcontractors was an integral part of the project’s success.

The methodology was effective in addressing early Covid-19 delays and allowed rapid responses to unforeseen issues in exterior and interior restorations. It facilitated coordination of new systems and structures within the theater.

The process involved the following steps:

- » Initial inspection
- » Initial demolition and follow-up inspections
- » Repair assignment and detail development
- » Periodic inspections and site coordination
- » Punch list and final inspections

Adaptive reuse projects require design professionals to balance numerous factors, including historic preservation standards, code requirements, client expectations, and costs. Ownership of the Ramova Theatre project was new to adaptive reuse, and the design team provided practical guidance on preservation, restoration, and rehabilitation according to historic standards. This involved negotiating with preservation agencies about necessary repairs and beautification. Historic preservation involves balancing repair scope, replacement justification, when to forgo repairs, and managing client expectations regarding the patina of historic buildings. These challenges were amplified for the Ramova Theatre, as it had to meet requirements for new service, contemporary codes, and historic preservation tax incentives. The design team worked collaboratively with ownership to ensure that the project met aesthetic, functionality, and preservation expectations of all stakeholders, which were particularly important for the interior.

PROGRAMMING AND PLANNING

While preserving the Ramova Theatre’s historic charm was paramount, the adaptive reuse project aimed to create modern functional spaces that cater to contemporary needs. The auditorium, once home to captivating performances, was transformed into a



FIGURE 8. Interior view (from main entrance) of the restored plaster conditions of the lobby space. Photo credit: Eric Laignel.

versatile event space capable of hosting concerts, theatrical productions, and community gatherings. State-of-the-art lighting and sound systems as well as acoustic treatments were integrated to ensure that the space met the technical requirements of modern performances (Fig. 9).

From the outset, the client intended for the existing auditorium to be a standing room, live performance venue served by a brewery and kitchen in the adjacent commercial building. The brewery and kitchen were also to serve beer and food in the taproom housed in the commercial building. Financial modeling, combined with market analysis, determined the required capacity for any auditorium reconfiguration, as well as the volume and styles of beer to be brewed, which in turn determined the size of the brewery. Auditorium and brewery size requirements, coupled with the existing building conditions, such as structural capacity and access, informed the final location and sizing of all the large program elements.

SUSTAINABILITY AND ENVIRONMENTAL CONSIDERATIONS

Adaptive reuse is inherently sustainable, as it reduces the environmental impact associated with building new structures. The revival of the Ramova Theatre incorporated additional sustainability measures, such as energy-efficient lighting, HVAC systems, and water-saving fixtures. Additionally, the use of locally sourced materials and the preservation of existing architectural elements minimized the project's carbon footprint.

The project met the Chicago Sustainable Development Policy by exceeding the Chicago Energy Code by more than 20% and by utilizing plumbing fixtures that contribute to a 40% reduction in water usage. Additionally, the project is a recipient of a loan through the Commercial Property Assessed Clean Energy (C-PACE) finance program, based on use of high-efficiency building systems and high-performing roofing and window wall systems. Additionally, this project is an example of the most

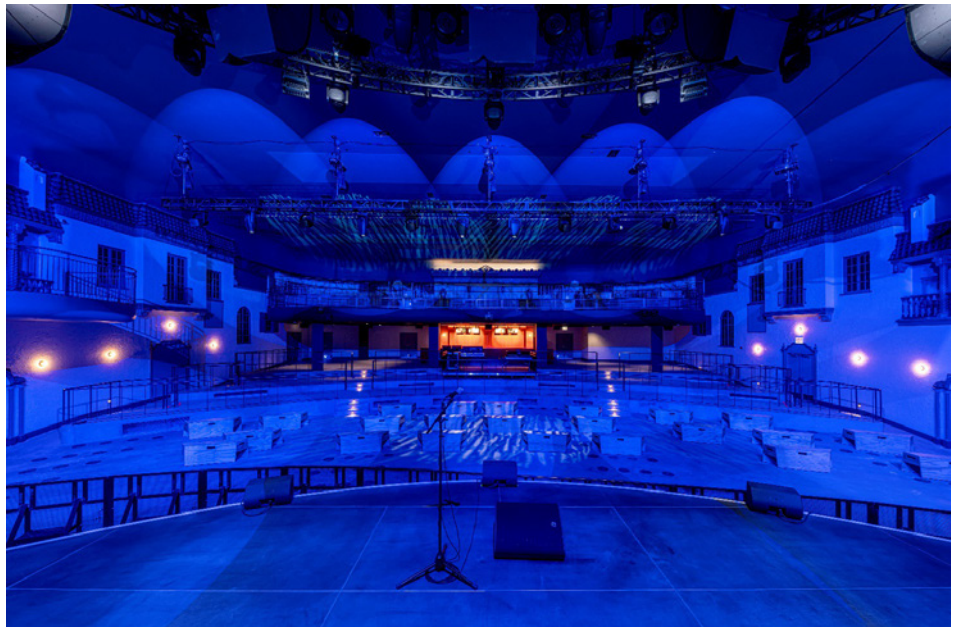


FIGURE 9. Interior view (from the stage) of the theater space showing the restored plaster conditions of the auditorium following completion of the project. *Photo credit: Eric Laignel.*

sustainable building being the one that is already built and rehabbed to be energy efficient using exterior wall and roofing materials coupled with mechanical system upgrades.

CHALLENGES AND TRIUMPHS

The adaptive reuse of the Ramova Theatre was not without its challenges. One of the primary obstacles was balancing the preservation of historic elements with the need for modern functionality, which was most notable on the interior of the theater space, where new theater and restaurant requirements would often conflict with the historic plaster ornamentation. The design team often meet onsite to review existing conditions and develop revised solutions that would preserve historic intent while meeting the needs of the contemporary live event space. Ensuring that the building complied with contemporary safety codes and accessibility standards while retaining its architectural heritage required innovative solutions and creative problem solving.

Securing funding for the Ramova Theatre's adaptive reuse was challenging, requiring numerous investment partners, public grants, private donations, and community efforts. This collaboration displayed collective action in achieving

shared goals.

The design team played a vital role in helping navigate the complexities of renovating the Ramova. They spent considerable time on-site collaborating with subcontractors, adjusting scopes and repairs within the budget. Instead of detailed project documents, strong working relationships and frequent interactions ensured timely resolution of issues. Their expertise allowed them to anticipate project needs and adjust repairs as needed during the process.

COMMUNITY IMPACT

One objective behind the Ramova Theatre project was to create a space for community engagement. The restored theater provides a platform for artistic expression and includes spaces for art exhibitions, workshops, and educational programs.

The Ramova Theatre maintains its cultural position within the Bridgeport community. By reopening the building as a concert hall, brewery, taproom, and grill, the building has had a positive impact on the local community by attracting visitors, enhancing the cultural scene, and stimulating economic growth. Increased visitors have benefited local businesses and



FIGURE 10. View of east facade of Ramova Theatre upon completion of adaptive reuse project in winter 2024. *Photo credit: Eric Laignel.*

contributed to the neighborhood's vibrancy. The project has also created job opportunities.

Additionally, the project emphasizes community engagement and collaboration. By involving local

stakeholders, adaptive reuse projects create spaces reflecting community values. Partnering with local entities such as Chef Kevin Hickey, his Duck Inn restaurant, and Other Half Brewing has introduced new energy to the south side of Chicago.

CONCLUSION

The Ramova Theatre demonstrates how the collaboration of a project team is an integral part of successfully navigating the challenges of maintaining authenticity, integrating contemporary regulations and codes into a historic building, and balancing preservation and contemporary functionality of a live-event venue while providing ownership and others with a successful project.

The adaptive reuse of the Ramova Theatre confirms how historic buildings can be transformed into dynamic spaces that serve communities. Through restoration, innovative design, and community collaboration, the theater has been redeveloped as a cultural hub that connects the past and the present (**Fig. 10**). Its development from decline to revival illustrates the importance of preserving heritage while embracing modernity. In summary, the Ramova Theatre's adaptive reuse is not just about restoring a building, it is about revitalizing a community, recognizing history, and creating a space where future generations can experience it. Its transformation highlights the lasting significance of cultural heritage and the potential of adaptive reuse.

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Assessing Value from What We Learned Through Facade Ordinances

ABSTRACT

The *International Existing Building Code* (IEBC) prescribes a minimum standard to maintain buildings as safe. But is there an expected duration to maintain this safety? If there are no guidelines as to what sort of duration or benchmark we as designers/consultants are trying to achieve, how can we encourage Owners to maintain minimum safety standards and expect them to perform periodic inspections and maintenance. In cities like New York, Chicago, Boston, Philadelphia, and San Francisco, the implementation of facade ordinances has mandated that inspections of building exterior walls and regulatory reporting be performed and has, in turn, allowed for architects and engineers to make informed decisions and recommendations on repair campaigns based on expected service life to either last to the next inspection cycle or become a longer-term solution. With the knowledge of knowing when a subsequent inspection is due, owners are able to then choose whether to make it to the next cycle or surpass the expectation.

LEARNING OBJECTIVES

- » Discuss *International Existing Building Code* (IEBC) standards with respect to minimum standards for maintaining building safety.
- » Assess the challenges of determining the duration for maintaining building safety in the absence of specific guidelines.
- » Analyze the impact of the inspection and maintenance of a building's exterior walls due to facade ordinances in cities such as New York, Chicago, Boston, Philadelphia, and San Francisco.
- » Examine how architects and engineers make informed decisions and recommendations on repair campaigns based on the expected service life and inspection cycle of the building.

SPEAKER



**Mike Lopez, RA,
AIA, NCARB**

Director, Technical Services,
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Rimkus

Mike Lopez has extensive building enclosure consulting and construction administration experience, specializing in exterior restoration, waterproofing, roofing, and leak remediation. As a registered architect in the states of Rhode Island, New York, Texas, Louisiana, and Florida, Lopez has the unique ability to provide both technical and aesthetic perspectives for any project and has been a part of numerous historic projects involving the New York City Landmarks Preservation Commission. He is also a member of the American Institute of Architects and holds a National Council for Architectural Registration Boards (NCARB) certificate.

AUTHOR:

Mike Lopez, RA, AIA, NCARB



INTRODUCTION

Facade ordinances are established to safeguard public welfare by mandating periodic inspection and maintenance protocols. However, despite the presence of millions of buildings across the US and Canada, such ordinances are currently enforced in only 14 cities and 1 province.¹ In most jurisdictions where they do exist, facade ordinances typically apply to buildings exceeding a specified height—commonly five or six stories. Consequently, a substantial portion of the building population that meets these height criteria remains outside the scope of regulatory oversight.

The absence of comprehensive facade maintenance, repair, and upkeep often results in the progressive deterioration of the building facade. This includes the degradation of masonry elements, spalling of decorative stone or terra-cotta, water infiltration, and, in severe cases, personal injury or fatalities (Fig. 1). This paper aims to examine the structure and intent of facade ordinances, assess their influence on the practices of design professionals, and evaluate how mandated inspections affect property owners' ability to maintain buildings in a safe and compliant condition.

To draw a comparison between buildings and automobiles: how frequently is a vehicle brought in for maintenance or scheduled for routine inspection? Depending upon the inspection type, this could be every 3 months to every 5 years.³ Automobile manufacturers establish minimum inspection and maintenance schedules to be followed at designated intervals



FIGURE 1. View of 2023 facade collapse debris in Philadelphia's Center City district. Image courtesy of 6ABC.²

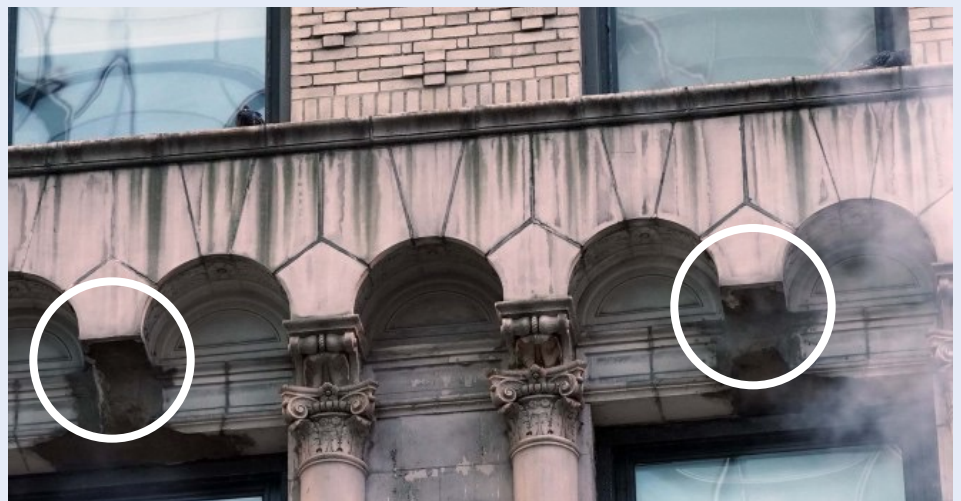


FIGURE 2. Close-up view of terra-cotta failure that led to fatality in New York City, 2019. Image courtesy of the New York Post.⁴ Annotations by Mike Lopez.

throughout the vehicle's expected lifespan. These schedules often include the repair or replacement of specific components, which the owner may choose to adhere to or disregard. Neglecting such maintenance can lead to severe consequences, potentially rendering the vehicle inoperable.

Similarly, buildings require regular inspections and ongoing maintenance to ensure continued functionality and adherence to safety standards. If left to natural weathering and deterioration, a decorative terra-cotta element could turn from an architectural feature to a fatal projectile (Fig. 2).



FIGURE 3. Facade collapse in New York City’s Little Italy neighborhood. *Image courtesy of The Structural Engineer.*⁷

FACADE ORDINANCES 101

Facade ordinances are legal mandates enacted by local jurisdictions that typically define the requirements for periodic inspection and reporting of a building’s exterior facades or elevations. Many of these ordinances are modeled after ASTM E2270-14 (2019), *Standard Practice for Periodic Inspection of Building Facades for Unsafe Conditions*, which outlines the minimum procedures and standard practices for identifying hazardous or unsafe conditions during facade inspections.⁵

While ASTM E2270-14 (2019) offers architects and engineers a structured framework for conducting such inspections, the *2024 International Property Maintenance Code (IPMC)*—specifically Chapter 3, Section 304.1—states that buildings must be maintained in a safe condition.⁶ This is with the understanding that “safe” implies free from defects that would otherwise harm public health and safety. The IPMC further identifies conditions that may be deemed “potentially unsafe,” yet it does not prescribe specific methods or reference standards for conducting inspections. Instead, it delegates the responsibility to building owners to establish their own inspection and maintenance protocols. Although this may appear to be a reasonable expectation, the financial burden of repairs and maintenance is not always a top priority for owners.

Establishing a formalized annual inspection and maintenance schedule could significantly enhance long-term planning and budgeting efforts.

THE WHY

It is indisputable that buildings are subject to continuous aging. They no longer reflect their original condition at the time of construction; materials specified during design may have exceeded their intended service life, and natural weathering and environmental

exposure contribute significantly to the deterioration of exterior walls and architectural elements.

For example, a building located in Manhattan’s Times Square neighborhood, featuring decorative terra-cotta and stone facade elements, had not undergone any repairs for over a decade. The neglect of such ornamental elements led to the death of a pedestrian walking on the sidewalk along the building.⁷ Another building in the Little Italy neighborhood that had not undergone maintenance attempted to perform work without a permit, which led to a partial building collapse (**Fig. 3**).

Building owners require support from architects and engineers to ensure that exterior facades and their components are maintained in a safe condition, thereby preventing public injury or even fatality. Unfortunately, there have been documented cases of serious injuries and deaths resulting from inadequate building maintenance and insufficient public protection. In New York City, a fatal incident in 1980 led to the enactment of Local Law 10, the city’s first facade ordinance. Subsequent failures in 2013 and 2019 prompted further amendments to the ordinance, introducing stricter inspection and reporting requirements.⁸

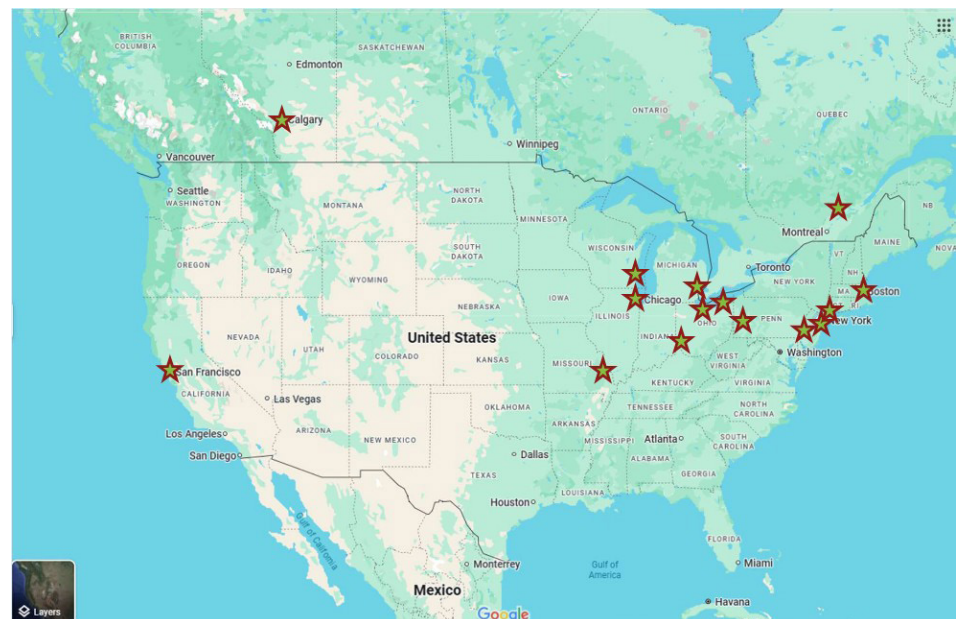


FIGURE 4. Diagram of US and Canada cities with facade ordinances. *Map image by Google Maps (<https://www.google.com/maps/>), edited by Mike Lopez.*

TABLE 1. Comparison of facade ordinance by age and inspection frequency

City	Boston	Calgary	Chicago	Cincinnati	Cleveland	Detroit	Jersey City	New York City	Philadelphia	Pittsburgh	Quebec	San Francisco	St. Louis
Year enacted	1995	2017	1996	2016	2016	2010	2020	1980	2010	2004	2018	2016	2018
Age	30	8	29	9	9	15	5	45	15	21	7	9	7
Inspection frequency	5 yrs	5 yrs	Varies	Varies	5 yrs	5 yrs	TBD	5 yrs	5 yrs	5 yrs	5 yrs	10 yrs	5 yrs

Table by Mike Lopez. ^{9,10,11,12,13,14,15,16,17,18,19,20,21,22}

Similarly, in San Francisco, a series of facade failures involving glass buildings led to a mandate requiring owners to submit inspection reports within 6 months of receiving notification from the Department of Building Inspection.⁷ In other cities, instances of owner negligence, lack of awareness, or disregard for responsibility have compelled building departments to take regulatory action.

Currently, cities in the US with facade ordinances include Boston, Chicago, Cleveland, Cincinnati, Columbus, Detroit, Jersey City, Milwaukee, New York City, Pittsburgh, Providence, San Francisco, and St. Louis (Figs. 4, 5). The province of Quebec and the city of Calgary in Canada have also implemented similar regulations.

COMPONENTS OF THE FACADE ORDINANCE

A facade ordinance developed with guidance from ASTM E2270-14 (2019) generally consists of four key components: inspection qualifications, inspection preparation, execution of the inspection (both general and detailed), and reporting procedures. While the level of prescriptiveness varies among ordinances, most provide explicit guidance regarding the location and scope of inspections or critical examinations, the qualifications required of individuals conducting the inspections, and the format and content of the resulting reports.

INSPECTION QUALIFICATIONS

Each facade ordinance enacted in the US and Canada applies to buildings that exceed a specified height threshold. In 6 of the 13 cities with such regulations, buildings that are five stories or taller are required to comply. In contrast, jurisdictions such as New York City and Philadelphia apply the ordinance to buildings six stories and above. The remaining five cities define the threshold based on absolute height, typically set at 60, 70, or 80 ft.

In addition to height criteria, many ordinances also incorporate building age requirements. For instance, Cincinnati, Milwaukee, and San Francisco mandate compliance for buildings that are 15 years or older. In New York City, the age requirement is determined by the date of the building’s first issued certificate of occupancy, which generally results in buildings as young as 5 to 7 years being subject to the ordinance.

Once the applicable building size is established, each ordinance also specifies the required frequency of inspections. In 6 of the 13 cities, inspections must be conducted every 5 years. Chicago, however, varies this requirement based on building classification, with mandated inspection intervals of 4, 6, or 8 years depending on the category.

PREPARATION

As with any professional undertaking, the inspection process—guided by ASTM E2270-14 (2019)—commences

with thorough preparation. This includes the review of prior inspection reports, documentation, existing building drawings, and any other relevant materials that contribute to a comprehensive understanding of the building’s construction and condition. The licensed professional conducting the inspection assumes responsibility for accurately assessing and reporting the status of the building’s facade. In this capacity, the inspector effectively assumes the role of the designated professional accountable for the integrity of the evaluation. Architects and engineers routinely perform comparable tasks when conducting building or property condition assessments, applying similar principles of diligence and technical expertise.

PERFORMING THE INSPECTION

The third component of a facade ordinance is the execution of the inspection itself—often referred to as the critical examination, hands-on inspection, or close-up inspection. This phase typically involves direct observation at close range, facilitated by suspended scaffolding, aerial platforms, or industrial rope access, enabling inspectors to physically engage with the building surface—touching, listening, and documenting observed conditions (Fig. 6, 7). ASTM E2270-14 (2019) specifies the percentage of a building’s surface area that must be examined at close range to meet compliance standards.



FIGURE 6. Inspector performing facade inspection via industrial rope access. Photograph by Mike Lopez, May 23, 2024. Rimkus.



FIGURE 7. Inspector performing facade inspection via industrial rope access. Photograph by Mike Lopez, January 25, 2022. Rimkus.

The objective of the close-up inspection is to identify conditions that cannot be reliably assessed from street level using binoculars or high-powered lenses. While the use of drones has gained popularity as a tool for preliminary assessments or for accessing difficult-to-reach areas, it is important to note that drone technology does not eliminate the need for physical, close-up inspections.

In addition to the close-up, some ordinances, along with ASTM E2270-14 (2019), require that probes of the existing exterior wall cavity be performed with the intent to determine and observe the condition of cavity wall ties or the underlying structure, as observation of the exterior can only do so much without more information.

REPORTING PROCEDURES

The final component, following the review of documentation and completion of the inspection, is the development, preparation, and submission of the ordinance report. The format and organizational structure of these reports vary depending on the requirements of the local building

department or enforcement agency, as no standardized reporting template currently exists. Typically, reports include extensive photographic

documentation to accurately illustrate observed conditions, with the expectation that identified issues will be addressed either in the



FIGURE 8. The Barclay-Vesey Building at 140 West Street. Photograph by Mike Lopez, May 08, 2024. Rimkus.

near term or as part of a long-term maintenance strategy.

In many jurisdictions, reports must be submitted either electronically or in hard copy format to the appropriate regulatory authority. Additionally, property owners are often required to retain copies of the report on-site or ensure they are readily accessible in the event of an incident or an audit conducted by an inspector.

PENALTIES

Many facade ordinances include penalties for non-compliance or failure to maintain building exteriors, intended to compel owners to take corrective action. However, these penalties are often nominal when compared to the substantial costs associated with performing necessary repairs. The rising expenses of materials, labor, and restoration work far exceed the financial impact of fines, penalties, or even prolonged scaffolding rentals. This disparity highlights an area of opportunity for local jurisdictions to strengthen enforcement mechanisms and incentivize timely compliance with maintenance requirements.

TECHNOLOGY

Determining whether a building is classified as safe or unsafe can often be subjective, particularly when assessments are based solely on minimum standards. This subjectivity is compounded by unknown variables, existing and unforeseen conditions, and deviations that may hinder the architect's or engineer's ability to make a fully informed judgment. To enhance the accuracy and reliability of such evaluations, emerging technologies have become valuable tools for design professionals. One such advancement is the use of drones to generate "digital twins" of buildings, which enables a higher level of detail and precision in identifying and documenting facade conditions.

Located along New York's West Side Highway, the Barclay-Vesey Building at 140 West Street is a 34-story steel-framed masonry structure constructed in 1923 (Figs. 8, 9). Once the tallest



FIGURE 9. Close up view of cracked decorative stone at the Barclay-Vesey Building at 140 West Street. Photograph by Mike Lopez, November 21, 2022. Rimkus.

buildings in New York City at the time of construction, the building recently has undergone extensive restoration over the past 5 years due to prolonged neglect of maintenance and inspection responsibilities by its owners. Since 2017, Rimkus's New York team has worked with the building that has been designated as unsafe, due to cited non-compliance with mandated inspection, reporting, and maintenance requirements along with various facade conditions that were in need of immediate repair.

Although restoration efforts in 2019 and 2020 temporarily removed the need for scaffolding, subsequent water infiltration and additional deterioration necessitated renewed intervention. This led to the building owners implementing and approving a plan for a more comprehensive, all-hands-on-deck approach to restore the building to a safe and compliant condition. The approach included inspections performed at 100% of all building elevations in order to address any and all defects to restore the building to a safe condition.

CONCLUSIONS

In summary, facade ordinances serve as a critical mechanism for ensuring public safety through the regulation of building inspections and maintenance. While existing ordinances provide a foundational framework—often modeled after ASTM E2270—they vary significantly in scope, enforcement, and effectiveness. The disparity between the cost of compliance and the penalties for non-compliance underscores the need for stronger regulatory incentives. Moreover, advancements in technology, such as drone-assisted inspections and digital twin modeling, offer promising avenues to enhance the accuracy and efficiency of facade assessments. As buildings continue to age and urban environments evolve, it is imperative that local jurisdictions strengthen their ordinances, promote proactive maintenance, and support building owners and professionals in safeguarding the built environment. The future of facade safety depends not only on regulation but on a collective commitment to accountability, innovation, and public protection.

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Emerging Materials: Benefits and Limitations of MgO-Based Sheathing Products

ABSTRACT

Exterior sheathing panels made with magnesium oxide (MgO) chemistry represent a newer but growing product category that, compared to more familiar sheathing options, are not as widely known or understood amongst even experienced building enclosure experts. Commonly asked questions include the following:

- » Are MgO boards, chloride boards, and sulfate boards all referring to the same thing?
- » Are they all functionally interchangeable, or are some better for specific applications?
- » Why are people talking about sweating boards from Denmark?
- » Can they be a value-adding part of a robust and resilient building enclosure?

Since the early days of MgO composite panels, which have been around in their modern form for about 20 years, significant advancements in understanding the chemistry and process control for MgO-based sheathing have improved the quality of available products.

This session will demystify MgO and provide a window into the academic research investigating the synthesis, structure, and stability of composite panels based on MgO starting materials. Learners will walk away with an industry leading understanding and the necessary tools to speak confidently and accurately about MgO-based boards. They will have clarity on how to evaluate and select boards based on quality and long-term performance for certain applications and will see how incorporating this product into their building(s) can improve the constructability and long-term performance of exterior walls and roof systems.

LEARNING OBJECTIVES

- » Discuss the difference between the chemistry of chloride- and sulfate-based magnesium oxide (MgO) composite sheathing boards, including cement chemical structure, additives, and the manufacturing process.
- » Identify the properties of MgO-based boards and the benefits over traditional sheathing during the construction and long-term operation of commercial buildings.
- » Address early board prototypes' challenges and highlight advancements in MgO technology, both with stand-alone boards and within a complete wall system.
- » Outline quality control measures, such as specific testing methods, and performance targets to ensure the supplied boards meet the requirements to provide a long-lasting performance in the building enclosure.
- » Describe the performance of MgO systems in fire code testing, including NFPA 285 and combustibility testing, and be able to identify when they can and cannot be used.

SPEAKER



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Adam Broderick is a research and design scientist with DuPont Performance Building Solutions focused on applying material science and building science fundamentals to drive innovative building enclosure products and applications. He is on the front lines of developing and testing the newest technologies available to enable easier construction of higher-performing, more resilient buildings. Despite having a background in formulating and evaluating products in the lab, he's happiest when on a building site, collecting feedback on new products and application methods under development, and learning about the most challenging unsolved problems facing builders today as they give rise to the innovations of tomorrow.

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Michelle Hudack, PhD, is a senior lead scientist at DuPont with expertise in polymer chemistry and building science. She earned

her doctorate from the University of Rochester, NY, and has led field evaluations of MgO-based sheathing products across diverse climates to assess durability and corrosion resistance. Her work bridges laboratory research with real-world performance, focusing on how emerging materials impact long-term building integrity. Michelle is driven by the rewarding challenge of ensuring buildings maintain fire safety and insulation performance, contributing to the advancement of resilient, high-performing structures.



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Senior Lead Scientist
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Michal Porter-McCarthy is a senior lead scientist at DuPont with a PhD in chemical engineering. She is currently focused on MgO-based

panel products, where she has played a key role in defining lab testing procedures to evaluate corrosion risks linked to low-quality MgO sheathing materials under accelerated conditions. Her work includes ensuring robust quality control methods to identify potential product issues. She has a passion for driving innovation informed by sound science and life-cycle thinking and for understanding the role of new materials like MgO-based sheathing panel products in the decarbonization of the built environment.



Gregory Stewart

Applications Development Leader
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Greg Stewart serves as the roofing applications development leader in shelter solutions at DuPont, bringing over 25 years of expertise in product, process,

and applications development. He actively represents DuPont in key roofing industry groups and is known for his inventive approach to solving complex technical challenges. Stewart's leadership has energized innovation across shelter solutions, contributing to multiple successful development initiatives. He holds eight granted patents and was part of the DuPont team honored with the prestigious ACS Heroes of Chemistry award in 2024 for groundbreaking reduction in embodied carbon.



Mark Rickard

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Mark Rickard started his career in analytical chemistry and materials development at Dow Chemical in 2008 and transitioned to DuPont's Shelter Solutions business in 2019.

He has developed innovative products that help solve important sustainability problems. Two examples are Low GWP Froth-Pak Spray Foam, which is a more sustainable spray polyurethane foam that uses carbon dioxide (CO₂) to reduce its global warming potential by more than 99%, and Low-GWP Styrofoam Brand XPS Insulation, which delivers a 94% reduction in embodied carbon.

CHEMISTRY OF CEMENTITIOUS MATERIALS

Cement is a generic term for a binding material commonly used in construction, composed primarily of inorganic crystals. These crystals are formed in two general steps. First is hydration, during which activated cement compounds (e.g., calcium silicates in portland cement, calcium sulfate in gypsum, or magnesium oxide [MgO]) dissolve and then react with water. This is followed by solidification, where the ingredients, which include hydrated cement, additional water, and other salts present in the admixture, arrange themselves via a complex series of steps into a regular lattice of alternating components.¹

The shape, size, composition, and structural pattern of crystals that form in these processes depend on many factors, including concentration of different components, temperature and water content during cure, surface area of the activated cement, and the presence of catalyst-like compounds that promote or inhibit certain crystal forms. The nature of the crystals that form can vary substantially in their properties, even in cases where the initial mixtures are identical but curing conditions favor formation of one type of crystal or packing density over another.

Generally, practitioners in the space of building enclosures are likely to be familiar with concrete (calcium silicate or portland cement with aggregate) and gypsum (recrystallized calcium sulfate) and the conditions under which one or the other can be used without risk of compromising the function of the

materials. In contrast, cements based on MgO, which differ in key ways from both cement and gypsum, are less widely understood and may be unnecessarily avoided or used incorrectly.

MGO CEMENT AND BOARDS

Calcined MgO readily converts to magnesium hydroxide, a soft mineral similar in consistency to gypsum, when hydrated as a single component. When hydrated in the presence of magnesium salts such as magnesium chloride (MgCl₂), magnesium sulphate (MgSO₄), or magnesium phosphate (MgPO₄), a much harder and more durable microscopic structure is formed. To date, commercially viable construction panels have been produced using cements based on MgCl₂ and MgSO₄, colloquially referred to as *chloride* or *magnesium oxychloride (MOC) boards* and *sulfate* or *magnesium oxysulfate (MOS) boards*, respectively.

For both types of boards, a particular crystalline phase has been identified that provides maximum strength and resistance to water damage (**Table 1**). Unlike cement or gypsum, which form via the hydration of a single primary component, MgO involves synergistic effects of two different components in addition to water, and manufacturers must take care to ensure that raw material ratios and curing conditions allow the formation of the correct crystalline phase.

The manufacturing process involves precise mixing of dry and wet components, casting, and curing under controlled conditions to ensure consistency and quality. A typical board formulation is shown in **Table 2**. Quality

control is critical, focusing on the homogeneity, purity, and reactivity of MgO; ratio control with the components of the cement; as well as proper curing processes. Poorly manufactured boards may contain improperly formed cement crystal phase or excess salts that can leach out of the cement, both which can lead to reduced strength and increased corrosion risk.

EARLY USE AND STANDARDIZATION OF ACCEPTANCE CRITERIA

Early applications of MgO panels in the construction industry in Scandinavia as part of the exterior building enclosure led to a significant failure. Boards were not designed specifically for exterior use and lacked the protection of a weather-resistive barrier, making them even more susceptible to moisture condensation in the cold humid climate. Even so, while quality boards may have resisted degradation, there was a large variability in the quality of manufacturing likely due to poor control of compositions, resulting in variability in the water stability of those boards. Because of this, many boards suffered from degradation of the MOC cement, leading to issues with leaching, corrosion of adjacent metals, mold growth in wood structure, and loss of panel strength.⁵ In response to these issues and due to the lack of existing MgO standards or guidance in model building codes, industry groups and code officials in China, Europe, and the US worked to establish minimum performance acceptance criteria to provide an alternate compliance pathway for MgO-based boards used in construction projects,

TABLE 1. Comparison of magnesium oxide (MgO) with other types of cement materials

Type of inorganic cement	Crystalline structure	Typical compressive strength	Hydrolytic/temperature stability
MgO-based	5Mg(OH) ₂ ·MgCl ₂ ·8H ₂ O 5Mg(OH) ₂ ·MgSO ₄ ·7H ₂ O	50–200 MPa 40–100 MPa	Variable stability when soaked; Stable to 90°C/194°F (dry)*
Gypsum	CaSO ₄ ·2H ₂ O	2–3 MPa	Soluble in water; stable to 150°C/302°F (dry)
Portland cement	3CaO · SiO ₂ + (2CaO · SiO ₂) + (3CaO · Al ₂ O ₃) + (4CaO · Al ₂ O ₃ Fe ₂ O ₃)	30–55 MPa†	Stable to water saturation, temperatures >200°C/392°F

* Walling and Provis (2016), † Zhang (2011)

TABLE 2. List of common raw materials used in manufacturing a typical magnesium oxychloride board

Raw material	Approx. percentage of board	Purpose
Magnesium oxide	30–45%	Cement formation
Magnesium chloride	30–45%	Cement formation
Water	10–25%	Cement formation and filler hydration
Perlite	0–20%	Reduces density
Wood flour	0–15%	Reduces density, increases toughness
Additives	<2%	Defoaming or foaming, water stability additives, processing aids

Data from Doggett and Davis (2024).

including interior walls and ceilings, exterior sheathing, sub-roofing, and underlayment. ICC-ES AC308 was the first ICC acceptance criteria for this product type, and covers a broad range of considerations, including physical properties, installation requirements, and ongoing quality control. There are ongoing efforts to update AC308 and convert the acceptance criteria to a standard in mandatory language to allow direct reference by model codes; “ICC 1125 Standard Specification for Classification of Magnesium Oxide Board and Construction” is on track to be published in early 2026.

Acceptance criteria serve as an alternative compliance pathway designed to identify products that align with the intent of the building code, which is developed through an industry consensus process representing the best available expertise for maintaining effective building operation throughout its lifespan. These criteria typically concentrate on properties of the manufactured board that, based on correlation or accelerated testing, most reliably predict whether a product will meet its intended, code-mandated function. Since model building codes primarily emphasize critical life safety, they often do not provide explicit guidance regarding durability and long-term performance. More rigorous testing protocols, incorporating extended durations and more severe conditions, can further mitigate risk and demonstrate differences in long-

term performance among products, even when all may meet baseline acceptance criteria.

Monitoring the performance of MgO products under both real-time and accelerated conditions offers valuable insights into their long-term behavior within buildings. Exterior sheathing materials are subjected to fluctuating environmental factors, such as changes in temperature and humidity, which are often challenging to replicate accurately in laboratory settings—especially when aiming to accelerate testing. By integrating laboratory evaluations with systematic real-world exposure, it is possible to more effectively assess potential failure mechanisms and bridge gaps in understanding product performance.

Ongoing work within the industry continues to push the boundary on what is known about the long-term performance of MgO boards in response to various external conditions. This report will consider several studies evaluating the extension of accelerated lab testing with real-time monitoring of the same or similar properties.

Experimental Methods: Exposure Conditions

Samples selected for evaluation in all of the studies were chloride-based MgO boards rated for use as exterior sheathing boards with direct cladding attachment. All samples, unless indicated otherwise, were initially equilibrated in a controlled environment held at 75°F (24°C) and 50% relative humidity (RH) for a minimum of 24 hours prior to any measurements or change in conditions. From there, they were either placed in a controlled environmental chamber at a specified condition or in a small open air test box (Fig. 1). The temperature and RH of the environmental chamber were validated using a calibrated digital thermometer and humidity sensor and were maintained constant for the indicated duration of the test.

A more dynamic, real-world exposure regime was provided by the open air test boxes, or “test huts” (Fig. 1). Samples include boards predrilled with fasteners for fastener withdrawal measurements or steel coupons for tracking corrosion over time. Test huts were placed in four locations intended to represent different medium to very high humidity



FIGURE 1. Small test hut used to house various panel configurations containing magnesium oxide boards and expose them to local ambient conditions without direct exposure to rain, such as might be experienced in a vented air gap behind typical claddings. The bottom and top of the enclosure are open to allow airflow through the enclosure (left image), with a hinged roof assembly allowing access to the samples evenly spaced within the enclosure (right image).

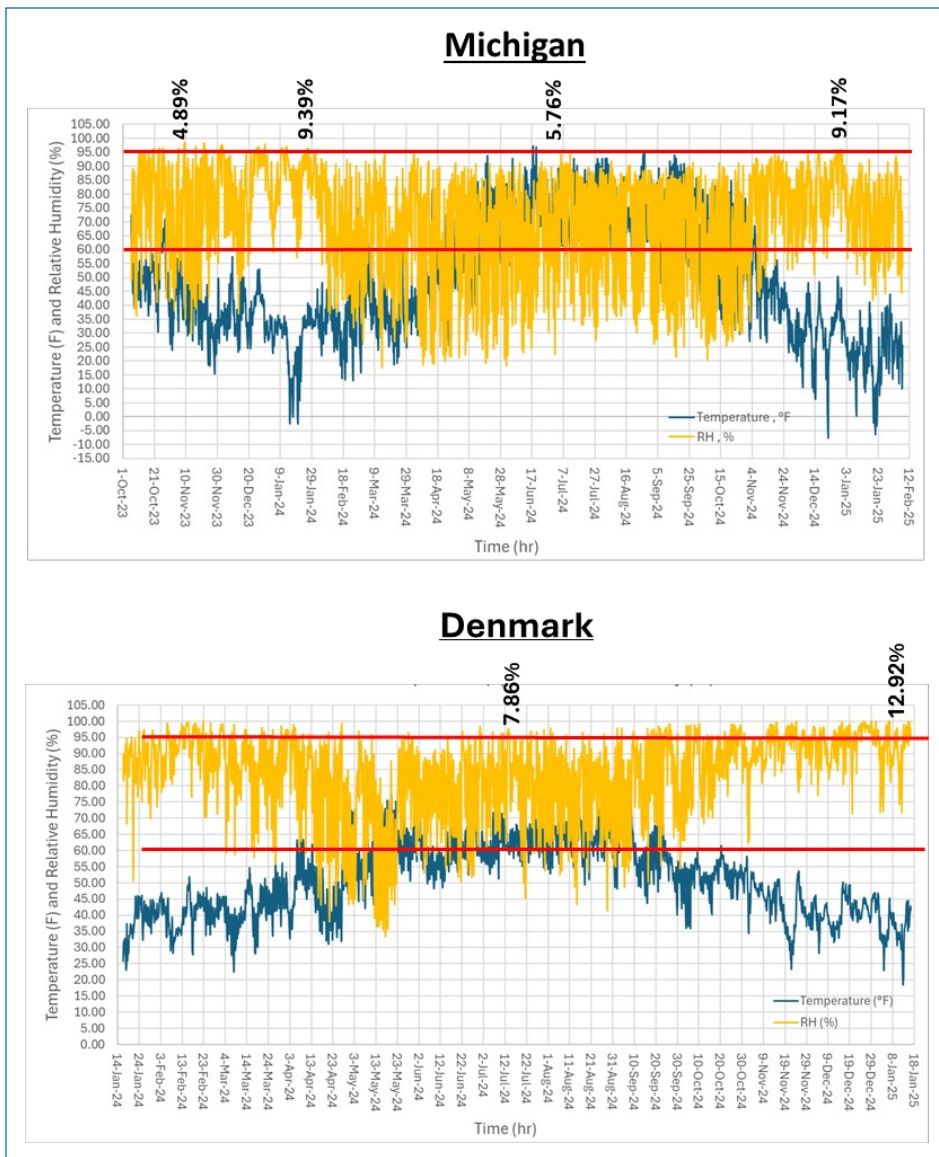


FIGURE 2. Plots of temperature (blue) and relative humidity (orange) recorded within the small test huts at two locations: Midland, Michigan (top), and Jyllinge, Denmark (bottom), over the course of 12–16 months. At several points, magnesium oxide board samples with water resistive barrier were removed from the test hut to measure moisture content, which is reported above the plot. The red lines indicate 60% and 95% relative humidity.

conditions, including Midland, MI; Tacoma, WA; Miami, FL; and Jyllinge, Denmark.

Internal conditions within the open-air enclosure were monitored continuously for temperature and relative humidity. Data for two of the locations are shown in **Fig. 2**. The Michigan location is IECC climate zone 5A, and the Denmark location 5C. While they are in the same climate zone number based on heating degree days, the marine climate of Jyllinge, Denmark creates a higher

relative humidity for much of the year, with relative humidity rarely dropping below 60% and staying above 70% RH for the majority of the wintertime.

Experimental Methods: Property Evaluation

Moisture uptake was measured by weighing the sample before and after complete drying at 108°F (42°C) for a minimum 1 week and until weight change dropped to less than 0.5%, and assuming all mass loss is excess water. Corrosion testing followed AWPA E12-20

methodology using G60 and carbon steel coupons sandwiched on both sides with uncoated MgO boards and held in place with nylon bolts. Fastener withdrawal was evaluated using ASTM D1761-20 using #10-9 ultra-low-profile head screws.

FASTENER ATTACHMENT STRENGTH

One of the key advantages of some MgO boards rated for use as structural exterior sheathing (typically, 1.3 cm or thicker and density > 1.0 gm/cm³) is the ability to fasten cladding attachments directly to the sheathing, rather than ensuring fasteners extend through the sheathing (and other building envelope layers) and attach directly into structural framing members. This provides numerous benefits towards installation and building performance, including: flexibility and speed in placement of attachment brackets independent of framing pattern; minimizing thermal bridging through insulation panels behind sheathing; decreasing the length (and cost) of fasteners; eliminate risk of missing a stud and having to address errant holes in the water, air, and thermal control layers; and in some cases a reduction in the number of fasteners required due to more equal distribution. To be used in this way, boards should have appropriate measurements and engineering calculations by a reputable third party to validate the “as-manufactured” cladding attachment requirements and fastening patterns.

Pushing beyond testing the boards as manufactured, AC308 includes a component of short-time exposure to water spray, followed by repeating the fastener testing, and establishes the requirement that fastener strength does not drop after such exposure. This test is intended to confirm that a board does not suffer from short-term water instability of the cement crystal in the event of a single severe wetting event. Two other weakening mechanisms not captured here that could degrade fastener holding power over time include load cycling that slowly causes local damage to the cement surrounding the fasteners, and moisture-driven degradation of the cement crystal structure over time.

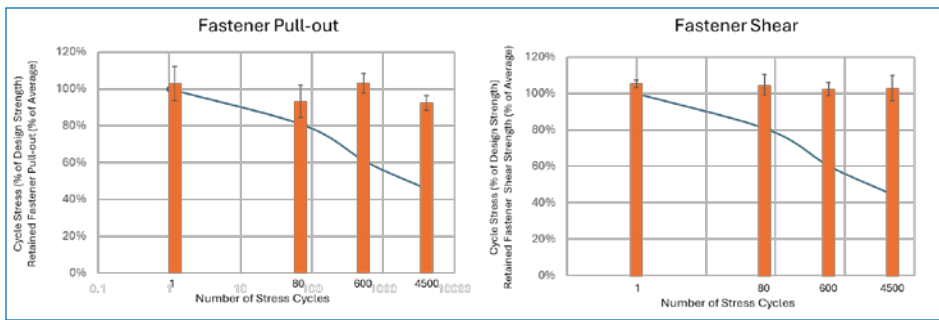


FIGURE 3. Graphs of fastener pullout (left) and fastener shear (right) as a function of the number of load cycles, shown as orange bars and reported as a percentage of the average control prior to cycling. Also shown on the graph is an x-y plot of the cycling load value (calculated as a percentage of the minimum spec value) versus the number of cycles. Read together, each orange bar represents the relative peak pullout strength when tested to failure after cycling the indicated number of times, at the percent load indicated by the blue line.

As with many product data measurements, the minimum performance value reported for a product is often lower than what would be typically measured to ensure the ability to consistently hit that minimum target. For the following data set, the fastener pull-out strength is considered both from the perspective of the minimum value reported in the literature for the boards tested in this study (“minimum specification”) before application of any safety factors, and from the historical quality control measurement averages (“historical average”).

To evaluate the risk of the first mechanism, fasteners were screwed into an MgO board, cycled up to 4500 times through a load (either in tensile pull-out or shear) ranging from 45–100% of the minimum and then pulled to failure.

The relationship between the number of cycles and the cycle load follows a nearly exponential relationship, as shown in the blue line in **Fig. 3** (plotted on a logarithmic x axis). The plot starts with pre-stressing the fastener with a single pull-out or shear stress cycle at 100% of the minimum specification and then stepping down to eventually hitting 45% of the minimum specification with 4500 load cycles. The values of the final stress-to-failure data point are normalized to the historical average, not the minimum specification, to better illustrate changes to performance as a result of the cycling.

In most cases, the peak force stayed within a standard deviation of the historical average, indicating no statistical change in performance. For those that did drop, the historical average is sufficiently higher than the minimum specification load that all samples had a final peak force average above the minimum specification. The highest drop, ~7%, came for the highest number of cycles for fastener tensile pull-out, and while the value is still above the minimum specification, follow-up studies will be needed to push the total number of cycles at that and even lower load stresses do not accumulate over time.

The other potential long-term failure mechanism considered for fastener holding power was longer-term exposure to atmospheric moisture. As noted in **Fig. 2**, simply exposing these MgO boards to the environment led to peak moisture loads of 9–13%, depending on the duration of high-humidity conditions without periods of drying. The samples left in the test huts provided an opportunity to look at fastener withdrawal after exposure to 6 and 12 months of ambient environment. **Fig. 4** shows the fastener pull-out data for two boards from different manufacturers without any exposure or after 6 or 12 months of exposure.

All of the boards show no loss in strength through one year of continuous exposure to ambient humidity (board B

did not have data for the Midland, MI, location). Locations with higher humidity in general (Denmark and Florida) did not behave differently from those in lower humidity. Additional samples continue to be exposed in these test huts, and will be evaluated at later time points to confirm the strength retention over time.

CORROSION RESISTANCE

One of the signs of poor board manufacturing practices in early MgO board use was corrosion of fasteners and steel profiles from the facade [5]. Due to poor ratio control and/or degradation mechanisms that liberated salt from cement crystals, enough excess magnesium chloride salt was present in the boards to cause deliquescence, a process in which a substance (such as $MgCl_2$) absorbs moisture from the atmosphere until it dissolves in the absorbed water and forms a solution. This evidences itself as the spontaneous formation of water droplets on an MgO board surface, often referred to as “tears” or “sweating.” Any MgO board used in a location where exposure to high humidity is a possibility must be tested to ensure it will not deliquesce.

AC308 Appendix A takes this a step further by requiring testing the corrosion potential of MgO boards in direct contact with metal (but not sweating) using AWWA E12-20 with grades of steel expected to come in contact with the MgO boards. This test, as written in the acceptance criteria, combines evaluating the potential for MgO board sweating as part of the sample conditioning pre-step, as well as measuring the accelerated corrosion rate at moisture loads above ambient humidity.

One approach to expand understanding of corrosion risk is to “super-accelerate” and test materials in a scenario that exceeds the minimum requirements for the accelerated corrosion tests. While results are likely to be worse, it provides a better understanding of the actual performance boundary. For the test data shown in **Fig. 5**, two factors of the testing were made more aggressive: test temperature and metal coupon material. Higher temperatures both increase the kinetics of corrosion and increase

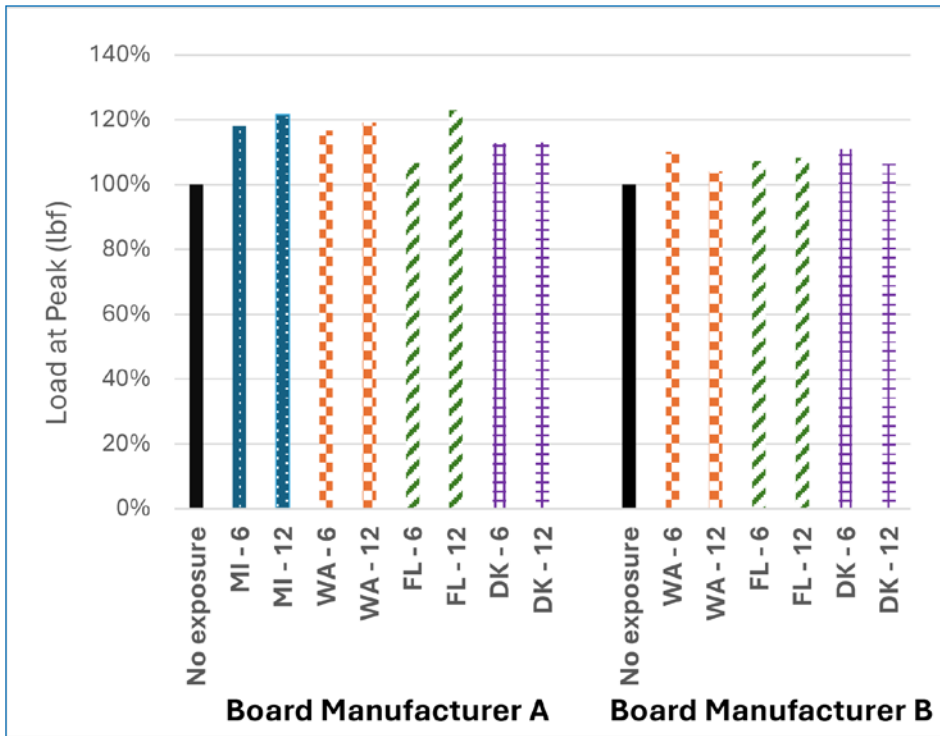


FIGURE 4. Graph of peak load measurements from ASTM fastener pull-out testing for two board manufacturers. Samples of each board were evaluated after 6 and 12 months in each of the tested locations, as indicated (Michigan [MI], Washington [WA], Florida [FL], and Denmark [DK]); the “no exposure” data points reflect the long-term average test measurement for boards as received from the respective manufacturer.

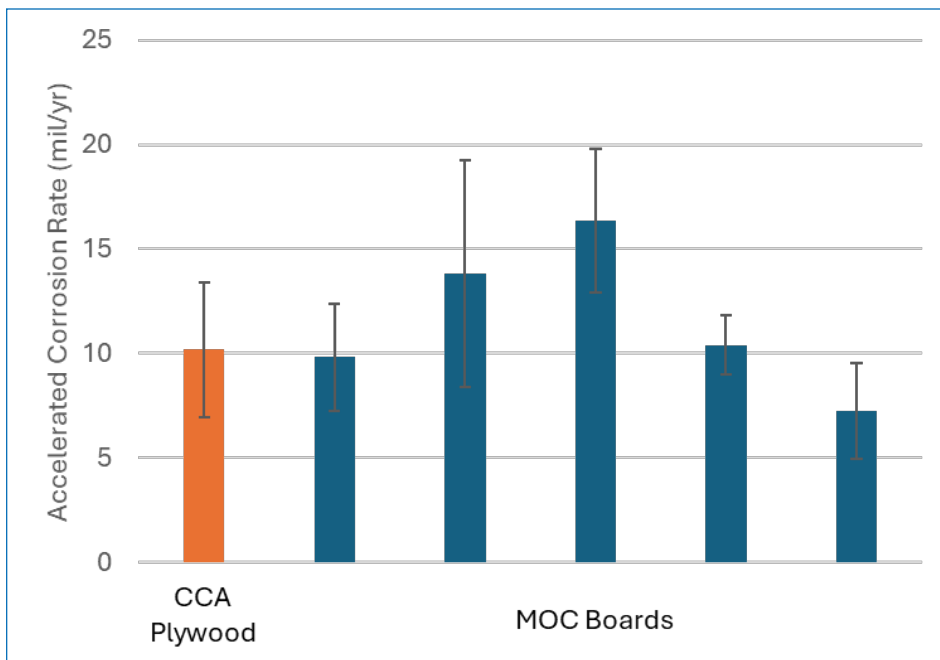


FIGURE 5. Plot of annualized corrosion rate for chromated copper arsenate (CCA)-treated plywood (orange) and magnesium oxide (MgO) boards (blue) in contact with low-carbon steel for five different lots of boards from two manufacturers. The corrosion test was run at 50°C and 90% relative humidity.

the moisture present to accelerate corrosion. In this study, increasing the temperature from 86°F to 122°F (30°C

to 50°C) while maintaining relative humidity (90%) increases the total water content in the air by over a factor of

three. Additionally, using a carbon steel metal coupon without any galvanization treatment instead of the more common materials such as G60 allows corrosion to progress without the generation of a zinc passivation layer.

There is a fair amount of variability between different boards, which primarily indicates the variability of the test method itself but does suggest there are small differences in the boards themselves. All fall below the standard requirement of 20 mil/year corrosion rate established as the limit for chromated copper arsenate (CCA) wood to be used with steel fasteners.

Corrosion data in real time is generally difficult to accomplish due to the very long time scales involved; hence the need for the accelerated test above. However, real-time data, such as that coming from the outdoor exposure test hut, eliminates the assumptions associated with the accelerated test and helps benchmark real-world performance.

Unaccelerated corrosion rates are reported in **Fig. 6** for the four locations of test huts described earlier. Samples placed in the test hut were assembled using the process outlined in AWP A E12-20, and post-exposure corrosion rate measurements were completed in the same way, such that the only modification to the method was the variable, real-world exposure conditions. Compared with the accelerated data in Fig. 5, corrosion-rate values are over an order of magnitude lower for steel even at the most aggressive climates (highlighting acceleration due to the high temp / RH for samples in Fig. 5), and as much as another order of magnitude lower for G60, showing the effectiveness of standard galvanization protection, in NA climates.

To put these numbers in perspective, ISO 9223-12 “Corrosion of metals and alloys” lists a range of expected corrosion rates for some metals, including carbon steel, in various atmospheric environments. With the exception of the Florida sample, all of the data points for carbon steel in contact with the MgO boards tested fall well within the expected corrosion rate for a “Low” or “Very Low” corrosive environment. Florida, on the other hand,

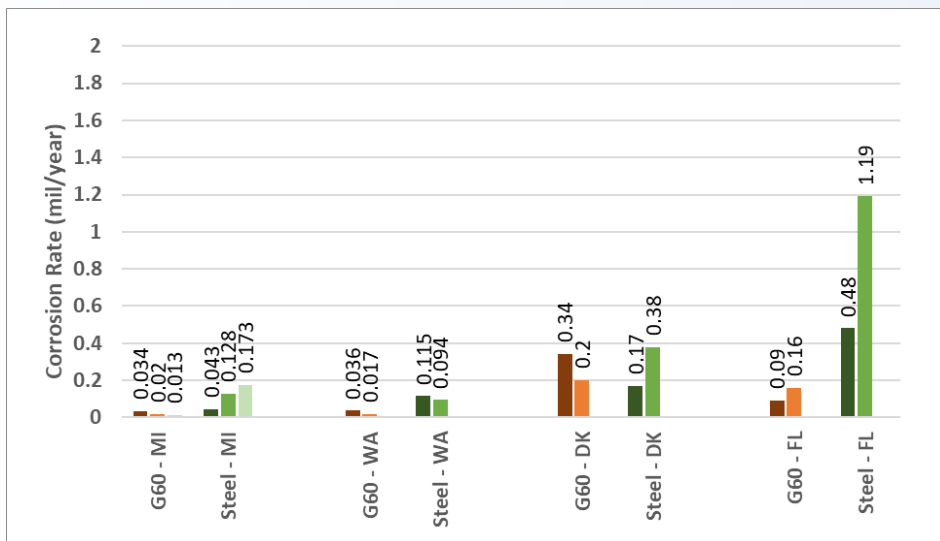


FIGURE 6. Measured annualized corrosion rate for G60 galvanized steel (orange) or carbon steel (green) coupons exposed for 6 months (dark), 12 months (medium), or 18 months (light, Michigan [MI] only) to ambient conditions in small test huts at all locations (Washington [WA], Denmark [DK], and Florida [FL]), as indicated.

falls just outside of that range, in the “Medium” corrosive environment. At this point, it is not clear whether this is truly representative of effects from the MgO sample, or simply reflects the more challenging environment in Florida (or some combination of the two).

One particular point of interest is the similarity between the G60 and carbon steel corrosion data from the Denmark samples. While this is still a limited number of data points, the trend (if

continued) warrants additional study to understand the particular effect of long-term exposure to cold, moist climates and potential differences in the corrosion mechanisms there compared to other climates.

For most of the G60 samples, the decrease in corrosion rate at 12 months (and 18 months, for Midland) data compared with the initial 6 months is expected. Early in the exposure process, passivation of the surface is technically

a corrosion-related process and due to the way the test is run becomes part of the measured corrosion. Once that initial passivation is complete, the overall corrosion rate drops due to the passivation. Florida is an interesting outlier in that regard, and while samples conditioned there do not show the highest corrosion rate, it does increase between 6 and 12 months. Data collection on samples in these test huts is ongoing and measurements at 18 months and later will show how these trends continue, but up to this point real-time corrosion of G60 in contact with MgO boards does not cause a concerning amount of corrosion.

CONCLUSION

As with all cementitious materials, MgO-based cement boards need to be prepared with appropriate formulation and curing control to ensure that the crystalline structure is stable, with minimal excess salts present in the cement matrix. High quality boards, such as those evaluated in this study, retain their strength as a cladding attachment base during extended exposure to ambient moisture, as well as during stress cycling of fasteners. In addition, corrosion potential is within acceptable limits both during highly accelerated corrosion testing, and over a long period of exposure to ambient moisture.

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Sealing the Deal: Avoid Getting Blown Away by the New IECC Air Leakage Requirements

ABSTRACT

Recent iterations of the *International Energy Conservation Code* (IECC) have prioritized the reduction of building enclosure air leakage as a means of energy efficiency. Historically, code requirements for building enclosures have focused on water leakage, which is the leading cause of construction claims in the United States, and thermal value, which energy models use to predict building performance. However, as the field of building science continues to evolve, the industry has recognized that these measures alone may not result in an efficient enclosure due to the potential of air leakage to cause moisture issues, by means of condensation, and thermal inefficiencies, by means of air leakage bypassing insulation materials. As a result, recent changes to the energy code now dictate that commercial buildings undergo “verification” (i.e., design and construction reviews) and/or testing in an effort to reduce the energy and performance loss associated with air leakage. It is critical that designers, contractors, and consultants understand how and when to implement the new air leakage requirements on their projects to avoid schedule delays and cost overruns. This paper covers each IECC air leakage compliance path, nuances of the various air leakage testing standards, and common challenges encountered in the process.

SPEAKER



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Alex Kosis has extensive experience as a building enclosure consultant, specializing in roofing and waterproofing system design and repair and in thermal analysis for optimal building performance. He leads Simpson Gumpertz & Heger’s building technology presence in the US Mountain Region, working with clients and project partners to solve technical challenges on a range of new design, failure investigation, and repair and rehabilitation projects. He brings wide-ranging expertise and insights to his technical work gathered from his practice as a senior engineer and project lead in Denver, Colorado; the San Francisco Bay Area; Southern California; and Washington, DC.

LEARNING OBJECTIVES

- » Identify how air leakage impacts energy consumption.
- » Discuss the *International Energy Conservation Code* (IECC) compliance paths for air barrier and thermal envelope assemblies.
- » Contrast the subtle differences between the various air leakage testing standards as well as discuss the project factors that may dictate one method over another.
- » Review common pitfalls in the IECC building enclosure compliance process.

The first version of the *International Energy Conservation Code* (IECC) was issued in 1998 and was preceded by ASHRAE Standard 90/90.1 and the *Model Energy Code* (MEC), dating back to 1975. The IECC is tasked with regulating the design and construction of buildings for the effective use and conservation of energy over the useful life of each building, while remaining flexible enough to allow innovation in the industry. Air leakage has become a priority for energy improvements for two reasons:

1. Air leakage has a large impact on the efficiency of mechanical equipment, which is the largest consumer of energy in buildings.
2. As the industry continues to improve the efficiency of mechanical systems, air leakage increasingly becomes the "low-hanging fruit" to improve overall building performance.

The U.S. Department of Energy conducted a study in 2014, which found that air leakage is responsible for 6% of the overall energy usage in commercial buildings.¹ Furthermore, EnergyStar estimates that 25–40% of overall energy

usage in single-family homes can be attributed to air leakage.² Although this paper will focus on the commercial energy code requirements, the growing understanding of air leakage and its effects has resulted in a shift in how we design and build these assemblies across the construction industry.

WHAT IS AIR LEAKAGE AND WHY DO WE CARE?

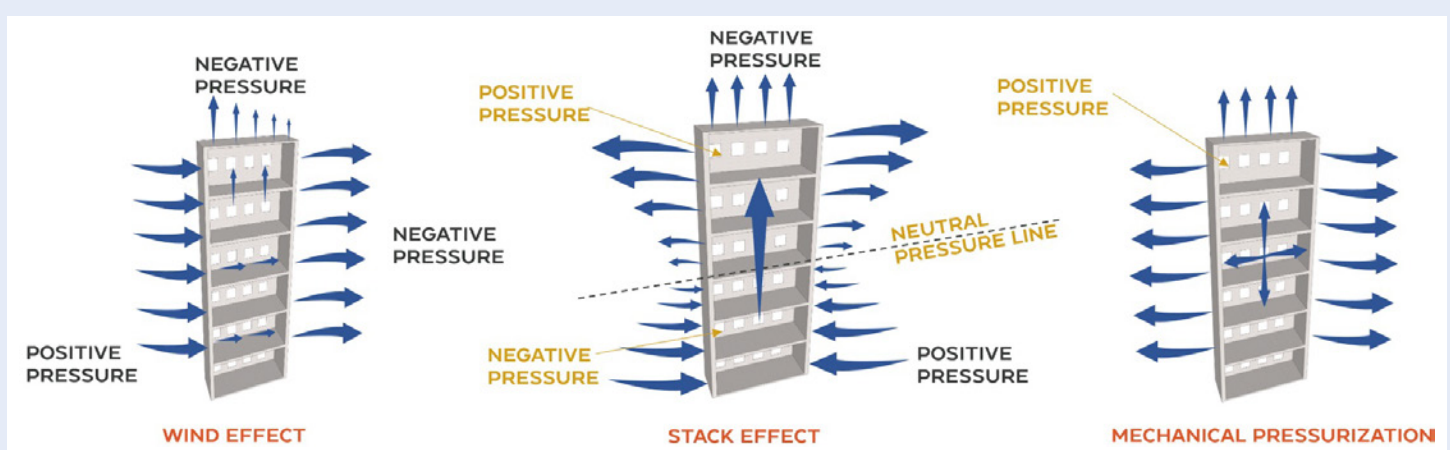
Buildings are designed to intake outdoor air and exhaust interior air, primarily through heating, ventilation, and air conditioning (HVAC) systems. However, when the infiltration and exfiltration of air in a building is uncontrolled, there are a variety of issues that can arise. These issues include condensation, ingress of pollutants, high/low interior temperatures, elevated humidity levels, higher utility bills, and premature wear of HVAC equipment.

For air leakage to occur from one space to another, there needs to be a difference in air pressures and a path for air to travel between the spaces. Some of the factors that create these pressure differentials are wind, stack effect, and HVAC operation.

Due to the variable and cumulative nature of these factors, building pressures can change seasonally, daily, or even second-by-second. There is typically an air pressure differential between the interior and exterior spaces. Depending on how the building is constructed and operated, there may also be an air pressure differential between interior spaces with different uses (e.g., server rooms, clean rooms, laboratories, natatoriums) or at different locations within the same building (e.g., stack effect).

AIR LEAKAGE IS TERRIBLE; HOW DO WE STOP IT?

With an increasing emphasis on energy efficiency in buildings, as well as rising energy costs, the ability to mitigate building pressurization issues solely through the use of mechanical systems is becoming less practical. Air barriers provide a means to passively (i.e., without external energy input) control the air leakage caused by pressurization, either between interior and exterior spaces or between interior spaces with different uses and mechanical setpoints.



Air barriers are one of four weather barriers used to control the natural elements, joining water, vapor, and thermal barriers. Historically, the construction industry has focused more on water barriers, primarily because of the prevalence of water leakage issues, the structural hazards they can cause, and their visibility to building occupants. Most water barriers can also serve as air barriers, however, the detailing required for water barriers is less arduous since water generally follows gravity downward. Air barriers, on the other hand, need to be detailed to stop air movement, which can travel in all directions. For example, sheets of building paper, if properly lapped to shed water, do not need to be sealed or taped at joints to serve as a water barrier but would be considered an air barrier. Soffits on the underside of balconies will typically not be prone to water leakage but would need to be treated for air leakage.

The Environmental Protection Agency conducted a study of 100 buildings across various climate zones in the continental United States as part of their Building Assessment Survey and Evaluation (BASE) study and found that 85% had experienced water damage in the past and 45% were experiencing ongoing water leakage causing damage.³ Due to the issues associated with water leakage, water-resistive barriers have been required since the first version of the *International Building Code* (IBC) was released in 2000 and for decades prior in the *Uniform Building Code* (UBC). Conversely, air barriers were not explicitly required in commercial buildings by model codes in the United States until the issuance of the 2012 IECC. The inclusion of air barrier requirements in the code is only the first step; as we have seen with water leakage, prescriptive code requirements do not prevent widespread issues in service. However, unlike requirements for water-resistive barriers, the IECC has implemented additional performance-based provisions as of the 2012 IECC, which include testing that quantifies air leakage, to ensure that new air barrier assemblies perform to a reasonable threshold.

IECC AIR LEAKAGE REQUIREMENTS

Starting in the 2012 IECC, the code has provided a performance-based compliance path for air leakage in the form of quantitative air leakage, or blower door, testing. Prior to 2012, air leakage requirements were entirely prescriptive and loosely enforced. As with other design disciplines, prescriptive requirements are often impractical for large and complex buildings. Allowing some elements of a building to be noncompliant, assuming that the overall performance of the building meets the required threshold, provides greater design flexibility and allows for more innovation, which aligns with the IECC's primary mission. Additionally, quantifying air leakage in buildings, and diagnosing problems when buildings do not meet the required threshold, allows the industry to learn and grow. The older, prescriptive requirements did not have the proper mechanisms in place to enforce them so, although well-meaning, they did not actually make appreciable improvements to the issue of air leakage.

Much of the language regarding air leakage in the IECC remains prescriptive and focuses on common sources of leakage, such as joints, penetrations, and fenestration assemblies. However, recent versions of the IECC (2021–2024) have implemented requirements for design reviews and site observations, which help to enforce the prescriptive requirements through third-party reviews during design and construction. In the following sections, we will summarize the compliance paths that are now available through these new provisions.

Thermal Envelope Verification

The IECC defines the “thermal envelope” as “Basement walls, exterior walls, floors, ceiling, roofs, and any other building element assemblies that enclose conditioned space and provide a boundary between conditioned space and exempt or unconditioned space”. Thermal envelope “verification” is offered as a path for air leakage compliance starting with the 2021 IECC. The IECC requires that verification include a review of the air barrier during both design and construction. At the end of the project, the team must

submit a final report summarizing any issues raised during these reviews and how each issue was resolved. This verification is prescriptive in nature and necessitates that project teams look at each air barrier requirement and explain how it was fulfilled. It also provides another level of quality assurance during the design phase and quality control during the construction phase, giving project teams additional opportunities to identify shortcomings that could result in future air leakage.

In addition to facilitating higher-performing air barrier assemblies, this process provides additional benefit because it requires a registered (or otherwise approved) professional to review the building enclosure. This process can identify other performance issues—especially with the water-resistive barrier, because the air and water barrier are typically the same material. For example, conducting site observations to review the air barrier installation can allow trained professionals to identify unique conditions that may not have been considered during the design phase and develop solutions before a performance issue arises.

The primary challenges with the implementation of this requirement are that it adds an upfront cost to the project and, if not properly coordinated in advance, could add time to the schedule. In our experience, the verification process is an asset to projects that properly coordinate it. However, to the extent that this requirement is overlooked early in the project, the value of verification decreases and the difficulty of implementing any resultant changes, in either the design or construction, increases. If a project team finds out about the verification requirement after they receive permit comments from the authority having jurisdiction (AHJ), it is unlikely that there will be extra design phase budget to cover the review and it would be challenging to implement any substantive design changes at that juncture in a project.

Thermal Envelope Testing

Thermal envelope testing became an air leakage compliance path for commercial buildings starting with the 2012 IECC, where the code provided an option

that allowed teams to conduct an air leakage test in lieu of some prescriptive air leakage requirements (note: prescriptive requirements for air intakes/exhausts, stairways, shafts, loading docks, and vestibules are still required if the testing path is used). We note that the 2021 IECC allows the option for air leakage compliance through either verification or testing and the 2024 IECC generally requires testing but allows for verifications of areas that are not tested. Although the industry has historically embraced the idea of performance-based compliance, due to the design and programming flexibility it provides, air leakage testing may be challenging or undesirable to implement for the following reasons:

- » Air leakage testing usually cannot be conducted until the end of the construction phase. In addition to roofing, fenestration assemblies, and wall weather barriers, all components impacting air leakage performance need to be installed, including door hardware, mechanical dampers, dryers, and other similar items. By the time the building enclosure is ready to be tested, there is often little room for failure because budgets are exhausted, the schedule does not have room to accommodate additional work, and access to any components allowing air leakage is likely limited.
- » In the absence of “verification” (i.e., enclosure design review and site observations), the likelihood of passing the test will decrease. Under the 2021 IECC, project teams have the option of verification or testing. Due to the prescriptive nature of verification, as well as the inherent value it provides to a project, we generally recommend that project teams select verification over testing, assuming there are no prescriptive air leakage requirements that need to be avoided to accommodate the design.
- » Air leakage testing for commercial buildings was not common in the United States prior to these code changes. The required air leakage targets are not unreasonable to meet but, in some instances, require a level of detailing that was not always common to an industry previously

focused on water leakage. Failed tests will become less common as the industry becomes more familiar with these requirements, but this has caused some growing pains as we acclimate to this testing.

Since the initial inclusion of air leakage testing in the IECC, the following changes have been made to these requirements in subsequent versions of the code:

2021 IECC

- » The air leakage testing requirements are identical in the 2012 to 2018 versions of the IECC and generally apply to “whole-building” air leakage testing. The 2021 IECC allows projects to test subsets of the building (areas under roofs, with public entrances, with loading docks, and 25% of the remaining above-grade areas), as well as “in-unit” air leakage testing. For the “in-unit” testing, only 20% of the dwelling units need to be tested (or seven units, minimum). However, for each failed test, an additional two units need to be tested.
- » In addition to the ASTM E779 standard referenced in the 2012 to 2018 IECC, the 2021 IECC allows testing in accordance with ANSI/RESNET/ICC 380, ASTM E1827, and ASTM E3158. Although these standards are all similar to each other, their

subtle differences can have a large impact on the testing and can often be the difference between a passing or a failing result. Some of these differences include the following:

- Whether the testing needs to be conducted using positive pressure, negative pressure, or both
- The number of data points that need to be collected
- How, or whether, to provide temporary seals over building openings and penetrations (e.g., mechanical openings)
- Allowable, or required, induced test pressures
- » The allowable threshold for “whole-building” air leakage under the 2021 IECC is 0.40 cfm/ft², which is the same limit listed in the 2012 to 2018 IECC. However, this version of the code provides an allowance where the building does not need to be retested as long as the leakage result does not exceed 0.60 cfm/ft² and diagnostic methods (i.e., tracer smoke or infrared imaging) are conducted to identify leakage sources and, to the extent they’re accessible, repair them.
 - “In-unit” testing does not provide any provisions or tolerance for air leakage rates above the 0.3 cfm/ft² at 0.2 inch water gauge threshold.

TABLE 1. IECC air leakage testing summary

IECC Code Year	Required?	Relevant Standards	Maximum Allowable Air Leakage Rate
2015	N	ASTM E779	0.40 CFM/ft ² at 75 Pa
2018	N	ASTM E779	0.40 CFM/ft ² at 75 Pa
2021	N	ASTM E779, ANSI/RESNET/ICC 380, ASTM E3158, or ASTM E1827 (whole-building) ASTM E779, ANSI/RESNET/ICC 380, ASTM E1827 (in-unit)	0.40 CFM/ft ² at 75 Pa, but diagnostics (not retesting) allowed if rate is below 0.60 CFM/ft ² (whole-building) 0.30 CFM/ft ² at 50 Pa (in-unit)
2024	Y*	ASTM E3158 (whole-building)** ASTM E779, ANSI/RESNET/ICC 380, ASTM E1827 (in-unit) ASTM E1186 (diagnostics)	0.35 CFM/ft ² at 75 Pa, but diagnostics (not retesting) allowed if rate is below 0.45 CFM/ft ² (whole-building and in-unit)

* Testing is generally required but verification is allowed for areas that meet exceptions

** If test area is smaller than 10,000 ft², ASTM E779, ASTM E3158, or ASTM E1827 can be used

2024 IECC

- » Allowable air leakage thresholds were reduced as follows:
 - Whole-building testing: 0.35 cfm/ft² at a pressure differential of 0.3 inch water gauge (75 Pa), with allowance for diagnostics (not retesting) if the leakage rate does not exceed 0.45 cfm/ft².
- » Whole-building testing for projects larger than 10,000 ft² must comply with ASTM E3158. Previous versions of the code allowed testing for commercial buildings of all sizes to comply with ASTM E779, ASNI/RESNET/ICC 380, ASTM E1827, or ASTM E3158, which provided for

more flexibility in testing procedures.

- » Building larger than 25,000 ft² in Climate Zones 0–4 do not need to conduct whole-building testing, except for Group I and R occupancies, which are still subject to “in-unit” testing.
- » For each failed “in-unit” test, and additional three units need to be tested (increased from two additional units in the 2021 IECC).

CONCLUSION

The new IECC air leakage requirements, which include design reviews, site observations, and air leakage testing, are intended to confirm that prescriptive

air leakage requirements in the energy code are properly implemented. While these provisions can add initial costs and, if not properly coordinated, time to projects, they serve to reduce long-term costs and resources associated with air leakage. In addition to their impact on air leakage, these provisions could serve to reduce the risk of other building-enclosure-related issues, such as water leakage, thermal bridging, condensation, material compatibility, and constructability. As the construction industry acclimates to these new requirements, their implementation onto projects will become more seamless and the performance of building enclosures across the industry will improve.

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Building Enclosure Forensics and the Need for a Site Communications Strategy

ABSTRACT

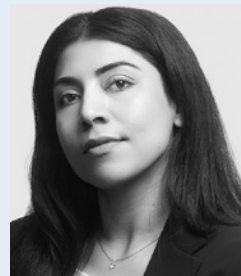
The durability of the building enclosure relies not only on the quality of its design but also on the precision of its execution during construction. This paper examines the critical interface between architectural detailing and on-site installation, focusing on the translation of information from architects to installers. Building forensic professionals often identify how minor oversights during design or installation evolve into significant issues, such as moisture intrusion or thermal inefficiencies. Drawing on forensic insights, the paper highlights common communication breakdowns that compromise enclosure performance and durability. It emphasizes the importance of clear documentation, effective communication tools, and installer training to align design intent with real-world practices. Practical recommendations drawn from recent forensic case studies span every phase of a building's life cycle. They include the following:

- » Annotated design drawings that explicitly show moisture control components, such as kick-out diverter flashings
- » Permitting checklists that flag any missing water management details before construction begins
- » Step-by-step installation guides and on-site communication protocols so trades can translate design intent accurately
- » Inspector training and digital visualization tools that spotlight high-risk interfaces during field review
- » Homeowner handbooks that explain maintenance routines and warn of early signs of enclosure distress

LEARNING OBJECTIVES

- » Illustrate how minor design or construction oversights can lead to significant building enclosure failures, such as moisture intrusion or thermal inefficiencies.
- » Analyze root causes and discuss measures to prevent bulk water ingress and moisture damage due to condensation from air leakage.
- » Describe what constitutes a communication breakdown scenario from the standpoint of building enclosure forensics.
- » Illustrate the use of detailed documentation, visual aids, and precise instructions to prevent errors, enhance collaboration, and ensure long-term performance and durability of the building enclosure.

SPEAKER



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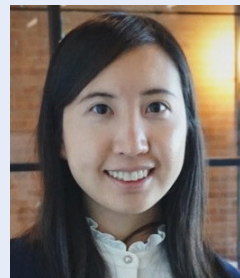


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Vice President and Practice Lead
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Jeff Reitsma is vice president and practice lead of 30 Forensic Engineering's Construction group, with nearly 25 years of experience in the engineering consulting and

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Forensic investigations into building enclosure failures typically begin when moisture-related problems escalate beyond routine maintenance. These issues can lead to disputes and often result in structural deterioration, requiring significant repairs. Such failures are usually associated with serious moisture damage stemming from bulk water intrusion or condensation through air ingress. Investigations require the collection of various types of information and an in-depth analysis to determine root causes and inform liability. This paper examines single-family, custom-built homes in Ontario through three detailed forensic case studies. Each case highlights critical events in the five stages of the building life cycle:

1. Preparation of design and construction documents
2. Permitting
3. Construction
4. Inspection
5. Occupancy

The key stakeholders involved in these processes include architects, builders, inspectors, and homeowners.

The case studies reveal several common patterns. First, inadequate architectural detailing stands out, alongside potential lapses in compliance with the *Ontario Building Code* (OBC). Additionally, there were concerns about insufficient oversight during inspections and instances of homeowner negligence. The forensic analyses highlight vulnerabilities in critical building components. These include roof-wall intersections, air and vapour barriers, attic ventilation, and wall flashing. Each case raises important questions regarding the responsibilities of key stakeholders. For instance, could architects or builders have identified and resolved moisture-related issues earlier in the construction process? Were inspectors negligent, allowing these deficiencies to go unnoticed? Finally, did homeowners unknowingly engage in actions that exacerbated or triggered the underlying problems?

CONTEXT

The increase in weather-related construction claims related to building enclosure failures highlights wider legal

uncertainties and financial risks. The building enclosure serves as the crucial barrier between indoor and outdoor environments. It must effectively manage both liquid water and airborne moisture to ensure structural integrity and indoor health. Unfortunately, many failures remain hidden until they cause significant damage. This often leads to costly repairs and legal disputes. Such failures are especially prevalent in single-family residential structures, where oversight issues, budget constraints, and misaligned responsibilities among tradespeople can further complicate and worsen defects.

Forensic investigations often reveal persistent moisture problems in above-grade enclosure components. These issues typically arise from inadequate design details and construction oversights, which are worsened by harsh environmental conditions. Ingham and Leek studied numerous cases and documented instances of water ingress due to insufficient waterproofing, poorly executed rainscreen cladding installations, and the lack of necessary flashings and sealants around window interfaces.¹ Their analyses highlighted that water infiltration usually results from a combination of factors. Designers may fail to anticipate extreme weather, contractors might neglect essential details, or building products may fall short of their expected performance in actual conditions.

Persistent moisture intrusion can have devastating effects. Over time, it leads to the corrosion of structural metals, decay in wooden elements, and mould proliferation. This cascade of issues ultimately contributes to structural instability. Each of these problems not only increases the scale of necessary repairs but also raises legal liability. In attic spaces, the accumulation of moisture and the resultant mould growth add further complications. These challenges disrupt our traditional assumptions about ventilation efficacy.

In their 2018 study, Ge, Wang, and Baril examined moisture and condensation problems in attics. Their research focused on residential buildings in a cold Canadian climate that closely mirrors the conditions found in

Ontario, Canada.² The study revealed significant issues related to attic ventilation. Although standard practices are often followed, attics lacking adequate ventilation consistently face moisture problems, especially in winter. Condensation and frost formed when warm, humid air from indoors infiltrated the cold attic spaces. In contrast, ventilated attics maintained acceptable moisture levels due to effective drying processes, whereas unvented attics kept high moisture levels year-round. While this underscores the importance of adequate ventilation for controlling moisture, the root cause often lies in a compromised environmental separation, namely, persistent air leakage from the conditioned to the unconditioned space, so ensuring air barrier continuity should be the primary diagnostic and remedial focus.

The studies reveal consistent central themes. First, inadequate detailing and a lack of redundancy in water management layers often lead to construction execution failures. These issues frequently arise under a backdrop of unclear or unenforced accountability. The findings emphasize the critical need for effective water shedding, proper material compatibility, and coordinated execution among trades. Moreover, they underscore an important point: code compliance alone is insufficient for ensuring durability. Enclosure resilience relies not only on good design but also on thorough construction oversight.

BUILDING ENCLOSURE FORENSIC CASE STUDIES IN SINGLE-FAMILY HOMES IN ONTARIO

This section presents three case studies investigated as part of forensic engineering practice. As is common in forensic investigations, the objective extends beyond merely identifying the cause of failure for the purpose of repair. It also involves formulating an expert opinion that may be utilized by legal teams to assign liability.

The three case studies include the following:

1. A five-year-old custom-built residence exhibiting exterior wall moisture damage resulting from the intrusion of bulk water from outside

2. A seven-year-old home experiencing moisture damage within the roofing cavity, attributed to the condensation of airborne moisture
3. A 10-year-old residence where bulk water infiltration led to significant interior water damage

Water Damage on an Intersecting Wall

Problem

A five-year-old, two-storey, custom-built, single-family home in Ontario, featuring a brick masonry veneer exterior wall system, began displaying subtle but progressively worsening signs of water damage. The damage was localized specifically at the intersection where the west-facing wall joined the north-facing wall. Early symptoms included efflorescence, dark staining on the brick surface, intermittent spalling of bricks, and a persistent musty odour noticeable indoors, particularly after rainstorms. Interestingly, other areas of the house did not exhibit similar damage, highlighting the unique vulnerability of this particular wall intersection. Homeowners initially attributed these signs to minor cosmetic issues, unaware of the severity beneath the surface (Fig. 1).

Forensic Investigation Findings

A comprehensive forensic investigation combining visual inspections, moisture measurements, thermal imaging, and destructive testing was undertaken. Initial moisture meter readings indicated critically high moisture levels within the wall cavity, exceeding 30 percent moisture content, which far surpasses the safe range of 15 to 17 percent for wood framing.³ Upon opening sections of the wall, extensive hidden damage was found, including severely rotted oriented strand board (OSB) sheathing, advanced decay of structural framing members, and widespread mould growth.

Detailed examination pinpointed the primary cause: improperly managed rainwater runoff from the north-side roof. The absence of a critical kick-out diverter flashing and gutter at the roof-wall intersection was discovered. This omission allowed large volumes of rainwater to cascade directly onto the vulnerable west-facing wall. Compounded by prevailing local wind

patterns, wind-driven rain pushed water deeper into the wall assembly, exacerbating moisture penetration (Fig. 2). Over time, persistent runoff had gradually eroded mortar joints, creating additional pathways for water intrusion behind the brick veneer. The investigation further noted poor construction practices, including inadequate cleaning of the drainage cavity, improperly spaced and maintained weep holes, and poorly sealed seams in the weather-resistive barrier. Additionally, the hygroscopic nature of OSB contributed significantly, as it absorbed and retained far more moisture than plywood would have.

The unique geometry, wall assembly construction, and microclimatic conditions of this specific wall intersection made it exceptionally vulnerable to moisture-related deterioration. As required by the OBC, flashing must be installed at roof wall intersections to prevent water infiltration (Fig. 3):⁴

OBC Division B, Section 9.26.4.4.: Requires that the intersection of shingle roofs and masonry walls or chimneys be protected with flashing to prevent water infiltration at these vulnerable roof-to-wall interfaces. This provision ensures that runoff is properly diverted away from the wall surface, reducing the risk of moisture intrusion behind cladding materials.

Outcome

The homeowners faced substantial repair costs due to these previously concealed defects. Architects neglected to detail this crucial roof-wall intersection clearly in the construction drawings, a critical lapse that went unnoticed during the permitting process. The competence and diligence of contractors and roofers were also questioned, as their practical experience should have alerted them to the potential for severe water intrusion, prompting them to raise concerns proactively. Furthermore, inspectors overlooked this detail during site reviews. This case highlights the necessity of rigorous oversight, detailed architectural documentation, and proactive communication among all stakeholders.

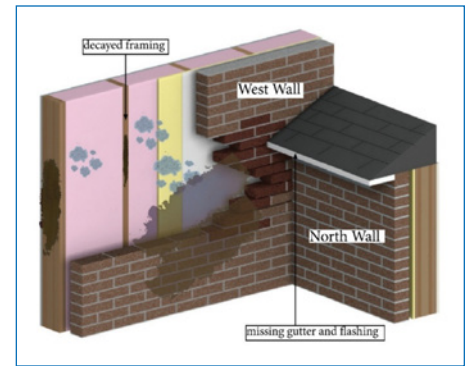


FIGURE 1. Structural damage (rotting and mould growth) on the west wall due to water deposition from the roof-wall intersection.

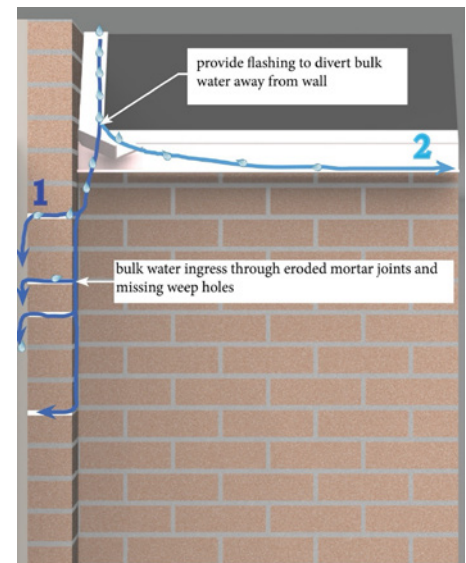


FIGURE 2. At the critical roof-wall intersection, the natural water pathway (indicated as 1 on image) needed to be diverted to a controlled route of water shedding (indicated as 2 on image).

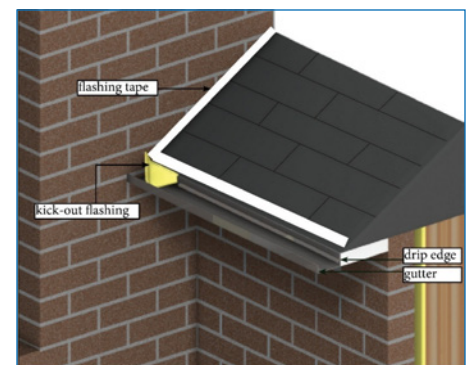


FIGURE 3. Moisture damage on the west wall could have been avoided with the inclusion of proper kick-out flashing, drip edge at the roof, and gutter specified on architectural drawings and verified during construction.

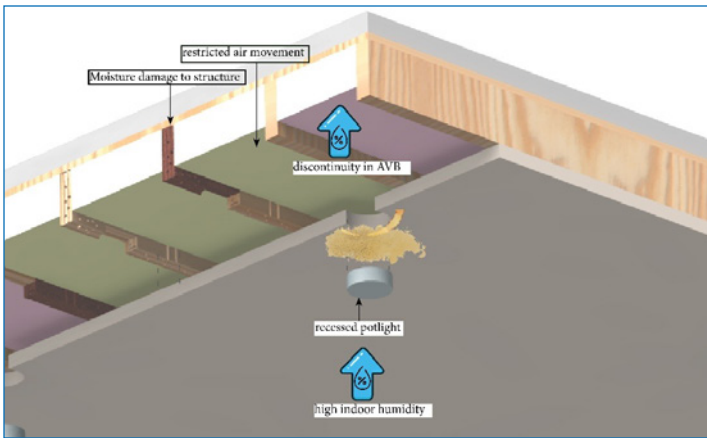


FIGURE 4. Roof structural system condensation damage due to air barrier discontinuities and inadequate attic venting.

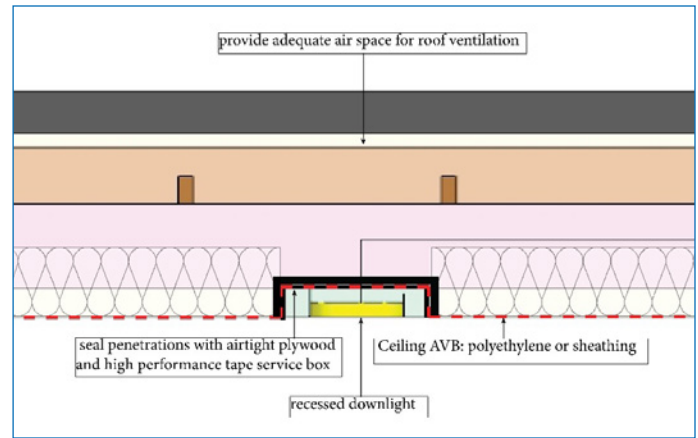


FIGURE 5. Seal penetration of recessed downlight with airtight plywood and high-performance tape service box to prevent heat and air bypass.

Roof Structural System Damage Due to Air Barrier Discontinuities and Inadequate Attic Venting

Problem

A seven-year-old, two-storey, custom-built, single-family home in Ontario, featuring a flat roof system, began to exhibit signs of attic moisture issues. Initial observations by the homeowners included intermittent damp patches and discoloration on ceilings, coupled with a persistent musty odour that intensified during colder months. Upon inspection and removal of the gypsum ceiling, a significant accumulation of water was discovered within the attic space. This condition became evident when an incision was made through the polyethylene vapour barrier, resulting in water actively draining from the attic area. The presence of extensive moisture accumulation indicated a critical underlying issue requiring immediate engineering assessment and remediation (Fig. 4).

Forensic Investigation Findings

A forensic investigation utilizing both visual and destructive inspection methods revealed significant concealed damage within the attic space. Severe decay resulting from condensation was evident on roof joists and plywood sheathing, indicating prolonged moisture exposure. Additionally, the home's interior environment exhibited high humidity levels and substantial air movement facilitated by the HVAC system. The investigation confirmed that the compromised polyethylene air and

vapour barrier allowed indoor humidity to infiltrate the attic, where it condensed upon cooler surfaces.

These moisture issues coincided with recent interior renovations, specifically ceiling height modifications and the installation of new lighting fixtures, which inadvertently punctured the polyethylene barrier and compromised its continuity. Although the attic featured standard soffit ventilation, improper installation practices and compressed insulation materials obstructed these vents, severely restricting airflow and trapping moisture within the attic. Other areas of the home did not show similar moisture-related issues, indicating specific vulnerabilities associated with the flat-roof construction and recent modifications.

Outcome

The homeowners incurred substantial repair costs primarily due to their oversight in modifying the ceiling without adequately restoring the continuity of the air barrier. Additionally, the contractor was responsible for deficiencies in the roof ventilation system—specifically, constructing a roof cavity with inadequate space to ensure proper airflow and permitting batt insulation to obstruct the already limited ventilation pathways. These issues had not been identified during the inspection stage.

This case highlights the importance of homeowner awareness when making interior modifications that affect air barrier continuity, emphasizing the

potential risks such changes pose to the integrity of the building enclosure. (Fig. 5).

Inadequately Installed or Damaged Through-Wall Flashing Causing Water Leakage in the Basement

Problem

In a 10-year-old single-family home with a brick masonry veneer exterior, the homeowners reported water leakage in the basement during moderate to heavy rainfall. The leakage was observed along the upper portion of the interior basement wall, particularly near the interface between the above-grade exterior brick cladding and the cast-in-place concrete foundation wall. Water staining, localized dampness, and efflorescence on the interior face of the basement wall were the initial indicators of moisture intrusion. These symptoms suggested an exterior enclosure failure near the wall transition (Fig. 6).

Forensic Investigation Findings

Visual and destructive inspections were conducted at the exterior wall assembly and the basement perimeter. Upon removal of select brick units and inspection of the drainage cavity, the investigation revealed that the through-wall flashing, intended to direct moisture outward at the brick-to-foundation transition, either had slipped out of position or had been improperly installed. The flashing material used was a flexible-membrane-based material, which was found to have delaminated or displaced over time. In some locations, the flashing was reverse lapped over the

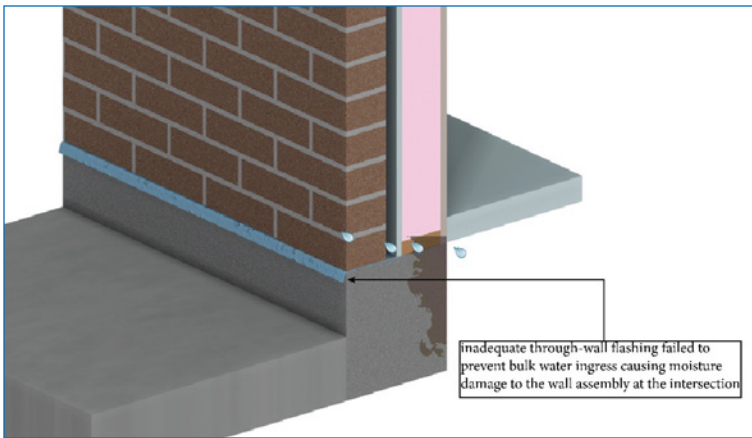


FIGURE 6. Inadequately installed through-wall flashing causing water leakage in the basement.

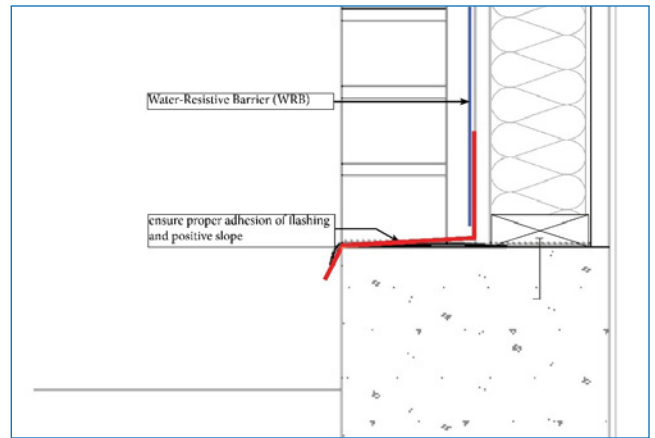


FIGURE 7. Stakeholders must ensure the water-resistive barrier is properly integrated with the flashing and the flashing is securely fastened at the transition.

weather-resistive barrier, allowing water to migrate behind it rather than being expelled through the wall face.

Additionally, the weather-resistive barrier was not properly integrated with the flashing, and there was no termination bar or mechanical fastening to secure the flashing at the transition (Fig. 7). As a result, water penetrating the brick veneer through porous mortar joints or microcracks was able to travel down the cavity and bypass the compromised flashing. The water then infiltrated at the critical junction between the exterior wall and the top of the foundation, leading to basement leakage.

Outcome

Responsibility for the failure rested primarily with the masonry subcontractor, who failed to properly install and secure the through-wall flashing and to ensure it was lapped correctly with the weather-resistive barrier. The use of an unreinforced membrane-based flashing without mechanical support contributed to the material slipping over time. This issue was also missed at the inspection stage. The oversight led to ongoing water entry, basement wall dampness, and potential deterioration of foundation wall interfaces.

LESSONS LEARNED

These case studies highlight the critical importance of rigour and meticulous attention to detail across all phases of the building process. Each case

demonstrates that lapses at specific stages, whether they occur during the design, construction, inspection, or occupancy stage, can contribute to building enclosure failures (Fig. 8).

Architectural Drawing Stage

Design professionals must visualize not only the aesthetic and functional aspects of design but also how water interacts dynamically with building components.



FIGURE 8. Each stage of a building’s life cycle plays a part in adhering to building science principles and ensuring the durability of building details.

In the section “Water Damage on an Intersecting Wall,” the absence of a detailed kick-out diverter flashing at a critical roof-wall intersection led directly to extensive moisture damage due to the unique geometry of the building interface. Detailed drawings should explicitly indicate such critical components, ensuring their locations and installation requirements are clearly articulated to avoid misinterpretations or oversights by contractors.

Permitting Stage

City permitting reviews should critically examine the completeness of submitted drawings with explicit attention to water management details. The oversight in the sections “Water Damage on an Intersecting Wall” and “Inadequately Installed or Damaged Through-Wall Flashing Causing Water Leakage in the Basement,” where inadequate flashing installation resulted in bulk water-related damage, highlights the necessity for permitting reviews to catch incomplete detailing related to moisture management systems before construction begins.

Construction Stage

Contractors play a crucial role in accurately translating design intent into construction. As demonstrated in the section “Water Damage on an Intersecting Wall,” reasonably competent and trained parties would have identified these issues at the outset or promptly raised a site query. Trades must rigorously adhere to industry best practices and manufacturers’ guidelines, and contractors should foster

an environment that encourages clear communication whenever specifications are unclear or incomplete.

Inspection Stage

Inspection represents critical checkpoints where construction compliance must be verified rigorously. In the section “Water Damage on an Intersecting Wall,” the absence of necessary flashing went unnoticed by inspectors, highlighting the importance of thorough inspection of vulnerable components, such as flashing, barriers, and drainage details. Enhanced training for inspectors in identifying early signs of moisture intrusion and detailed checks of vulnerable intersections can significantly reduce the likelihood of overlooked deficiencies.

Occupancy and Homeowner Stage

Homeowners should be provided comprehensive guidance, including manuals detailing maintenance requirements and signs of potential enclosure failures. The section ‘Roof Structural System Damage Due to Air Barrier Discontinuities and Inadequate Attic Venting’ highlights the importance of homeowner education, showing how unauthorized interior modifications can inadvertently compromise critical barriers. Early detection and informed intervention can prevent minor issues from escalating into significant structural damage.

CONCLUSION

As weather extremes become more frequent and severe, buildings are

increasingly exposed to intense rainfall, wind-driven moisture, freeze-thaw cycles, and prolonged humidity. These environmental stressors amplify the risk of enclosure failures, making it essential that every stakeholder, from design professional to homeowner, understands their role in safeguarding building performance. In an era marked by economic uncertainty and inflationary pressures, the financial cost of remediating preventable failures is rising sharply. Poorly managed water intrusion can lead to mould, rot, and structural compromise, which are issues that often remain hidden until significant damage prompts forensic investigations, insurance claims, or litigation. For developers and homeowners alike, the consequences are severe: costly repairs, delayed occupancy, reduced property value, and increased legal exposure.

In this context, this paper’s lessons drawn from recent case studies take on heightened significance. They demonstrate that successful enclosure performance depends on more than just good intentions; it requires meticulous design detailing, proactive permitting reviews, vigilant construction oversight, comprehensive inspections, and informed homeowners. Each phase of the building process represents a critical opportunity to intercept failure before it occurs. Effective communication, clear delineation of responsibilities, and strict adherence to building science principles are essential not only to ensure resilience but also to manage financial risk in an increasingly unpredictable weather and economic landscape.

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Advances in Education and Evaluations for Polyvinyl Chloride Single-Ply Membrane Roof Recycling Practices

ABSTRACT

Polyvinyl chloride (PVC or vinyl) materials have been recycled for decades as production scrap or when products have reached their end-of-life. PVC recyclers use these reclaimed materials to make recycled content feedstocks to be processed back into roofing products (closed loop) or other vinyl products such as flooring (open loop). This process recaptures the carbon benefit recycled membranes offer from a life-cycle assessment (LCA). These benefits can be quantified using comparisons of replacing virgin PVC materials with recycled content materials. In addition to carbon avoidance, certification credits for waste management and recycling from green building rating systems such as Green Building Initiative (GBI) Green Globes, US Green Building Council LEED, and Building Research Establishment Environmental Assessment Method (BREEAM) are available to building owners that can add value to a building's portfolio.

As part of their sustainability initiatives, the Vinyl Institute (VI) and the Coated Fabrics and Film Association (CFFA) Vinyl Roof Division advocate for additional PVC recycling. Under a grant from the VI, the CFFA has developed recycling roof guide specifications and suggested techniques for removing the existing PVC roof. They will be presented. Additionally, a video will highlight how to remove and prepare a single-ply roof membrane for shipping to a recycler after a cycle renovation. Communication and education are key factors within the roofing industry to ensure single-ply roof membrane recycling becomes more widely known and practiced. This will ultimately enhance sustainability within the industry.

LEARNING OBJECTIVES

- » Identify the types of polyvinyl chloride (PVC) single-ply roof systems currently being recycled.
- » Provide educational tools that are available for incorporating PVC roof membrane recycling specifications into a cycle renovation bid package.
- » Describe acceptable practices and illustrate the steps involved in packaging and bundling the existing roofing membrane for recycling instead of the landfill.
- » Explain how much carbon equivalent emissions can be avoided by recycling end-of-life PVC roof membranes.
- » Summarize how green certification systems such as Green Building Initiative (GBI) Green Globes, US Green Building Council LEED, and Building Research Establishment Environmental Assessment Method (BREEAM) specific to recycling or using products with recycled content can add value for building owners.
- » Discuss applications that use recycled content PVC roof membrane as feedstock.
- » Analyze the quantity of PVC single-ply roof membranes recycled each year.

SPEAKER



Richard Krock, PE
Principal
VyChlor Advisors LLC

Richard Krock is a principal with VyChlor Advisors LLC, a consulting company he formed in 2022 to assist manufacturers, recyclers, suppliers, and trade associations in advancing their positions in the vinyl value chain. He retired as senior vice president for regulatory and technical affairs at the Vinyl Institute and has worked in the PVC industry for 37 years. He joined the Vinyl Institute in 2009 to advocate for the industry's regulatory positions and technical matters and advance its sustainability. A registered professional engineer, Krock holds a bachelor of science in chemical engineering and an MBA from Marshall University.

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Jennifer Oblock
Executive Director
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Jennifer Oblock is an account executive at Thomas Associates Inc., a trade association management company headquartered in

Cleveland, Ohio. Since 2013, she has been immersed in association duties, working closely with associations of all sizes. She represents the Chemical Fabrics and Film Association, where she serves as its executive director. Oblock's experience covers the full range of association activities, including all aspects of project and meeting management, and she serves as the principal liaison to association directors and officers. She holds a bachelor of arts degree in business with a concentration in marketing from Mercyhurst University.

INTRODUCTION

Two main principles of sustainability are 1) doing more with less and 2) continuous improvement.^{1,2} Thus, recycling materials either from manufacturing scraps or from products at the end of life (EOL) to recover their resources fits well with these principles. The Coated Fabrics and Film Association (CFFA) Vinyl Roofing Division (VRD) members and some non-VRD members have collectively been tracking their progress toward these principles for the past 3 years for their polyvinyl chloride (PVC) roof membranes manufactured at their own facilities as well as for EOL recovery at their customers jobsites in order to advance resource conservation within this industry.

OVERVIEW OF PVC RECYCLING

The Vinyl Institute (VI) tracks pre- and postconsumer recycling in the US and Canada on a 3-year cycle. The latest information available for the year 2022 indicates that approximately 960 million lb (435,500 metric tons) of preconsumer and over 140 million lb (63,500 metric tons) of postconsumer PVC materials were recycled by over 100 recyclers and manufacturers.³ These numbers show the significant volumes of PVC materials already being recycled and the network that is in place to collect, transport, recycle, and make new materials with these waste reduction streams. In an effort to boost postconsumer PVC material recycling, the VI created its VIABILITY™ program that offers grant money to fund research, equipment, and market development programs specific to this initiative. The CFFA VRD has been a recipient of VIABILITY™ grants to promote its EOL recycling program.

CFFA ROOFING PRECONSUMER RECYCLING INITIATIVE

The CFFA VRD began surveying its members' PVC roof membrane recycling in 2014 in order to track its progress to improve the industry's sustainability stewardship. In total, over 209 million lb of PVC roof membrane have been diverted from landfill and used to make other materials. The surveys indicate that some 196 million lb of preconsumer manufacturing scrap PVC roof membranes have been recycled since 2014 (**Fig. 1**).⁴ (Note: This amount does not account for potential yield losses during the recycling process.)

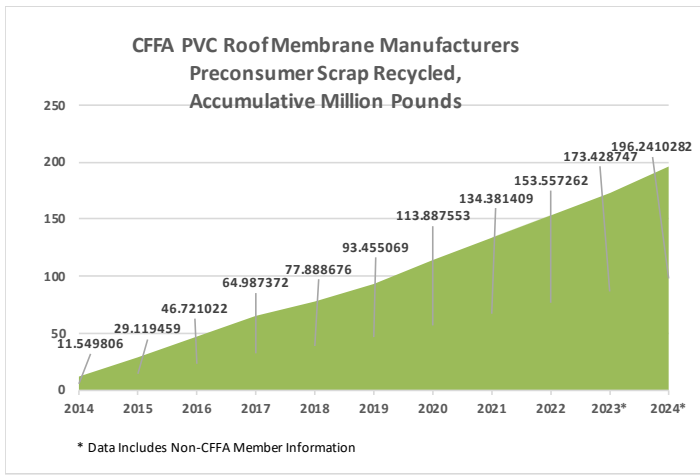


FIGURE 1. Accumulative preconsumer manufacturing scrap recycled. Note: CFFA = Coated Fabrics and Film Association; PVC = polyvinyl chloride. Note: Recycled volumes represent quantities designated for recycling and do not account for varying yield loss estimated at 10% overall.

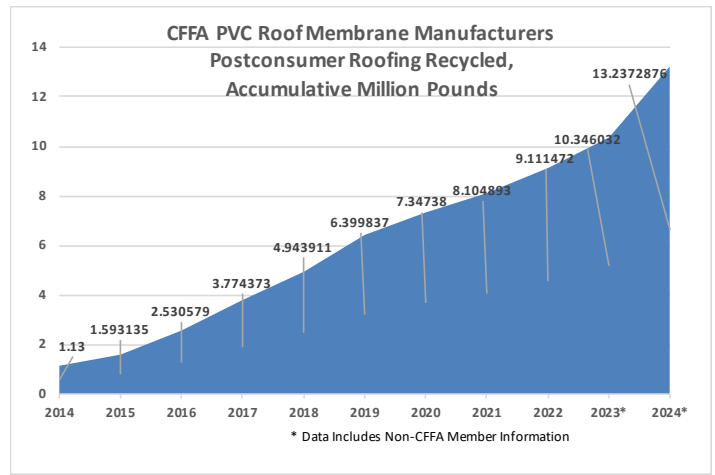


FIGURE 2. Accumulative postconsumer polyvinyl chloride (PVC) roof membrane recycled. Note: CFFA = Coated Fabrics and Film Association. Note: Recycled volumes represent quantities designated for recycling and do not account for varying yield loss estimated at 10% overall.

PATHWAY TO ZERO

An initiative undertaken by the CFFA VRD members in 2023 is their “Pathway to Zero,” where as much manufacturing scrap as possible is diverted from landfills.⁴ When comparing 2024 to 2023 performance, CFFA VRD members were able to work with recyclers to reduce amounts of waste sent to landfills from 976,000 lb down to 386,000 lb, a 60% reduction. This is a significant conservation of resources and a good industry sustainability improvement.

their PVC roof membrane. Many roofing contractors have not been involved with recycling the roof membrane, so there is little understanding of the costs and a reluctance to recommend it. The CFFA VRD addresses these challenges with communications efforts and training tools. By spreading the word about recycling through success stories, the CFFA VRD can help more building owners become better informed about who has recycled their roofs from a cycle renovation. By creating tools such

as a training video, the CFFA VRD can teach contractors how to package and bundle the original PVC roof membrane so it can be safely removed from the roof and loaded onto a truck to ship to a recycler. This training video is available to view at <https://vinylroofs.org/sustainability/post-consumer-recycling/#roof-recycling-video>. The CFFA VRD believes the more PVC roof membranes are recycled, the more the entire process will become more routine and widely practiced.

POSTCONSUMER RECYCLING

Postconsumer PVC roof membrane recycling hit a record high of 2.9 million lb in 2024, a remarkable 74% increase over 2023.⁵ On an accumulative basis, some 13 million lb of PVC postconsumer membrane have been recycled over the previous 11 years, as shown in **Fig. 2**.⁵ (Note: This amount does not account for potential yield losses during the recycling process.) The number of roof jobs recycled in 2024 increased to 139, which translates to almost 12 per month. Also, the amount of square footage of roof membrane being recycled more than tripled, reaching the 10 million ft² mark for the first time.

While there was nice progress made in 2024, there is still much work to do. Many building owners and specifiers are unaware of the potential to recycle

TABLE 1. Typical reroofing steps overview: tear off and dispose of the roof versus tear off and recycle the polyvinyl chloride (PVC) roof membrane

Tear off and dispose of the roof	Tear off and recycle the PVC roof membrane
Pre-job conference	Pre-job conference
Blow the roof free of debris	Blow the roof free of debris
Load the roof with new materials	Load the roof with new materials
Slice the existing membrane and roll up	Slice the existing membrane and roll up
Throw the roof membrane with other roof debris into a dumpster	Saves a step , as the PVC membrane is not thrown into a dumpster
Install the new roof	Install the new roof
	Package/bundle the old roof rolls
	Remove packages from the roof
	Lift packages onto a flatbed
Lift or crane the roof equipment and roofing materials from the roof	Lift or crane the roof equipment and roofing materials from the roof

MECHANICALLY ATTACHED PVC MEMBRANE FOCUS FOR RECYCLING

Mechanically fastened or induction-welded membranes do not use adhesives to bond the membrane to the roof substrate. Rather, the membrane is ultrasonically welded to metal fasteners typically connected to a metal roof deck or fastened in the membrane overlap, and the seams are welded. A smooth-backed membrane is used for this type of installation, which facilitates its removal. Slicing the membrane around the metal fasteners and plates loosens it so that it can be rolled up.

Adhered roof systems are available with a barebacked or a fleece-backed membrane to enhance the bond between the adhesive and the roof substrate. When the adhered roofs are peeled off, portions of the substrate, such as insulation and hardboard, can often be pulled off with the membrane. The extra fiber from the fleece backing, the adhesive, and any remnants of adhered insulation or hardboard make this type of roof challenging for today's mechanical recyclers. That being said, evaluations are underway to utilize EOL adhered roofs in some type of product capable of utilizing all the composite in the recycle stream.

ADDITIONAL STEPS TO RECYCLE A ROOF MEMBRANE

Because every job is different, it is not possible to give a single value about what the added costs are for recycling a mechanically fastened PVC roof membrane. The animated video created by the CFFA VRD confirms that on a reroofing project where the PVC membrane is already being removed, there are only two to three additional steps, as listed in **Table 1**, that are needed to prepare the PVC roof membrane for transporting from the roof onto the recycler's truck. The answer is that the additional cost to recycle the PVC membrane is minimal, and there are some savings from not hauling it in a dumpster to a landfill.

RECYCLING SPECIFICATIONS FOR MECHANICALLY ATTACHED PVC ROOF MEMBRANE

The best way to know the added cost for recycling is to include the option to recycle the PVC roof membrane in the reroofing bid package. In the boxes below, suggested language is provided for a guide specification for the reroofing project and for a line item that can be added to the bid form. Spelling out the recycling cost for the owner provides transparency and allows the building owner to make a

more informed decision for that specific property and their company.

EOL PVC ROOF RECYCLING EXAMPLES

There are several options available to recycle a PVC roof membrane. Knowing what those options are provides a better understanding by the building owner, specifier, and contractor as to what is being done with the EOL membrane and why some of the steps to recycle it are important.

PVC ROOF RECYCLING GUIDE SPECIFICATIONS

[Note to specifier: PVC roofs have a proven track record of being recycled into new roofing products and other products/applications. If you have an existing mechanically attached PVC roof and you plan to remove the PVC roof, then it is an ideal candidate for recycling. It is recommended the recycling cost be estimated and listed as a separate alternate bid line item on the project bid form so the owner can make an informed decision. The example language below can be inserted into your reroofing project specifications.]

As part of an alternate bid line item, the roofing contractor shall provide a separate price for the existing PVC roof membrane to be packaged, removed from the roof, and shipped or picked up by the recycler. The roofing contractor should consult with their PVC roofing manufacturer or the CFFA website, vinylroofs.org, to determine the best course of action and the best method of packaging/bundling the original PVC roof.

As part of the project close-out documentation, working with the recycler, the roofing contractor shall provide confirmation of how many tons of PVC roof membrane have been received and diverted from landfill.

Roofing contractors shall follow all OSHA and normal rooftop safety protocols for all recycling steps.

SUGGESTED PVC ROOF RECYCLING BID FORM

[Note to specifier: Consider this language on reroofing projects where the existing mechanically attached PVC roof membrane is specified to be removed and recycled.]

Bid Form:

Alternate Bid No:

The proposed lump sum price to package the original PVC roof membrane, safely remove from the roof, and put on a flatbed/truck to ship to the recycler:

Dollars \$ (_____)

Price includes all labor, overhead, and profit and should take into consideration the reduction in dumpster and landfill costs for diverting PVC membrane from landfill and any additional shipping costs not paid by recycler.



FIGURE 3. Closed-loop applications for recycled polyvinyl chloride roof membranes: a) walkway in darker gray color; b) white-colored recycled hardboard.



FIGURE 4. Open-loop applications for recycled polyvinyl chloride roof membranes: a) roll goods resilient flooring; b) concrete pavement expansion joints.

CLOSED-LOOP APPLICATIONS

Closed-loop means that the EOL membrane may be recycled into a roofing product.⁶ Those products include the roof membrane itself, typically on the underside or in walkways, and even in recycled-roof hardboard underlayment. Each of these applications requires a different level of quality to be successfully used. For example, to recycle into the underside of the roof membrane, practically all the fiber reinforcement of the roof must be removed. This can be achieved through specialized fine grinding and aspiration.

Walkway mats utilized on roofs are not the protective membrane, so their function is to be a durable protective layer for the primary membrane when maintenance workers are on the roof. In some cases, walkway membranes can tolerate a higher level of fiber contamination to the extent it can be processed by the manufacturer making the walkway membrane. Examples are shown in **Fig. 3**.

Recycled roof board underlayment has been manufactured that contains

polyester fluff byproduct from PVC roof membrane recycling. This fibrous material contains some PVC material that, when compressed with the polyester fluff and other hardboard ingredients, acts as a binder and reinforcement to strengthen the board for handling and resistance to indentation or puncture. Examples are shown in **Fig. 3**.

OPEN-LOOP APPLICATIONS

Open-loop means that the EOL membrane may be recycled into a non-roofing type of product such as

flooring products, both roll goods and flexible tile types, or expansion joints for concrete or brick pavements.⁶ Each of these products requires certain qualities of recycled materials to be successfully used, but some residual fiber reinforcement typically does not present a functional performance deficiency; in fact, it can be just the opposite in that the fiber reinforcement augments the product's performance. Examples are pictured in **Fig. 4**.

The CFFA VRD members roof membrane manufacturers may be the best resource for determining which type of application that the torn-off roof could be utilized in.

CARBON AVOIDANCE ESTIMATES

According to Architecture 2030, "The built environment generates 42% of annual global CO₂ emissions. Of those total emissions, building operations are responsible for 27% annually, while building and infrastructure materials and construction (typically referred to as embodied carbon) are responsible for an additional 15% annually."⁷

The Architecture 2030 organization started its 2030 Challenge in 2006 to achieve net-zero carbon by 2030 for new buildings, developments, and major renovations.⁸ The American Institute of Architects (AIA) formed its 2030 Commitment in 2010 to apply the principles of sustainable design to every project, not just those seeking green certifications.⁹ AIA began its survey of embodied carbon by building project in 2021. In 2023, over 7,000 projects reported a range of 26 to 169 lb per ft² (125 to 825 kg CO₂e/m²) estimated embodied carbon across 10

TABLE 2. Summary of avoided emissions by recycling scenario compared to landfilling torn-off roof membrane¹¹

Recycling type	Closed-loop applications		Open-loop applications	
	85%	90%	85%	90%
Collected material suitable for recycling	85%	90%	85%	90%
Avoided emissions per ft ² (or per 1 m ²) membrane collected, kgCO ₂ e	0.338 (3.64)	0.363 (3.91)	0.281 (3.03)	0.344 (3.71)

TABLE 3. Partial Listing of green building rating system credits for recycled-content materials that reduce embodied carbon

GBI GG 2024 New Construction ¹³	GBI GG 2023 Existing Buildings ¹⁴	USGBC LEED v5 New Construction ¹⁵	BREEAM 2015 Std. 225 ND ¹⁶ Refurbishment and Fit Out Assessment
<p>5. Materials</p> <ul style="list-style-type: none"> » 5.1 WBLCA comparisons; » 5.2 Product LCA, number of third-party-certified EPDs; » 5.4 Sustainable Materials Index, % of materials costs with third-party-certified recycled content. 	<p>5. Materials</p> <p>5.1 Renovations</p> <ul style="list-style-type: none"> » 5.1.1.5 Construction, renovation, and demolition waste management policy, procedure, and plan for cycle renovation(s). 	<p>Materials & Resources</p> <ul style="list-style-type: none"> » WBLCA comparison, EPD analysis, use of materials to reduce embodied carbon; » Optimized building products for circular economy with recycled content; - Construction and demolition waste diversion, and recycling. 	<p>Mat 06 Material Efficiency</p> <ul style="list-style-type: none"> » Procure materials with higher levels of recycled content. <p>Mat 01 Environmental Impact of Materials</p> <ul style="list-style-type: none"> » Measured using LCA tools.

Note: GBI GG = Green Building Initiative Green Globes; USGBC = US Green Building Council; BREEAM = Building Research Establishment Environmental Assessment Method; WBLCA = whole-building life-cycle assessment; LCA = life-cycle assessment; EPD = environmental product declaration.

building use categories, of which 75% were new construction and 25% were retrofits.¹⁰ These numbers demonstrate the significant emissions of CO₂e attributable to building materials.

Material selection can be an important aspect in reducing the embodied carbon of a building. Roofing membranes themselves are a small contributor to the overall embodied carbon footprint of a new building. Therefore, it is recommended that membrane selection criteria also include proven track record, durability, energy savings, fire resistance, and safety.

However, the recurring embodied carbon footprint for cycle renovations is often overlooked in building life-cycle assessments. Cycle renovations include maintenance and refurbishment of interiors and exteriors, including roof replacements, to prolong the use of the building. Properly managing the end of life of torn off roofing materials can reduce the environmental impact of that building. The National Institute of Standards and Technology (NIST) recently estimated the carbon avoided by recycling EOL PVC roof membranes (Table 2).

The average PVC single-ply membrane roof size is 25,000 ft². Using the NIST estimates, by recycling the PVC roof membrane at a single cycle renovation project, the range of avoided carbon emissions would be between 7,037 and 9,081 kg CO₂e. This is equivalent to the emissions from driving a gasoline-powered automobile approximately 18,000 to 23,000 mi.¹² Extrapolating this for the CFFA VRD amounts of postconsumer materials recycled in 2024 (10 million ft²) results in avoided carbon emissions of 2.8 to 3.6 million kilograms. This is equivalent to removing between 650 and 840 gasoline-powered automobiles from the road for a year.¹²

VALUE OF GREEN CERTIFICATIONS

Opportunities exist for building owners to be recognized for their sustainability initiatives for example through the achievement of “green certifications” from rating systems such as Green Globes, LEED, and BREEAM. Each of the systems provides credits for certification when selecting new building products with recycled content or for proper management of construction waste materials. While not comprehensive, Table 3 lists some

example credits.

Green certifications have the potential to improve the appraised value of the building, command higher leases, and, in general, make the building a more marketable property.¹⁷ In addition, reducing amounts of construction debris put into landfills not only saves money but also extends the capacity of the landfill for other non-recyclable wastes, which community leaders could appreciate.

SUMMARY

The CFFA VRD is committed to doing its part to raise awareness and promote the benefits of roof recycling, which will improve circularity. The CFFA VRD sees this as a journey, not a final destination, to continually improve and do more with less.

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Parapets, Guardrails, and the Building Enclosure

ABSTRACT

Parapets and guardrails often overlap in purpose when they are located at the edge of a terrace, balcony, or roof. To make matters more complicated, these “secondary architectural elements” may directly impact the building enclosure in terms of water management, air, and thermal control. What are the key issues that come into play during the design, construction, and in service? These architectural elements have a unique array of considerations at a very complicated location: the structural, thermal, safety, waterproofing/roofing, and aesthetics of the enclosure all need to be considered and coordinated. The intersection of regulatory requirements (such as codes and local ordinances) with good design, detailing, and maintenance practices can help promote long-lasting parapets and guardrails for years to come without degrading the performance of the building enclosure.

LEARNING OBJECTIVES

- » Illustrate five different code considerations with regard to parapets and guardrails.
- » Describe how and where the discontinuities at parapets and guardrails can diminish the performance of the building enclosure.
- » Evaluate strategies to make parapets and guardrails more durable and resilient.
- » Summarize maintenance considerations with regard to parapets and guardrails.

SPEAKER



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INTRODUCTION

Parapets and guardrails protect. Safety has been their primary function. Often parapets and guardrails are combined as one feature. Sometimes guardrails are present without parapets (**Fig. 1**).

Since these are highly exposed and projecting up and away from the building enclosure, they are subject to abuse. Integrity is important. Parapets and guardrails impact the building enclosure's water management, thermal performance, and air/vapor barrier continuity.

DEFINITIONS

Parapet – a guarding wall at a sudden drop, a fire wall, or the part entirely above the roof.¹

Guardrail – a protective railing system along the outer edges of locations of an accessible roof or balcony.²

Building Enclosure – combined system of materials, components, and assemblies (such as walls, roofs, windows, doors, and foundations) that provide environmental separation and control heat, air, moisture, and sound transfer between the indoor and outdoor environments.

HISTORY AND CODE

Deuteronomy 22:8 says, "When you build a new house, put a parapet around the roof, so that you do not bring bloodguilt upon your house if someone falls off."³

Guardrails trace back to ancient Roman transennae used on stairs and elevated walkways. Medieval and Renaissance periods developed the balustrade. Parapets evolved from



FIGURE 1. Parapets and guardrails often both serve as perimeter guards. *Photo by author.*

medieval European castle walls that provided both defensive height and cover for soldiers. Later they became fire protection barriers between buildings in urban settings. Eventually, they became decorative architectural elements used even in non-urban buildings. The 18th-to-19th-century introduction of cast iron allowed mass production of guardrails for various buildings, particularly for fire escapes and balconies.

Devastating fires prompted the development of building codes to promote the health and safety of building users. Specifically, parapet walls were specified to provide fire protection from adjacent urban buildings if consumed with fire. Later, as these upward-projecting elements grew in size and stature, the structural implications of these parapets increased.

Guardrails could protect users without being a parapet wall, so standards were

developed to address sizes and shapes of guardrails.

For example, the following are 2024 *International Building Code* (IBC) criteria:

Fire

IBC 705.11, Parapets, describes requirements. If an exterior wall is required to be fire resistance rated, say in a dense neighborhood, then a minimum 30 in. parapet shall be provided, with noncombustible materials present at the top 18 in.

Structural

Many structural loads are imposed on parapets. Wind resistance performance is determined by IBC 1609, Wind Loads on Buildings, and 1504.1, Wind Resistance of Roofs. Seismic design is indicated in IBC 1613, Earthquake Loads, and 2107.3, Allowable Stress Design for Masonry, which also cross-references the American Society of Civil Engineers' ASCE 7. Parapets must be designed to



FIGURE 2. View of posted guardrail system with design that does not allow the passage of a 4 in. sphere. *Photo by author.*

resist lateral loads such as snowdrifts and the lateral pressure of water when they act as the perimeter for rooftop stormwater detention systems. While IBC Section 1608, Snow Loads, defines design requirements, the hydrostatic pressure from detained stormwater may require additional fluid pressure calculations, based on the volume and height of the water.

Additionally, parapets may need to support other dead loads, such as cellular equipment or dunnage for rooftop mechanical systems, which must be accounted for in the structural design. Importantly, if the parapet also serves as a perimeter guard, it must at minimum meet the structural performance requirements for guardrails.

In terms of seismic resistance, new parapets need to comply with structural design depending on Seismic Design Categories, defined via maps included in the IBC. Even old unreinforced parapets may need to be braced to improve seismic resistance per the 2024 International Existing Building Code, per 706.3.1.

IBC 1607.8, Loads on Guardrails, identifies resistance of linear load of 50 lb/ft and a concentrated load of 200 lb. Intermediate rails are designed to resist a concentrated load of 50 lb.

Per IBC 2406.4 Hazardous Locations, glazing in guardrails shall include safety glazing, which are fully tempered or laminated glass units.

Dimensions

Service-type roofs have no perimeter protection against falls, but local ordinances might kick in per IBC 1015, Guards. For example, rooftops with mechanical equipment that require servicing near edges of roofs with 30 in. drop or more may need guardrails in the vicinity of the mechanical unit being serviced. For rooftop locations that are also terraces, guardrails are required.

The minimum height is 42 in., with opening limitations for service roofs typically unable to pass a 21 in. sphere. For terrace guardrails, opening limitations are more stringent, typically designed not to allow the passage of a 4 in. sphere (**Fig. 2**). In earlier New York City building codes, other requirements existed, such as configurations that resist climbing.

Weather Protection

IBC 1403.2, Water-Resistive Barrier, requires a weather-resistant exterior wall envelope; this is applicable to parapets and guardrails that “intercept” the envelope. The exterior wall shall also include flashing.

Energy Conservation

Both prescriptive and performance requirement paths are outline in the 2024 *International Energy Conservation Code* (IECC). Key points include air barrier and thermal performance considerations. Section C402.5 Air Barrier, states that a continuous air barrier shall be provided throughout the building thermal envelope to mitigate air passage in and out of the building. Table C402.1.4 identifies thermal bridging performance criteria for parapets; C402.7.5 identifies insulation on both sides of the parapet- not than two feet above the roof covering. If thermal insulation is not provided on parapets, perhaps following a performance path, the risks can be assessed using programs such as 2d thermal studies (Lawrence Berkeley National Laboratory’s THERM) for evaluating heat loss and hygrothermal modeling such as Wärme und Feuchte Instationär (WUFI) for evaluating condensation risks.

Lightning Protection

The IBC does not require lightning protection systems at rooftop elements, but local jurisdictions may require them. If so, the National Fire Protection Association’s NFPA 780, *Standard for the Installation of Lightning Protection Systems*, has a Risk Assessment Guide. If lightning protection systems are required at rooftop elements, strike attachment points at the parapet and/or rooftop guardrails connected to the grounding system can be included. To have the system installed and secured, various penetrations and fasteners are typically used, which may cause risk of water penetration.

Bird-Friendly Materials

Section 1403.8 of the *New York City Building Code* states that bird-friendly materials are required up to 75 ft above grade; thus reflective patterns might need to be included on glass panel guardrails to mitigate the risk of bird strikes.

BUILDING SCIENCE

Water and Air Management

Drip edges, overhangs, flashing, and through-wall flashing systems help deflect, manage, and discharge water in

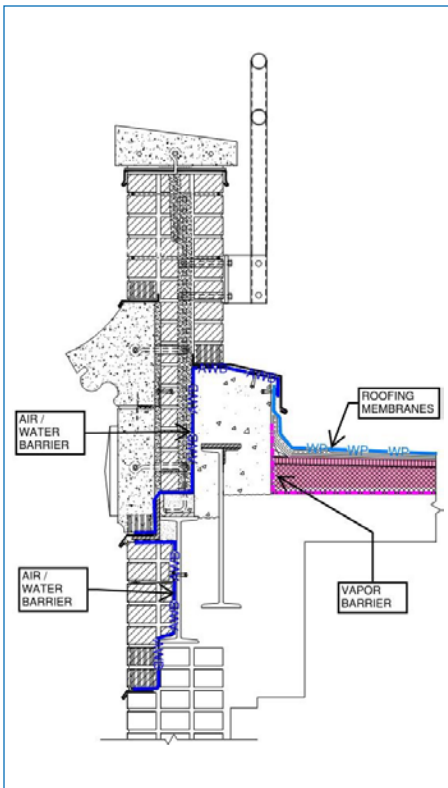


FIGURE 3. Circa 1910 parapet with bracketed guardrail. Replacement design includes embedded moisture and vapor control layers, typically not provided in original configurations. All anchorage that penetrates the embedded air/water barrier needs to be continuously sealed for air- and watertightness. *Drawing by author.*

parapets. It is prudent to design the air/water barrier and roofing membrane as part of the air barrier continuity so that air does not infiltrate and exfiltrate at complex conditions (Fig. 3, 4).

Where guardrails are posted and penetrate the roofing or waterproofing system present, baseplates and anchors intercepting the water management plane should be completely encapsulated with membranes or sealed (Fig. 5).

THERMAL PERFORMANCE

When a parapet interrupts the continuous thermal line between the roofing system and the exterior wall insulation, it creates a zone of thermal conductivity. The 2024 IECC, under C402.7.5, parapets require insulation either completely encapsulating parapets or extending at least 2 feet above the roof line to mitigate. Where thermal bridging and air movement coexist, condensation may form at points of temperature differential. If condensation occurs in these areas, it can lead to material degradation. Nondestructive analysis can be used to assess performance and evaluate the associated risks.

Likewise, when a metal guardrail is posted directly to a structural roof

deck, these posts often penetrate roofing insulation, resulting in thermal bridges. Unlike parapets, these posts are typically intermittent; thus, risk is diminished. In addition, nondestructive analysis can be performed to evaluate risks in very cold climates.

VAPOR DIFFUSION

Masonry parapets present a significant barrier to vertical vapor movement between interior and exterior spaces due to their height and layered construction materials. When properly built, these structures effectively restrict vapor passage. However, lateral vapor movement remains a concern. Without a vapor barrier below and beside the roofing insulation, vapor pressure can push moisture horizontally through the parapet and into the roofing insulation.

Metal guardrails are naturally impermeable to vapor. When condensation forms, it is caused by temperature differences in the configuration rather than by vapor pressure driving moisture through the material.

CORROSION

When uncontrolled water penetrates gaps or discontinuities at the parapet or guardrail, it often ends up at the structural

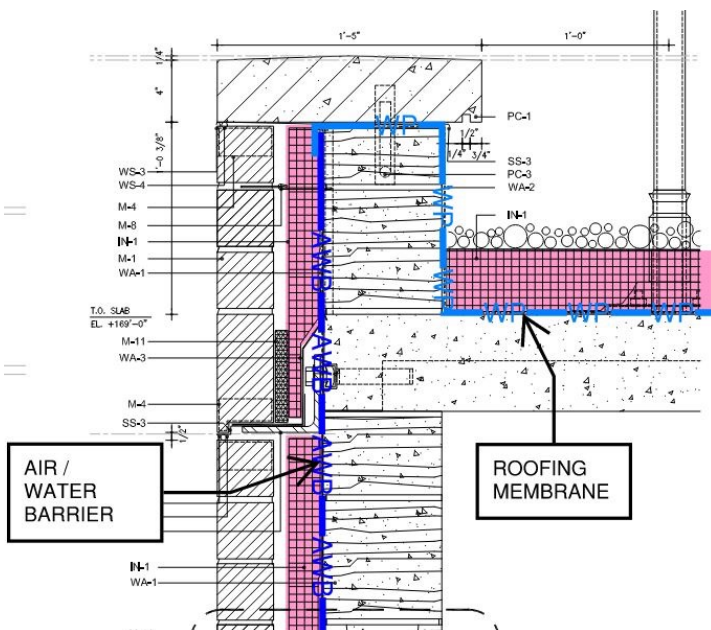


FIGURE 4. Parapet design, circa 2010, with continuity of roofing membrane with exterior wall air barrier. *Drawing by author.*

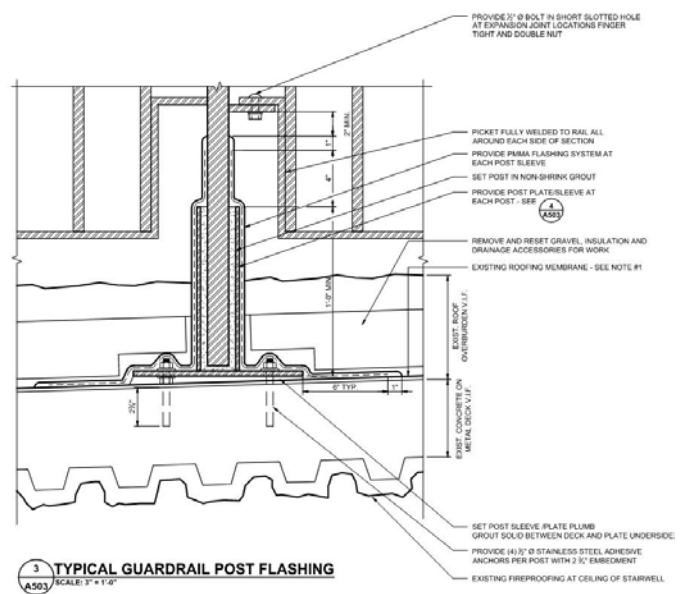


FIGURE 5. Guardrail post base completely encapsulated with fleece-reinforced, fluid-applied membrane. *Drawing by author.*



FIGURE 6. Posted guardrail completely corroded and post is left hanging. *Photo by author.*



FIGURE 7. Guardrail at building expansion joint—note deformation at remedial plate at top rail. *Photo by author.*

reinforcement or connections. If parapets or guardrails are not made of corrosion-resistant materials, or if protective coatings are chipped or missing, rust can develop. As rust progresses, it expands and exerts outward forces, weakening the integrity of the reinforcement or connections and creating additional cracks or breaches in the surrounding materials. These new openings allow even more water to enter, worsening

the problem in a destructive cycle. Left unaddressed, this process can lead to structural failure, directly putting life safety at risk (**Fig. 6**).

Galvanic corrosion occurs when two dissimilar metals come into electrical contact in the presence of an electrolyte (like moisture). The more reactive metal (anode) corrodes while the less reactive metal (cathode) is protected. For

guardrails and buildings, this may cause premature deterioration where different metals connect as well as at structural connections (**Fig. 9**).

EXPANSION/CONTRACTION

Structural movements of the building are typically controlled by expansion joints. Full-building expansion joints extend from the foundation, through all the exterior walls, and up to the roofs. At rooftops, parapets and guardrails will bridge these moving gaps and should be designed to move in tandem, or distress will occur (**Fig. 7**). Thermal movement of materials can be calculated using published data to aid in component joint design.

LONGEVITY

Parapets and guardrails are subject to significant wear and deterioration over time. Masonry parapets from the 19th and 20th centuries often combine masonry with embedded steel components, while guardrails often include steel and other materials prone to corrosion. If substantial displacement of the parapet occurs due to severe structural corrosion within (**Fig. 8**), or if sections of the guardrail are lost or severely damaged, replacement may be necessary. Regular inspections help assess these conditions, but structures 50 to 100 years old should undergo more thorough evaluation, including exploratory openings to investigate hidden issues. Safety becomes an even more critical concern when dealing with aging parapets and guardrails.

AESTHETICS

Parapets and guardrails touch the sky, articulate building edges, and can make or break an architectural composition's intent. Since they are three-dimensional, they can be viewed from grade, from terraces, and from other vantage points. Building enclosure consultants need to be sensitive to aesthetics when designing new or replacement parapets and guardrail systems.

DURABILITY, SUSTAINABILITY, AND RESILIENCE

Parapets should manage water. Water should be directed inboard from the top



FIGURE 8. View of unsafe parapet masonry where it has shifted. *Photo by author.*



FIGURE 9. View of guardrail post base and balcony edge distress. *Photo by author.*

surface—the coping—with proper slope, following both code requirements and best practices. Older masonry parapets often lack continuous water-resistive barriers, making it essential to design replacement parapets to shed as much water as possible. This includes using overhangs and drip edges and, if water does infiltrate, incorporating metal through-wall flashing systems that discharge water before it reaches structural elements or penetrates the building interior. Modern designs include continuous water-resistive barriers, which often also serve as air barriers, connecting the exterior wall's barrier system to the adjacent roofing membrane. The most recent single-ply roof systems even extend the roofing membrane over the top of the parapet, allowing it to integrate with the wall's air and water barrier system. When metal copings are used, they must be robust and designed to resist wind loads in accordance with the Single Ply Roofing Industry / American National Standards Institute (SPRI/ANSI) ES-1 standards.

When structural components like steel framing, rebar reinforcement, or cladding anchorage systems are embedded within parapets, using corrosion-resistant and galvanically compatible materials is essential. If there is a budget to prioritize higher-grade materials, such as stainless steel, parapets are the place to invest for maximum value, given their high

exposure to weather and water. Project specifications can reflect this priority, while allowing less exposed parts of the building enclosure to use standard, less corrosion-resistant materials.

Where roofing membranes do not extend up and over the parapet like contemporary single-ply membranes on new buildings, the National Roofing Contractors Association recommended using metal cap flashings to protect the top edge of the membrane flashing, positioned at least 8 in. above the roof walking surface.⁴ However, it is important to plan ahead: as energy codes tend to increase *R*-values, the added thickness of roof insulation will effectively reduce the parapet's exposed height after future roof replacements. To avoid having to remove and reinstall through-wall flashings every 20 years or so when replacing roofing systems, one might set the flashing height higher from the start—for example, 12 in. or more, with consideration given to the building's remaining useful life and cost studies.

Similarly, a 42 in. high parapet or guardrail may no longer be sufficient after a roof replacement that raises the roof surface. It might be wise to specify a taller guardrail—for example, 48 in.—from the start. While taller guardrails introduce higher connection stresses under load, upgrading to more robust fasteners and a taller rail is far less costly than a full removal

and replacement later. In some cases, you may be able to extend the existing guardrail by adding a supplemental top rail, provided the existing system meets code requirements for strength and dimensional standards. If there are concerns about thermal bridging in post-mounted assemblies, note stainless steel has significantly lower thermal conductivity compared to carbon steel or aluminum. Specifying stainless steel sections and fasteners not only helps reduce thermal bridging but also improves corrosion resistance.

To reduce roof penetrations, anchorage points, and thermal bridging, consider ballasted guardrail systems—but only on service roofs with ample space, not on terraces where aesthetics and space are limited. Another effective strategy is to mount the guardrail to a low parapet with sufficient strength using side-mounted bracket plates. This approach works even better if the parapet coping has a projecting design that extends over the bracket and fasteners, combined with a drip edge to help manage surface water. By contrast, installing guardrail posts through parapet copings is risky and best avoided, as it leads to ongoing maintenance challenges at the joints.

MAINTENANCE

Inspect all faces of parapets annually, checking for gaps in sealant joints, openings at the base flashing edges,



FIGURE 10. View of gap at coping stone, resulting in parapet masonry distress below. *Photo by author.*

damage from ropes or window washing equipment, open masonry joints, displaced copings, clogged or unsealed overflow scuppers, and failed expansion

joints. The goal is simple: keep the parapet shedding water effectively and free of gaps (**Fig. 10**).

On guardrails, look for signs of corrosion from coating loss, such as stains, missing framing members, or anchorage failures (gently push or tug components to check for unintended movement). Over time, cumulative loading, along with thermal expansion and contraction, can overstress connections and reduce structural integrity. For posts anchored directly to the deck, check for vegetation near their bases, as this often indicates standing water. On balconies without proper roofing systems, post bases are especially vulnerable: water can infiltrate through gaps or discontinuities, and galvanic corrosion may occur if incompatible materials are in contact, leading to potential structural damage.

CONCLUSIONS

Designers must consult relevant codes and apply sound building science principles when detailing parapets and guardrails in their drawings.

When designing, it is wise to “overdesign” for durability and futureproofing. Replacing guardrails is extremely costly on a per-linear-foot basis, and modifying parapets can be even more expensive, depending on the scope—especially in dense urban settings. While replacing a roofing system is one challenge, replacing parapets or guardrails introduces an entirely different set of logistical demands and site protection measures not typically encountered with low-slope roof replacements.

Effective water management and periodic maintenance are the two most critical factors influencing long-term performance.

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Building Enclosure Strategies: Resilience, Sustainability, and Code Compliance in Air Barrier Design

ABSTRACT

As climate change intensifies, the need for resilient commercial buildings has become increasingly urgent. A continuous, high-performance air- and water-resistive barrier (AWB) assembly serves as a critical defense against environmental stressors, safeguarding building enclosures from air leakage, moisture intrusion, and thermal cycling. This presentation offers practical guidance for building enclosure consultants and designers on integrating resilience into both new construction and retrofit projects. It examines the evolution of energy codes to identify key advancements and anticipate future requirements that shape enclosure design. Through detailed analysis, the presentation compares laboratory-tested and field-proven roof and wall assemblies, emphasizing the importance of material durability under real-world conditions. Additionally, it underscores the role of quality assurance protocols, such as building enclosure commissioning, the Air Barrier Association of America (ABAA) Quality Assurance Program, and whole-building airtightness testing, in aligning field performance with design intent. By bridging theoretical design with practical implementation, the presentation highlights best practices for achieving adaptable, durable, and energy-efficient building enclosures in the face of climate challenges.

LEARNING OBJECTIVES

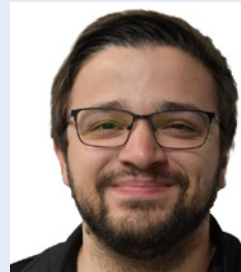
- » Explain how air- and water-resistive barriers (AWBs) enhance building resilience and sustainability by mitigating air leakage and moisture intrusion.
- » Identify the specific requirements of ASHRAE 90.1-2022 and *International Energy Conservation Code (IECC) 2024* energy codes that pertain to air barrier design, installation, and performance verification.
- » Analyze the impacts of environmental stressors, such as ultraviolet radiation, thermal cycling, and moisture intrusion, on AWB performance using the Koike theory framework.
- » Evaluate the importance of third-party quality assurance programs, including the Air Barrier Association of America's Quality Assurance Program, in ensuring proper installation and reducing enclosure-related risks.

SPEAKERS



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Benjamin Meyer serves as building enclosure business director for Siplast. He also serves as chair of the ASHRAE 90.1 Envelope Committee, director of the Air Barrier Association of America, past member at large on the NIBS BETEC board, past LEED Technical Committee member, and past technical advisor of the LEED Materials and Resources Technical Advisory Group.



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Luke Geoffrion has a PhD in applied physics from the University of Arkansas at Little Rock, where he studied thermodynamics and the processing of nanomaterials, and where he published 10 scientific journal articles. During his tenure at Siplast, he was responsible for developing WALLcontrol, Terapro, and roofing adhesives. He enjoys playing video games and hiking with his wife and five pets.

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Luke Geoffrion, PhD



RESILIENCE, SUSTAINABILITY, AND THE ROLE OF AWBS

Air- and water-resistive barriers (AWBs) can play a critical role in meeting both resilience and sustainability goals. Sustainability-driven frameworks emphasize strategies to minimize the environmental impact of construction projects through material selection, energy efficiency, and life-cycle performance. Well-designed AWBs can improve thermal efficiency and reduce operational energy use. However, life-cycle analysis (LCA) reveals that some “green” materials may not perform as sustainably in practice as they do in theory. Credits and certifications that guide sustainable design—such as LEED—may reward low-impact material use without accounting for the material’s long-term performance shortfalls or unintended environmental tradeoffs.^{2,3} Thus, while sustainable material strategies should be encouraged, they must be approached with scrutiny and supported by comprehensive performance data to avoid unintended consequences. When sustainability is prioritized without regard to resilience or constructability, buildings may fail to meet performance expectations under real-world conditions.

Figure 1 presents a conceptual matrix illustrating how resilience and sustainability intersect in strategic design decisions. The vertical axis represents a spectrum of sustainability, ranging from less to more sustainable, and the horizontal axis represents resilience, from less to more resilient. The four quadrants categorize design strategies based on their relative contributions to sustainability and resilience.

In the bottom-left quadrant, strategies lack both sustainability and resilience. The top-left quadrant includes measures that are highly sustainable but may not improve a building’s resilience to climate-related stresses. The bottom-right quadrant contains strategies that prioritize resilience but may rely on energy-intensive or fossil-fuel-dependent solutions, limiting their sustainability. Finally, the top-right quadrant identifies strategies that are both highly sustainable and highly resilient. The strategies in that quadrant simultaneously reduce environmental impact and enhance a building’s capacity to withstand disruptive events.

The matrix emphasizes the importance of integrating both sustainability and resilience in project decision-making. Optimal outcomes arise when design choices fall within the upper-right quadrant, where environmental responsibility aligns with climate adaptability. As building performance criteria continue to evolve under the pressures of climate change, the matrix

provides a useful tool for building enclosure consultants and architects to evaluate and prioritize strategies that offer long-term value and risk mitigation.

Translating this concept into building enclosure design requires anticipating both present-day climate stressors and future extremes. AWBs are critical components in this effort because they act as both thermal- and moisture-control layers within the enclosure. They reduce air infiltration, limit condensation risk, and improve the efficiency of heating, ventilation, and air-conditioning (HVAC) systems. As energy codes and green certification programs such as LEED and Phius increase expectations for airtightness and moisture control, AWBs are no longer optional; rather, they are essential components of resilient design.

ENVIRONMENTAL STRAIN AND BUILDING ENCLOSURE PERFORMANCE

The Koike theory of roof strains provides a conceptual framework for understanding how long-term exposure



FIGURE 1. Sustainability and resilience matrix.

to environmental forces such as thermal cycling, ultraviolet (UV) radiation, and moisture induces cumulative strain on building enclosure materials.⁴ This theory is particularly applicable to roof and wall assemblies, which endure multidirectional stresses over time due to solar loading, temperature swings, wind pressures, and humidity fluctuations. According to the theory, each environmental factor contributes to mechanical fatigue in a unique way, with the contributions of factors compounding. Daily and seasonal temperature changes cause repetitive thermal expansion and contraction, leading to stress at joints, seams, and penetrations. UV radiation further accelerates this degradation by breaking down polymer chains, particularly in surface treatments or coatings that lack

integral stabilizers. Moisture intrusion, either through vapor drive or bulk water, introduces hygrothermal stresses that swell, soften, or delaminate materials, especially in multilayered assemblies.^{2,5} When a building is exposed to simultaneous thermal and moisture cycling under UV radiation, the strain on materials is significantly magnified. The Koike theory emphasizes that building materials must not only resist individual stressors but must perform under their combined and repetitive application over the building's lifespan. Products that maintain cohesion, dimensional stability, and integrated resistance properties under such conditions will offer resilience.

AWBs mitigate a variety of stresses acting on the building enclosure, including wind-driven rain, vapor

diffusion, solar loading, and pressure differentials. These systems must perform reliably across a range of conditions. Improperly designed or installed AWBs can allow moisture intrusion, resulting in mold, corrosion, and material degradation. Likewise, excessive air leakage can disrupt HVAC performance, increase energy consumption, and reduce occupant comfort. Studies show that effective air barriers can reduce HVAC energy use in all US climate zones.⁶ For example increased airtightness can save 37% in cold and mixed climates, such as Minneapolis and St. Louis respectively, and 10% in extremely hot climate, like Phoenix. This makes whole building airtightness a critical link between resilience and operational sustainability.

TABLE 1. Summary of air barrier requirements from ASHRAE 90.1-2022

Compliance category	Requirement	Referenced section(s)	Project phase
Compliance testing options	Materials, assembly, or whole building testing is allowed.	5.4.3.1.2; 5.4.3.1.4	Design phase
Maximum air leakage level	Materials ≤ 0.004 cfm/ft ² @ 75 Pa; assemblies ≤ 0.04 cfm/ft ² ; whole buildings ≤ 0.35 cfm/ft ² (up to 0.45 cfm/ft ² allowable).	5.4.3.1.1; 5.4.3.1.4; Table H-3	Design phase
Exceptions	Semiheated spaces in Climate Zones 0–6; single-wythe concrete masonry in Climate Zone 2B.	5.4.3.1.4, Exceptions a–b	Design phase
Simplified path compliance	COMcheck: Default is 0.35 cfm/ft ² (testing); 0.45 cfm/ft ² is used for “verification only” compliance.	5.4.3.1; Table H-3	Design phase
Installation detailing	Detail and treat fenestration joints, wall intersections, penetrations, ducts, and projected components.	5.4.3.1.2 (1–7); 5.9.1.2 (b); 5.9.3.3	Design phase
Design and installation verification	Third-party verification is required if not using whole-building testing; construction documents must include inspection details, schedule/frequency, scope, documentation, and corrective action requirements.	5.4.3.1.2 (a–d); 5.9.1.2; 5.9.3.3; 5.8.3.1; 5.8.3.2; 4.2.5.1.1	Design & construction
Performance modeling compliance	Energy modeling must reflect specified/ tested leakage rates for energy credit.	4.2.5.1; 5.4.3.1.4	Design & construction
Whole building airtightness testing (WBAT) requirements	WBAT is required for buildings <10,000 ft ² and single-zone buildings; air leakage diagnostic testing/reporting is allowed up to 0.45 cfm/ft ² .	5.4.3.1.1–5.4.3.1.4; 4.2.5.1.2	Construction phase
Post-construction documentation	Submit report of field/WBAT testing, insulation data, FPT results within 90 days.	5.7.3.1; 5.9.1; 5.8.1.11; 4.2.5.1.2	Post-construction
FPT and verification documentation	Document completed tests and include deferred testing plans if applicable.	4.2.5.1.2	Post-construction

CODE EVOLUTION AND AIRTIGHTNESS PERFORMANCE

Modern energy standards and codes such as ASHRAE 90.1, Energy Standard for Sites and Buildings Except Low-Rise Residential Buildings; the *International Energy Conservation Code* (IECC); and various jurisdiction-specific codes are placing increasing emphasis on the control of air leakage through building enclosures. ASHRAE 90.1-2022 and the forthcoming 2025 version continue to raise the bar by tightening energy use intensity (EUI) targets and emphasizing the importance of air barrier systems.^{7,8} ASHRAE 90.1-2022 is recognized in the IECC 2024 as an alternative compliance path and serves as a benchmark for other standards such as California's Title 24, and various stretch-code programs. In jurisdictions or federal projects where it is adopted directly, full compliance with ASHRAE 90.1 is mandatory. Understanding the which energy standard is required and what options within the standards for compliance is essential for a specific project team enclosure strategies. The building enclosure industry and the associated standards and codes are shifting from a prescriptive approach to a performance-driven model in which results are verified through measurable airtightness outcomes. As energy codes advance, ASHRAE 90.1-2022 elevates the importance of air barriers in delivering high-performance, durable, and energy-efficient buildings, introducing rigorous requirements for limiting uncontrolled air leakage through the building envelope by mandating design-phase coordination, detailed construction documentation, robust field verification, and post-construction compliance as summarized in **Table 1**.

Utilizing the requirements of ASHRAE 90.1-2022, designers must specify whether projects will comply via whole-building airtightness testing (WBAT) or field-based verification. Construction documents must clearly identify all air barrier materials; include details for transitions and penetrations; and demonstrate resistance to pressure differentials and movement. A third-party verification and testing (V&T) provider must review documents,

oversee field inspections, and ensure systems can be tested and maintained. Drawings and specifications must align with ASHRAE 90.1 Section 5.4 continuity and performance requirements.

During construction, proper execution is critical. Under the guidance of ASHRAE 90.1-2022, V&T providers must conduct inspections while air barriers are accessible, confirming that assemblies meet design intent across typical weak points such as roof-to-wall intersections and fenestration openings. If WBAT is used, testing must follow the methodology in standards such as ASMT E3158, with documentation on leakage rates and conditions. Regardless of ASHRAE 90.1-2022 compliance path, the field inspection plan governs compliance oversight. After construction is complete, according to ASHRAE 90.1-2022, final documentation must be submitted to the designer or record, project owner, and building official within 90 days, including inspection or WBAT results, insulation compliance, and completed functional performance testing (FPT). Ultimately, achieving air leakage compliance in accordance with ASHRAE 90.1-2022 involves early project team coordination, detailed design integration, and reliable third-party oversight. These measures ensure that buildings meet both energy-efficiency goals and real-world performance expectations.

QUALITY ASSURANCE AND AIR BARRIER ASSOCIATION OF AMERICA OVERSIGHT

Designing high-performance systems is only half the equation; ensuring their correct installation is equally important. The Air Barrier Association of America (ABAA) provides a comprehensive quality assurance program (QAP) that includes installer accreditation, design review, and field audits.⁹ This program aligns with the requirements in ASHRAE 90.1-2022, sets US national benchmarks for AWB application and ensures alignment between specification and execution.

The ABAA QAP requires:

- » Preinstallation project team conferences

- » Product and assembly submittal reviews
- » Trained, ABAA accredited installers
- » Onsite audits by third-party quality assurance personnel
- » Final performance testing, including whole-building air tightness testing where applicable

Studies have shown that buildings constructed under the ABAA QAP consistently outperform code minimums in blower door testing and experience fewer warranty claims.⁹ The since 2009, ABAA QAP program has been utilized on more than 7,500 commercial building enclosure projects, resulting in more than 100 million square feet of field audited air barrier installations. By incorporating QAP-certified installers and enforcement mechanisms into project specifications, designers can help ensure that design intent is realized in the field.

BUILDING ENCLOSURE COMMISSIONING AND VERIFICATION TESTING

Whole-building airtightness testing is increasingly embedded in both energy codes and green certification programs. This testing process validates the performance of the AWB system and evaluates the quality of workmanship across critical details, such as joints, penetrations, and transitions. Building enclosure commissioning integrates this airtightness testing into a broader performance verification framework, offering multiple project benefits:

- » Quantifiable benchmarks for building enclosure performance are established.
- » Feedback loops for identifying and correcting installation issues are created.
- » Documentation required for programs such as LEED v4.1 Enhanced Commissioning are generated.

As resilience and carbon reduction become more embedded in building policies, third-party testing and commissioning will remain integral to demonstrating compliance and ensuring long-term durability.

NAVIGATING COMPLIANCE STRATEGIES

Whole-building air and water-resistive barriers are supported by evolving standards and quality assurance programs, including the International Energy Conservation Code (IECC), ASHRAE 90.1, and the Air Barrier Association of America's (ABAA) Quality Assurance Program (QAP). The IECC, introduced in 1998, establishes baseline energy efficiency requirements and has progressively emphasized airtightness in updates, including the 2024 version. ASHRAE 90.1, first published in 1975, provides detailed technical guidance for energy-efficient building design. The ASHRAE 90.1-2022 version, recognized as an alternative compliance path in IECC 2024, mandates rigorous airtightness testing and field verification.

Complementing the energy code requirements, the ABAA QAP, established in 2009, and Blower Door Certification Program help ensure field implementation aligns with design intent. This program requires accredited installers, third-party audits, and certifications for performance testing, creating a reliable pathway for compliance with ASHRAE 90.1 and other energy codes. For example, buildings designed to meet ASHRAE 90.1's stringent air leakage limits can utilize ABAA-certified processes to verify performance and ensure long-term durability.

Together, these frameworks can create a cohesive system. The IECC sets broad energy efficiency goals, ASHRAE 90.1 provides detailed design and performance requirements, and the ABAA programs reinforce quality assurance and testing through third-party oversight and certifications. By integrating these standards, designers and builders can deliver AWB systems that meet modern performance expectations, ensuring resilience, energy efficiency, and compliance with evolving codes.

CONCLUSION

AWBs are no longer optional. They are essential, multifunctional components that sit at the intersection of building resilience, operational efficiency, and long-term performance. Throughout this paper, we have explored how AWBs serve not only as protective layers against air and moisture infiltration but also as performance enablers shaped by evolving codes, testing standards, and quality assurance frameworks. The proper design, specification, installation, and verification of AWBs can reduce energy loads, mitigate moisture-related failures, and help maintain occupant comfort and health. As demonstrated by the Koike Theory, building materials must perform under compounded environmental stressors, and AWBs that maintain dimensional stability and resistance across these variables are foundational to climate-adaptive design.

The integration of third-party oversight through programs such as the ABAA QAP and the increasing adoption of performance verification such as whole-WBAT mark a shift toward accountability and durability in enclosure design. These tools, alongside commissioning protocols, give designers quantifiable benchmarks to validate performance and reduce risk. Ultimately, AWBs represent a convergence of code compliance, climate readiness, and risk mitigation. For building designs, the path forward lies in a proactive, systems-based approach, which is grounded in material science, guided by evolving standards, and validated through rigorous testing. As performance expectations rise, AWBs remain one of the most scalable, impactful solutions to future-proof the built environment.

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Analysis, Design Iteration, and Verification of Water Control Strategies for Steep-Slope Gutters

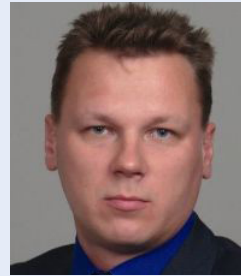
ABSTRACT

There are standardized approaches, codes, and best practices that can be referenced for the design of gutters on low-slope roofs; however, resources are limited for the design of nonstandard sloped gutter systems and water management. Using the remediation of an existing pavilion with sloped gutters as a case study, we will present an approach to the design, analysis, and performance verification of sloped gutter systems. This case study will provide tools and practical applications not only in the remediation and restoration of existing built-in and sloped gutters, but also for water control strategies of complicated roofs that may be derived from a growing trend of computational design in architecture without sacrificing long-term durability.

LEARNING OBJECTIVES

- » Define the design criteria, sizing, and best practices for gutter design.
- » Explain the physics of fluid flow and control strategies in sloped and steep-slope gutter applications.
- » Determine how to develop strategies for the analysis and design iteration of steep-slope gutters using “rules of thumb” appropriate boundary conditions, and computational fluid dynamics (CFD).
- » Summarize how to confirm modeling and benchmark performance of gutter systems through the use of in-situ mock-up and field-performance verification of steep-slope gutters.

SPEAKERS



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Andrey Ardashev has over 15 years of experience in enclosure consulting, with a focus on commercial and residential roofing

applications, including commercial low-slope, all-type roofing systems, as well as all-type, steep-slope roofing systems. He is proficient in all phases of roofing and facade assessment, design, and investigative and forensic work focused on water intrusion construction, and he uses nondestructive test tools for the assessment and verification of roofing assemblies and facade cladding, including infrared thermography and relevant ASTM testing.



Matthew Ridgway, PE
Regional Director
Intertek

Matthew Ridgway is a licensed architectural engineer specializing in the assessment, management of projects, design, analysis, and remediation of building

enclosure systems on historic and modern buildings for both public and private clients. He is well-versed in the contemporary analysis and issues of building enclosure design, serviceability, materials selection, and enclosure commissioning, and he often moderates discussions between stakeholders, consultants, and local code/historic authorities. His investigative and forensic work has focused on water intrusion, building instrumentation, and condensation analysis for both modern and historic roofing, waterproofing, fenestration, and opaque walls, as well as on manufacturing defects of prefabricated systems.

Acknowledgments: Sagar Shukla, Siemens (CFD Analysis); Robert Flagg, RA; Larry Just, RRO

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There are long-standing, standardized approaches to the design of gutters and steep-slope roofing systems for water management. However, standardized approaches can fail to anticipate the physics of water flow over complex geometries in sloped gutter systems. For both new, as well as existing buildings (where failures are understood and documented), analytical approaches as well as verification via physical testing can be used to iterate design strategies to ensure long-term durability and serviceability of sloped water management systems and buildings prone to uncontrolled water.

ANATOMY OF GUTTER AND DESIGN

Gutters systems are a critical part of water control in buildings with steep-sloped roofs. Gutters, crickets, and diverters are integrated with roofs and serve to control water flow and discharge into drainage systems or away from buildings. Gutters can drain through inlets when connected to a rainwater conductor or plumbing system, or through outlet tubes when connected to exterior downspouts (though the terms 'inlets' and 'outlets' are often used interchangeably). Built-in gutters refer to gutters that are integrated into the roof line upslope from the eave of a roof or inboard of an exterior parapet wall. Hanging gutters refer to gutters that are supported outboard of the rising wall and are "hung" at the roof eave to collect water at the edge of rooflines. Common resources and design guides for proper gutter design include:

- » *Architectural Sheet Metal Manual* published by the Sheet Metal and Air

Conditioning Contractors' National Association, Inc (SMACNA)

- » *Copper and Common Sense* published by Revere Copper Products, Inc.
- » *Designer Handbook: Standard Practices for Stainless Steel Roofing, Flashing and Copings* published by Specialty Steel Industry of North America
- » *Slate Roof Bible: Understanding, Installing and Restoring the World's Finest Roof* published by Joseph Jenkins
- » *Slate Roofs: Design and Installation Manual* published by National Slate Association
- » Design and installation guides for segmented, or prefabricated, gutter systems by various manufacturers.

A properly designed gutter must be:

- » Able to collect rainwater runoff and divert it away from the building's exterior surfaces, pedestrian walkways, and foundation walls. Water is typically drained into plumbing systems 5 to 10-feet away from the base of the building, with specific drainage requirements depending on the local jurisdiction.
- » Adequately sized to manage design rainfalls as defined by the *International Plumbing Code (IPC)*, *International Building Code (IBC)*, and other local or regional regulations.
- » Structurally stable. Structural stability includes gravity support for both hung and built-in gutters, and metal thickness/geometry to prevent buckling.
- » Able to handle thermal expansion and contraction without failing seams, buckling, or water leakage.

- » Compatible with other metals and adjacent construction to ensure long-term durability.
- » Integrated into roof and wall assemblies in a manner that controls ice and snow related failures or damming.

DESIGN STANDARDS AND PRACTICE

Gutters and drains are designed to manage water flow based on design rain fall intensity and capacity calculations in accordance with the IPC or the governing local codes. According to Section 1106 of the 2021 IPC, the size of drainage and branches of the water management system shall be based on the 1-hour rainfall intensity in inches as indicated on several rainfall intensity maps provided in the code. Rainfall intensity can be converted to gallons per minute (GPM) or liters per min (L/m) of fluid flow rate in accordance with equation 11-1.

$$GPM = R \times A \times 0.0104$$

where:

R = rainfall intensity, in/hr

A = roof area, ft²

The code prescribes vertical leader sizing (Table 1106.3), and horizontal gutter sizing (Table 1106.6) based on dimensions, slope and capacity in GPM. Additionally, some local codes prescribe the maximum allowable horizontal projected roof area in square feet that may be served by building drains or gutters at various slopes.

Traditional gutter accessories can be employed to further control water flows in sloped assemblies; such accessories include, but are not limited to, kick-out

flashings at roof-to-wall terminations to direct water into gutters; slopes built into gutters to increase flow; diverters in the field of roof or at the base of sloped assemblies to slow flow rate and/or control splashing; strainers at inlets/outlets to prevent blockages; expansion joints to control area drainage and ensure capacity limitations (in addition to accommodating thermal movements); and even siphonic assemblies to increase flow rate from horizontal surfaces into rainwater conductors. When using these systems, practitioners typically rely on a working knowledge of best practices and experience in controlling water for complex drainage geometries or steep slopes.

The physics of fluid flow and pressures can be understood using Bernoulli's principle and formula characterizing the pressure, kinetic and potential energies for fluid flow.

$$P_1 + \frac{1}{2} \rho v_1^2 + \rho g h_1 = P_2 + \frac{1}{2} \rho v_2^2 + \rho g h_2$$

where:

P = absolute pressure of the fluid

ρ = density of the fluid

v = velocity of the fluid

g = acceleration due to gravity

h = height of the fluid above a reference point

Computational analysis methods to calculate fluid flow may also need to include surface frictions, dynamic pressures, fluid losses, debris, and safety factors.

DELETERIOUS EFFECTS OF UNCONTROLLED WATER

Gutters can fail in a variety of ways due to design, fabrication, or installation errors. Arranged in a hierarchical fashion (based on spatial dimensions and time), the types of failures may be classified as follows:

1. **First order:** Point failures, (for example, pinholes in solder joints at rivets, or mechanical damage)
2. **Second order:** Linear failures, (for example, failures at lap, locked or soldered seams)



FIGURE 1. Overview of the east elevation of the Mann Center for the Performing Arts from the lawn via a drone survey performed in August 2019.

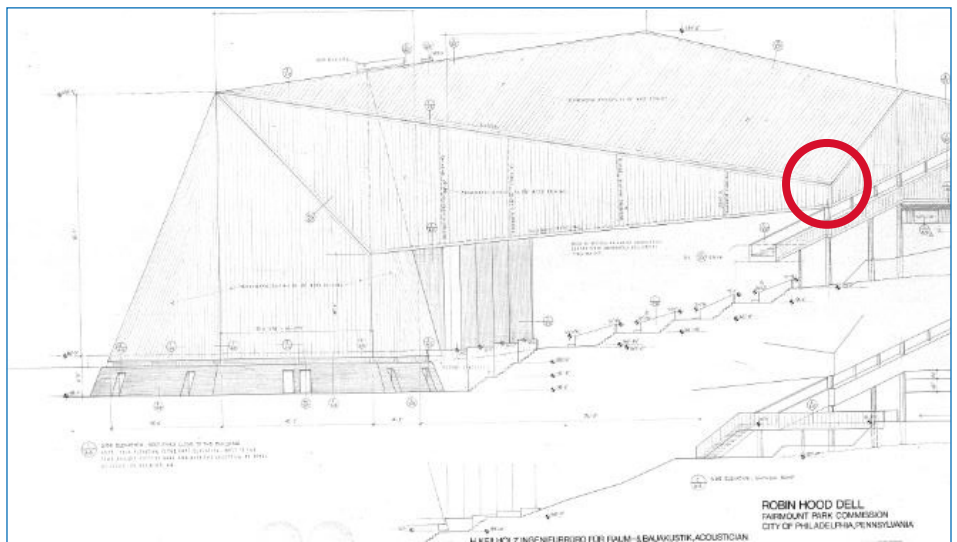


FIGURE 2. Excerpt of the original drawings showing the east elevation steep-sloped gutter and the downslope location of localized deterioration remediated before this analysis and design iteration

3. **Third order:** Capacity failures, (for example, undersized gutters for water volume, structural failure or buckling, or unaccommodated expansion/contraction)
4. **Fourth order:** Time dependent and serviceability failures (for example, corrosion, lack of maintenance, clogs, or material failure)

Uncontrolled water emanating from a roof or gutter system can lead to cyclical wetting of a building's exterior, which can shorten service life of adjacent assemblies like walls, windows and foundations or increase maintenance requirements for those assemblies. When leakage occurs from

uncontrolled water, the deleterious effects for building systems may include dampness, rot, mold, or soil erosion. Uncontrolled water over a long period can also decrease structural stability and diminish pedestrian safety below roof lines.

In practice, prescriptive methods are proven to be reliable for most buildings, especially those with traditional geometries. For complex building geometries driven by computational design methods, or existing buildings with known water management deficiencies, fluid dynamic analysis can be used to model and iterate design or remediation options.

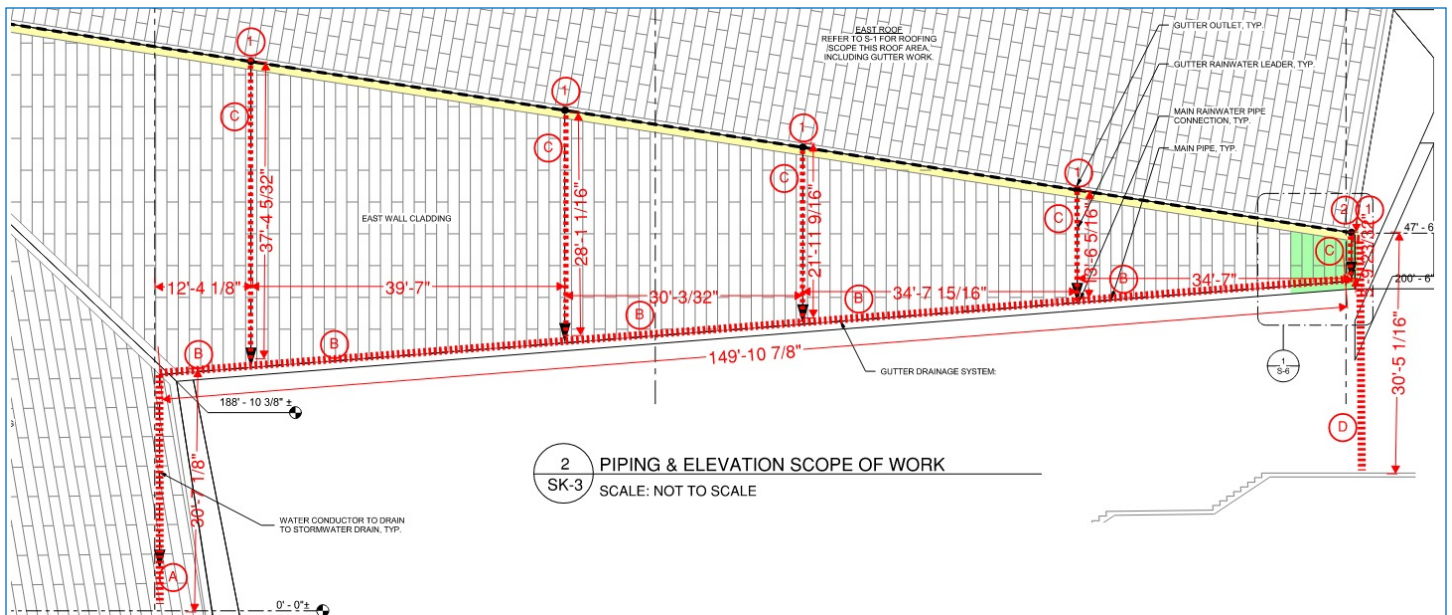


FIGURE 3. Piping elevations along the steep sloped gutter of the east elevation.

CASE STUDY BACKGROUND

The Mann Center for the Performing Arts (MCPA), an outdoor arts education and performance venue in Philadelphia, Pennsylvania, is a covered outdoor music hall/pavilion. The pavilion was constructed in 1975. All walls and steep-slope roofs have standing seam terne-coated stainless steel (TCS) panels that are installed over an asphalt-impregnated felt, and kraft paper. The perimeter steep-sloped roofing facets are drained to built-in gutters at the perimeter of transitions to similarly clad sloped walls on the east, west, and north sides of the building. These gutters are all sloped to the north elevation. Each of the east and west sloped gutters has four intermittent inlets into rainwater conductors (RWC) along the sloped gutter with a final inlet at the downstream corner of each side that captures water draining down the north elevation northeast and northwest facets. The north gutter has two inlets that drain sloped sections to the middle of the building. (Fig. 1–3).

Prior to this analysis and design iteration, and after several decades of service, capital projects were undertaken to review issues of localized wood deterioration of the tongue and groove sheathing and water infiltration. Historically, the most significant issues of localized deterioration to the

substructure were characterized as water infiltration due to failures of the gutter liner and roofing accessories. Identified concerns included cascading water running downslope of the steep-slope gutters and overflowing at the northeast and northwest corners of the building, and leakage along the built-in gutters due to a lack of expansion joints and poor detailing at transverse seams.

An architect prepared contract documents to refurbish elements of the pavilion including the built-in gutters. The built-in gutter scope included relining the built-in gutters with a new reinforced polymethyl methacrylate (PMMA) cold fluid-applied membrane. Additionally, the refurbishment included

the fabrication and installation of new traditional expansion joints immediately downslope of each inlet along the east and west steep-slope gutters similar to those shown in Fig. 4.

The Architect advised MCPA that the introduction of expansion joints would act as a remedy for the existing lack of expansion control in the gutter that had previously torn sections of the metal gutter liner. The Architect also noted that the gutters would compartmentalize segments of the gutter at each inlet along the length of the gutter which would help:

1. Resolve issues with high velocity water running down slope past inlets and collecting/overflowing at the northern corners of the building where historical overflowing water damaged the wood framing.
2. Direct water from its respective tributary roof area into the upslope inlet.

Following the completion of repairs, the owner experienced problems with the pavilion's steep-slope gutters overflowing at multiple locations along the length of the built-in gutters. Initially, overflows were most common during heavy rains, but the gutters then began to overflow during even light rain events. The overflows occurred at multiple points along the east and west

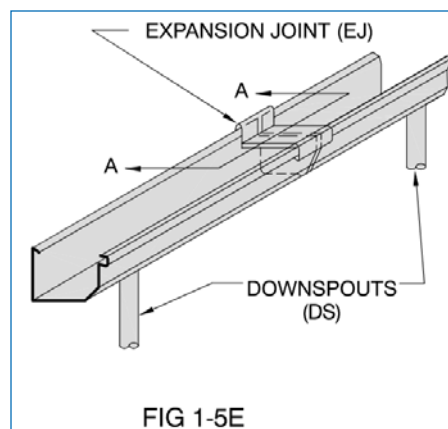


FIGURE 4. Excerpt from SMANA showing traditional expansion joint in gutters.

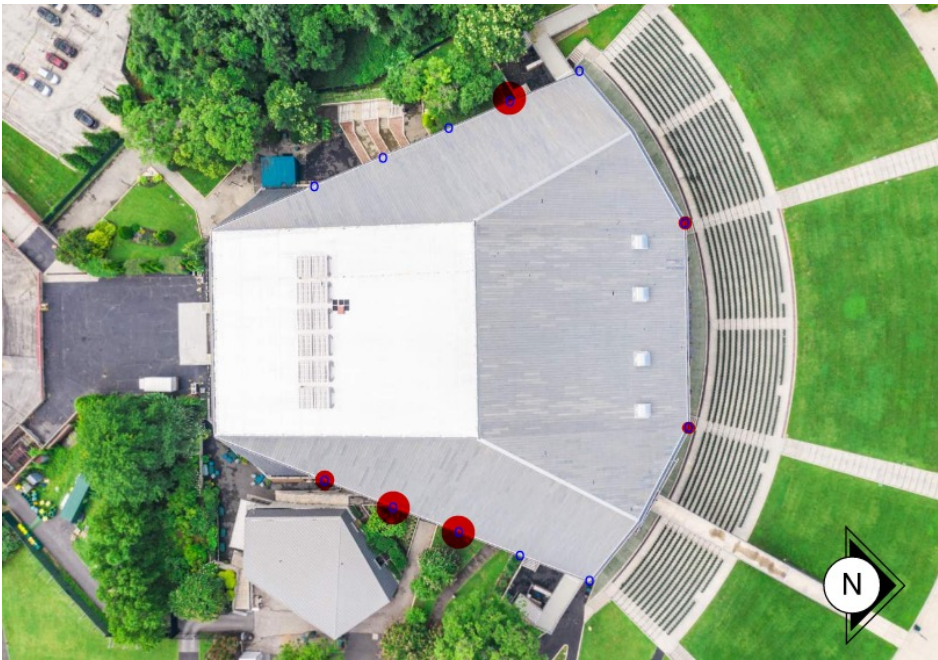


FIGURE 5. Aerial view of the Mann Center for the Performing Arts. Blue circles identify inlet locations, and red highlights show the degree of water flow over the gutter to the concourse recorded during a rain event (larger circles indicate more overflow).



FIGURE 6. Example of water overflows during initial survey.

sides of the pavilion and overflowing gutters spilling onto the circulation aisles directly beneath the edge of the roof (Fig. 5, 6)

ASSESSMENT FINDINGS

Following the reports of increasing overflows, the Owner commissioned the project to study the built-in gutter systems and aid in the remediation

of the gutters. The team consisted of building enclosure consultants, plumbing engineers and structural engineers.

It was noted that the overflows did not occur until after the recent capital program to refurbish the gutters. Observations revealed that water overflows from the east and west gutters occurred at locations where the expansion joints were installed.

While the behavior was limited to four locations along the east and west gutters, all expansion joint locations were subject to similar risk.

The primary cause of water overflows was a reduction in the drainage capacity of the built-in gutters to inlets of the drainage system including (Fig. 7). The net free area of inlets was reduced by upward of 40% in some instances by the new PMMA gutter liner terminating into the inlets. Additionally, there was debris accumulation and clogging of inlets upstream of the expansion joints that were added to the built-in gutters.

While the addition of standardized expansion joints to the gutters during the recent capital program addressed the issue of deterioration caused by cycles of thermal expansion and contraction, it also performed as a dam, limiting the original redundancy of water flow capacity downslope within the gutter. The design did not take into account that the gutters were steeply sloped and that debris entering the gutter would eventually be a problem at these locations. Given the steep slope and the newly installed dam/expansion joints, the water blockages tended to overflow the gutter liner to the pedestrian area below in a concentrated manner at each expansion joint. The issues were further exacerbated by a nearly complete lack of access to clean the gutters, which was a serviceability issue that was not identified during the prior project.

Recommendations were made after the assessment including:

1. **Increasing drainage flow.** To reduce the risk of localized water overflows and debris accumulation within gutter segments, the free flow of water between segments would be necessary.
2. **Slowing water flow.** Several options were recommended and considered to slow the water flow. After preliminary analysis, final recommendations were made that a sump be considered at each rainwater inlet. The physics of increasing the local drainage area of the gutter at inlets would have the effect of slowing the water velocity and increasing drainage pressures to

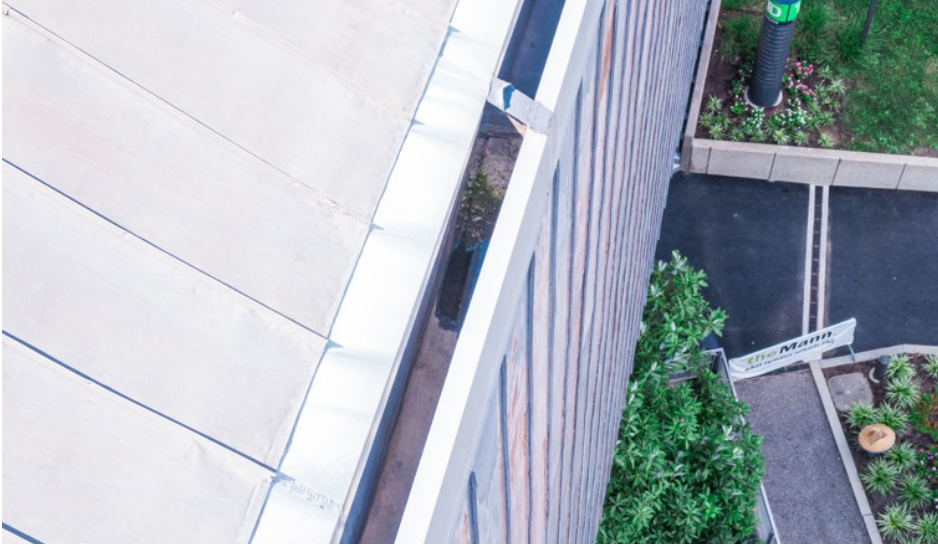


FIGURE 7. Typical blockage at representative outlet tubes due to debris accumulation.

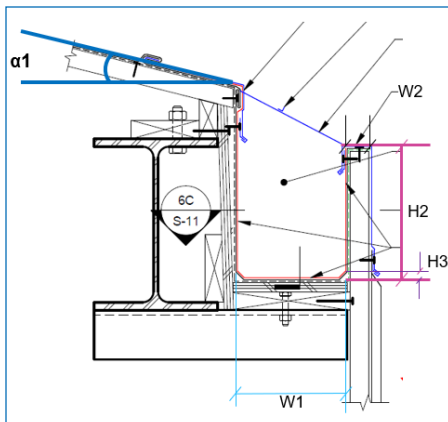


FIGURE 8. Gutter geometry based on previous design documents.

TABLE 1. Model dimensions of built-in gutter geometry for modeling

No	Dimension	Designation	Value
1	Gutter Width	W1	7.5"
2	Roof Slope	$\alpha 1$	30.8°
3	Gutter Height (outer wall)	H2	8.5"
4	Gutter Height (inner wall)	H1b	12.5"
5	Gutter Edge Width	W2	1.5"
6	Gutter Chamfer	H3	0.375"
7	Downpipe Diameter	D1	3"

Note: 1" = 1 in. = 25.4 mm.

the inlets. Thus, compared with the original design, the new arrangement would direct a higher percentage of water into the inlet.

3. **Conducting additional analysis.** The use of computational fluid dynamics (CFD) and iterative modeling were recommended to explore the feasibility and optimal geometry of

a prefabricated sump box with an integral expansion joint.

4. **Testing a mock-up.** A full-scale performance mock-up (PMU) was recommended in order to validate constructability of the sump, validate design/CFD assumptions and test the effects of debris-control options.

COMPUTATIONAL FLUID DYNAMICS ANALYSIS SUMMARY

During the project kick-off meeting, the stakeholders discussed owner project requirements (OPR) for the gutter system. Of primary importance to the MCPA in resolving the gutter overflow issues were the following points:

- » Eliminate overflowing gutters on pedestrians (in other words, control water).
- » Determine a solution that would involve zero maintenance or require only low-cost maintenance.
- » Reduced noise impacts of drainage.

The recommendations noted in the prior assessment were also integrated into the technical project requirements for the proper operation of the rainwater management system.

Base Model

A base model of a representative section of the as-built condition of the built-in gutter and inlet was constructed to simulate drainage. The purpose of the base model was to validate model parameters with the knowledge of in situ performance. The creation and calibration of the base model would facilitate future iterative design of remedial options. The geometry of the model was developed in accordance with Fig. 8 and Table 1.

Drainage modeling was set at the worst-case scenario for the built-in gutter segments; inlets were not equidistant along the length of sloped gutter but a representative section was determined to be a 35-ft (10.7-m) section of gutter that had the largest tributary roof area draining to it. The water inlet rate was selected based on the intensity of an observed storm and field measured dimensions.

Boundary conditions (Table 2) were also coordinated and became a constant for the various models with exception of the drain outlet backpressure, which was modeled by applying a mimicked back pressure on a smaller section of pipe following initial modeling simulating the full 13-ft

TABLE 2. Typical boundary conditions for computational fluid dynamics analysis

Boundary	Type	Value
Water Inlet	Mass Flow Rate	$\dot{m} = Q \cdot \rho$ $= c \cdot I \cdot A (\rho)$ $= 1 \cdot 5.75 \text{ in/hr} \cdot (1763.215 + 162 \text{ ft}^2) \cdot 62.275 \text{ lb/ft}^3$ $= 15.82625 \text{ lb/s}$ Where, c = surface run-off coefficient I = rain intensity A = area of roof ρ density of water
Pressure Outlet – Air	Pressure Outlet	Pressure : 0 Atm (gauge)
Pressure Outlet – Drain	Pressure Outlet	Ref Pressure : 0 Atm (gauge) Pressure Jump: 10kPa
Roof	Wall	No-slip
Gutter Wall	Wall	No-slip
Slip Wall	Wall	Slip

Notes: Back pressures and rainfall intensity were varied based on analysis iteration (as-built versus design).

1 in. = 25.4 mm; 1 ft² = 0.0929 m²; 1 ft³ = 0.028 m³; 1 lb = 0.454 kg; 1 kPa = 0.1450 psi.

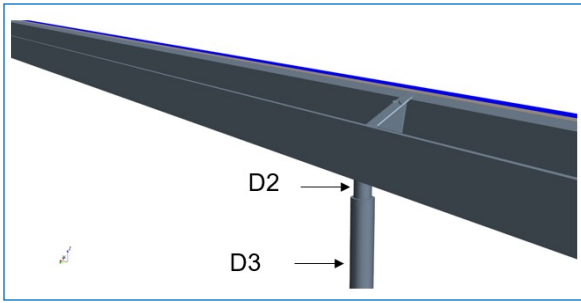


FIGURE 9. Base model geometry. Note: 1 lb/s = 0.454 kg/s.

TABLE 3. Mass flow balance for base model geometry and computational fluid dynamics analysis

Mass Flow Balance		
Mass Flow of Water Through Boundary	Mass Flow Rate (lb/s)	
Water Inlet	15.8263	100%
Drain / Downspout	-14.582	92.14%
Pressure Outlet (Downstream Extension)	-1.558	9.84%
Splash / Dissipation	-0.126	0.8%

(4-m) vertical RWC (the representative section). Each model was run for 35 seconds which in early iterations was determined to be a reasonable time for modeling to reach quasi-steady state.

The base model mean mass flow rate of water through the RWC was determined to be 13.68 lb/s (6.205 kg/s) of the 15.82625 lb/s (7.178666 kg/s) at the inlet. The splashing of water that occurred at the start of the simulation, volume fraction of water dissipated in air as mist, and water bypassing the inlet downstream was 3.205 lb/s (1.454 kg/s), or approximately 10% mass loss.

This approximation of fluid loss supported onsite observations and was enough to confirm boundary conditions for the design iteration (Fig. 9, Table 3).

Analysis of Remediation Options

For the design iteration, the water inlet rate was selected based on recommendations from the Plumbing Engineer. The International Building Code for the Eastern United States recommends a 100-year rainfall intensity of 3.25 in/hr (83 mm/hr) for Philadelphia. The current Philadelphia Plumbing Code recommends a rainwater design intensity of 4.5 in/hr (114 mm/hr), but bases the sizing of storm systems on a maximum 5 in/hr (127 mm/hr) rainfall intensity. Given the potential for increasing precipitation with

changing weather patterns, a design rainfall intensity of 5.5 in/hr (140 mm/hr) was used. This includes a factor of safety (FOS) of 15% over the basis of the storm systems design.

Several iterations of design models were made to modify sump geometries to achieve a higher capture rate at plumbing inlets and to limit water dissipation/splashing. Comparing the data sets of the baseline and modifications to one another demonstrated quantitative improvements associated with the various modifications that were made through the process.

Final Modification

During design, the flow into the sump was optimized to reduce splash/dissipation, the percentage of water flowing past the RWC inlet (and sump), and the net force accumulated on surface geometries by the flow of water.

A sump inlet grate and geometry of the sump (Fig. 10, 11) were optimized to permit washing of the grate at the upstream side of the sump so that potential future accumulation of debris within the built-in gutter would not collect on the upstream side of the sump.

The design modifications that were analyzed included: optimizing geometry of upslope and downslope sump flanges, reducing hard angles, tapering of geometry, and lofting of sidewalls. Although the changes and final design (Fig. 13) made the system more difficult to construct than a more angular sump box assembly (Fig. 12), the significant improvements in performance and long-term durability of the box were approved and deemed constructible by the fabricator.

Performance Mock-up Testing

Following design iteration, a full-scale PMU of a representative section of the gutter was constructed at the fabricator's shop (Fig. 14)

The test methods were devised to simulate varying conditions including rainfall intensity and other operational variances. Acceptance criteria was set to simulate the approved in-service performance of the built-in gutter modifications and validate the modeled representative gutter section at the MCPA pavilion. The test methods were limited to evaluating the sump box and grate system and were not designed to test the capacity or performance of the MCPA plumbing systems into which the built-in gutter RWC inlets feed.

For each test, water was supplied via a water truck to a 3-in.-diameter (76.2-mm) polyvinyl chloride (PVC) distribution system equipped with a flow meter at the supply side and pressure gauges at the high and low side of the distribution pipe. Holes measuring 1/4 in. (6.35 mm) in diameter were provided at approximately 3 in.

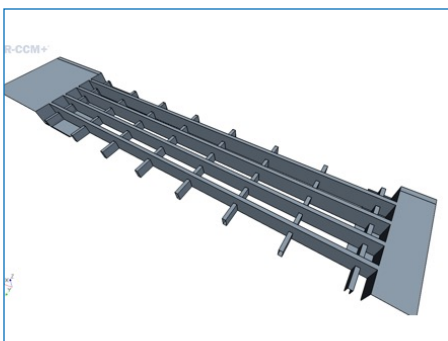


FIGURE 10. Geometry of grate at sump inlet of Modification 1.

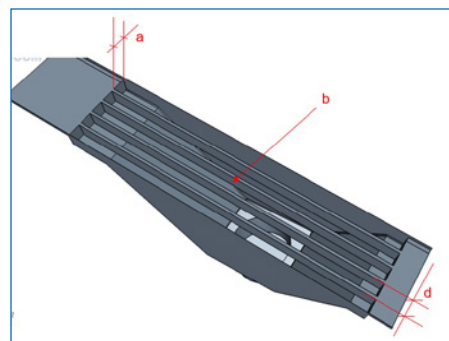


FIGURE 11. Geometry of grate at sump inlet of Modification 2.

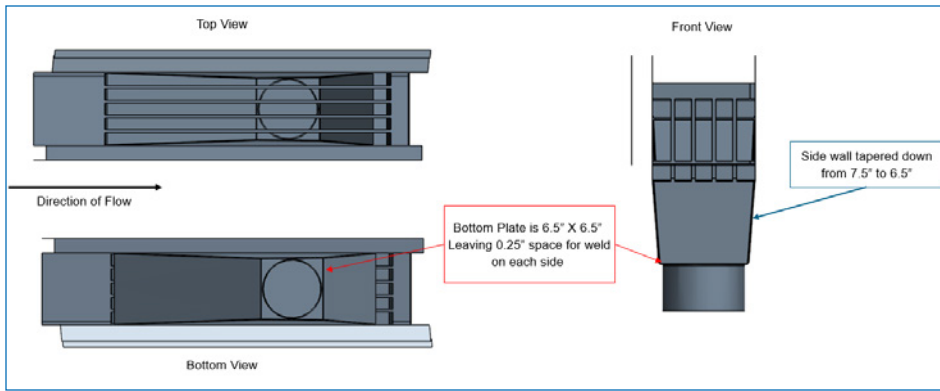


FIGURE 12. Design modifications showing tapered sidewalls and improved geometry. Note: 1" = 1 in. = 25.4 mm.

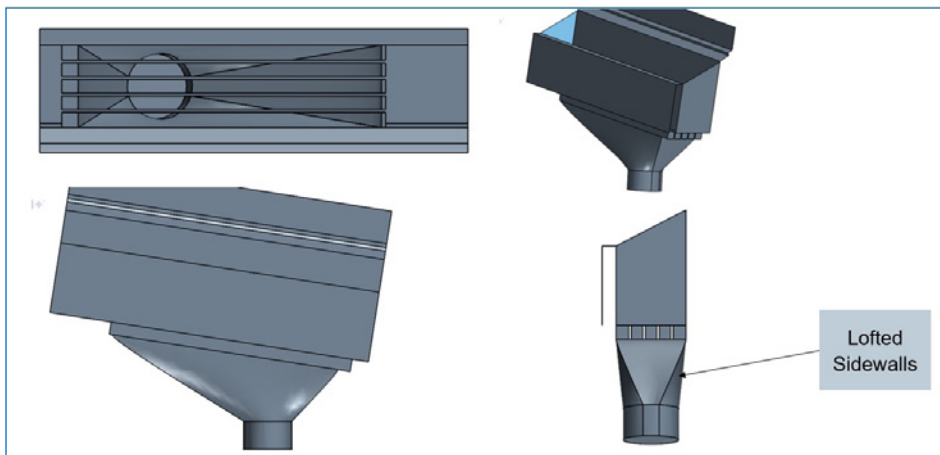


FIGURE 13. Final design with performance improvements gained from lofting sidewalls to promote drainage and reduce net force accumulated on the sump geometry from flowing water.

center for the pipe, and various holes were plugged during initial calibration of the distribution system to ensure even distribution of water across the roof flange. The water flow was measured for all tests, and where quantitative analysis of test results was required,

water was measured from collection totes or barrels connected to the RWC inlet. Qualitative observations were also made for all tests.

Drones were used to capture video for the duration of all tests at three

different angles to ensure adequate documentation of the test procedure for future reference (Fig. 15)

Performance Criteria

The following pass/fail criteria were based on OPR and previous analysis:

- » Qualitative criteria: No excessive water spillage over the side of the built-in gutter.
- » Quantitative criteria (for applicable tests): Based on results from CFD simulations. Similar flow of 86% water flow into RWC inlet, not more than 14.5% water flow passing sump to downstream, and ~0.5% dissipation.

Additional testing was performed for information purposes to evaluate the impact of leaf debris on the sump and grate construction at varying flow rates.

Testing Summary

Iterative testing was used to determine sensitivity to increasing water flows to simulate future rain events and make qualitative observations. The test plans included testing as documented in Table 4.

Quantitative findings indicated that the performance mock-up performed better than predicted by the CFD simulations. Qualitative findings indicated that debris management and washing downslope with grates at sumps were difficult issues to resolve (Tables 5–7).

Lessons Learned

The remediation project proceeded with the final iterative design determined



FIGURE 14. Overview of performance mock-up. Note the complex geometry of the roof slope and steep-slope gutter.

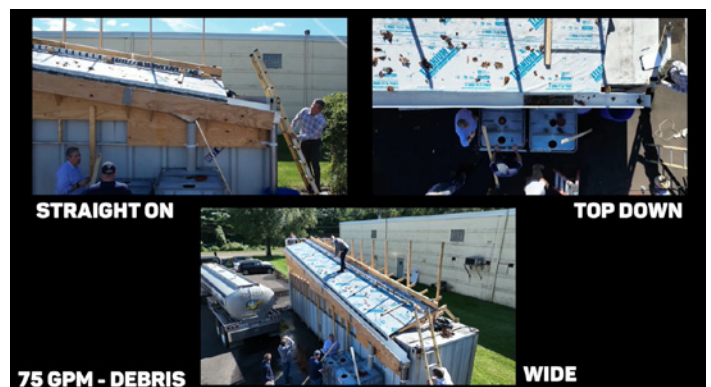


FIGURE 15. Videography from three angles was used for the duration of performance mock-up testing.

during the CFD analysis and then tested with a full-scale PMU. Since project completion in 2023, the roofs and gutters at the MCPA pavilion have been exposed to several rain events in

excess of the design rainfall intensity considered for the remediation of the steep-sloped built-in gutters. The owner has reported no overflows for any of the rain events.

The CFD analysis was a valuable tool for the repair of the complex and non-traditional built-in gutter system. CFD analysis allowed the team to efficiently evaluate the feasibility of

TABLE 4. Summary of physical testing at the performance mock-up

Test No.	Type	Intensity	Time	Test Notes
Pre-Test 1	Qualitative	75GPM	1min	The flow rate simulated an approximate rainfall intensity of 3.9 in/hr per ft ² of roof area the mock-up was representing.
Pre-Test 2	Qualitative	90GPM	1min	The flow rate simulated an approximate rainfall intensity of 4.7 in/hr per ft ² of roof area the mock-up was representing.
Test 1a	Design Test Qualitative + Quantitative	60GPM	2min	Intended distribution was 110 GPM for 2 min. Actual distribution was 60 GPM for 2 mins.
Test 1b	Design Test Qualitative + Quantitative	98GPM	2min	The flow rate simulated an approximate rainfall intensity of 5.1 in/hr per ft ² of roof area the mock-up was representing.
Test 2	Overload Test Qualitative + Quantitative	18 2GPM	1min	The flow rate simulated an approximate rainfall intensity of 9.5 in/hr of roof area the mock-up was representing.
Test 3.1	Debris (For Information Purposes)	25 GPM	1min	Leaves were provided at the sump and inserted between the grate bars. Handfuls of leaves were also scattered into the gutter at approximately 3-ft O.C. Leaves at the sump were pre-wetted.
Test 3.2	Debris (For Information Purposes)	75 GPM	1min	Leaves were provided at the sump and inserted between the grate bars. Handfuls of leaves were also scattered into the gutter at approximately 3-ft O.C. Leaves at the sump were pre-wetted.
Test 3.3	Debris (For Information Purposes)	110 GPM	1min	Leaves were provided at the sump and inserted between the grate bars. Handfuls of leaves were also scattered into the gutter at approximately 3-ft O.C. Leaves at the sump were pre-wetted.
Test 3.4	Debris (For Information Purposes)	75 GPM	5min	Handfuls of wet leaves were scattered into the gutter and along the roof intermittently.
Test 3.5	Debris (For Information Purposes)	75 GPM	5min	The grate was removed from the top of the sump box. Handfuls of wet leaves were scattered into the gutter and along the roof intermittently. During the test, additional leaves were added to the roof and gutter.

Notes: 1 in. = 25.4 mm; 1 gal = 3.78541 L

TABLE 5. Results for approximate design rainfall

Test Specimen #4: Test 1b (Design Test) (Qualitative and Quantitative): Intended distribution was 110GPM for 2min. Actual distribution was 98GPM for 2mins. (reference Video 4)		
Description:	PMU	
Overall Size:	34'-0" with 10'-0" roof flange and prefabricated sump.	
TITLE OF TEST	TEST RESULTS	ALLOWED
Qualitative	PASS	No spillage or dissipation
Quantitative	~99.75% water flow into RWC inlet, ~0.25% water flow passing sump to downstream, ~0% dissipation (PASS)	86% water flow into RWC inlet, 14.5% water flow passing sump to downstream, ~0.5% dissipation.
Observations: 1) All water drained into sump.		
Remedial Work: N/A		

TABLE 6. Results for overload test

Test Specimen #5: Test 2 (Overload Test) (Qualitative and Quantitative): Intended distribution was 200GPM for 1min. Actual distribution was 182GPM for 1mins. (reference Video 5)		
Description:	PMU	
Overall Size:	34'-0" with 10'-0" roof flange and prefabricated sump.	
TITLE OF TEST	TEST RESULTS	ALLOWED
Qualitative	PASS	No spillage or dissipation
Quantitative	~100% water flow into RWC inlet, ~0% water flow passing sump to downstream, ~0% dissipation (PASS)	86% water flow into RWC inlet, 14.5% water flow passing sump to downstream, ~0.5% dissipation.
Observations: 1) All water drained into sump.		
Remedial Work: N/A		

TABLE 7. Results for debris test at design rainfall

Test Specimen #8: Test 3.3 (Debris) (For Information Purposes): 110GPM for 1 min. (reference Video 8)		
Description:	PMU	
Overall Size:	34'-0" with 10'-0" roof flange and prefabricated sump.	
TITLE OF TEST	TEST RESULTS	ALLOWED
For Information Purposes Only (See Note 1)	See Observations	N/A
Notes:		
1) Leaves were provided at the sump and inserted between the grate bars. Handfuls of leaves were also scattered into the gutter at approximately 3'-0" O.C. Leaves at the sump were pre-wetted.		
Observations:		
1) Leaves washed downstream within the built-in gutter and collected at the pile in the sump. The pile pushed downstream along the grate but remained.		
2) Some leaves at the pile drained into the RWC.		
3) All water drained into the sump and RWC.		
4) No water splashed out of the built-in gutter, but water was bouncing vertically within the built-in gutter at the grate.		
Remedial Work: N/A		

repair recommendations and iterate designs in a quantifiable manner. The process of calibrating a base model was facilitated by working with an existing building where in situ conditions and performance were observed. CFD analysis also permitted project delivery at a reduced cost/earlier schedule compared to physical testing of multiple design modifications. Through the design process we noted the following:

- » 15% FOS for rainfall intensity was appropriate for the project conditions.
- » Previously modeled boundary conditions of larger models can be simulated for iterative design to reduce CFD analysis run times and expenses.
- » 35-second model runtime was appropriate for quasi-steady state in modeling the water flows on the project.
- » By tracking the net force accumulated on surface geometries by the flow of water, design iterations such as lofting or curving drainage assemblies significantly improved splash/dissipation and likely improved the long-term durability of the installed systems.

REFERENCES

International Code Council (ICC). 2020. *International Plumbing Code 2021*. Washington, DC: ICC.

Physical testing and the inclusion of the full-scale PMU was important to verify the CFD analysis, especially when making assumptions on boundary conditions. Through physical testing we noted:

- » Effluent must be captured and measured for all quantitative tests.
- » Water distribution for rainfall intensity does not need to be over-thought. The flowrate (GPM) through the distribution system must be measured and converted to rainfall intensity per surface area of roof, so distribution can be qualitatively calibrated prior to testing to ensure equal distribution upslope.
- » Smaller outlets in distribution piping aid in maintaining consistent distribution pressures in the main supply branch.
- » Flowrate measurements should be taken upstream of any valves used to modify GPM of distribution systems to take advantage of laminar pipe flows.
- » Complex gutter systems require accessible cleanouts in RWC piping systems as debris management and gutter cleaning can be difficult.

As the industry designs more complex buildings and water management systems, care should be taken to ensure that large sumps or basins with splash control at the base of steep-slope elements are employed to capture effluent water. Where this type of arrangement is not possible, sumps local to plumbing inlets can be used to effectively slow the water velocity and increase drainage pressures to storm water management systems. Successful water management in steep slopes needs to account for water overflow down-slope from intermittent drainage measures. For new design, CFD analysis can aid in the development of water management strategies by modeling worst-case scenarios so that standardized assemblies can be employed on newly constructed gutters. CFD allows for design iteration in an affordable and timely matter but is not a replacement for benchmarking design strategies and performance through physical testing.

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Finding Balance: The Next Chapter in Low-Slope Roof Design

ABSTRACT

This presentation aims to illuminate the interrelationships between common building and energy conservation codes and how such codes could be improved. The target audience includes architects, building code officials, roof system designers, building owners, and contractors who have an interest in the subject matter. This session will review the 2024 edition of the International Codes (I-codes) and will discuss why it is time to adopt a new strategy for low-slope roof design that encourages a balanced approach across all categories, leading to resilient roof assemblies that perform well over the long term. A review of the building and related codes relevant to low-slope roof design that are based on *International Energy Conservation Code* prescriptive provisions, along with how code provisions are based on new construction, will take place. Roof design principles and how pointers are used in the I-codes and an examination of how an expanded use of pointers would bring clarity across code disciplines will also be discussed.

This session will also review three different case studies on the following topics:

- » **Case Study 01**, The Reroofing Thickness Problem: Walk through the common reroofing design challenge where height limitations make compliance with building and energy conservation codes at odds with each other.
- » **Case Study 02**, The Cool-Roof Condensation Problem: Discuss common situations where a lack of flexibility in code provisions may result in condensation within or under highly reflective white roofs.
- » **Case Study 03**, The Roof System Material Problem: Discuss typical situations during the design and construction process where roof assemblies may stray from code compliance.

LEARNING OBJECTIVES

- » Recognize typical low-slope building code provisions.
- » Identify typical low-slope energy conservation code provisions.
- » Discuss interrelationships between building and energy codes and how these interrelationships could be made clearer.
- » Explain reroofing challenges and how codes could be improved to provide flexibility.

SPEAKER



**Jason Wilen, RRO,
AIA, NCARB, CDT**
Associate Principal
Klein & Hoffman

Jason P. Wilen is a board-certified architect and building enclosure specialist with over 30 years of experience. Wilen joined the Chicago office of Klein & Hoffman (K&H) in 2018 and is now an associate principal. Before K&H, he served 7 years as a director with the National Roofing Contractors Association technical services section and 18 years with architectural, forensic, and roof consulting firms. He holds a bachelor of architecture from the Illinois Institute of Technology, Chicago, and is a licensed architect in Illinois, Michigan, Minnesota, Maryland, New Jersey, North Carolina, Pennsylvania, Tennessee, Texas, and Wisconsin. Wilen provides leadership for K&H's roof system and waterproofing rehabilitation projects, participates in enclosure commissioning efforts, provides litigation support, and consults for building and energy code development. Additionally, he is a voting member of ASTM Committees D08—Roofing & Waterproofing, C16—Thermal Insulation, and E60—Sustainability, and he serves on UL's Technical Committee 580: Safety Testing for Uplift Resistance of Roof Assemblies. Wilen has authored over 25 feature articles for local and national trade journals and magazines. In 2022, he was awarded IIBEC's Richard M. Horowitz Award, honoring the best technical article published in its technical journal, *IIBEC Interface*.

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Jason Wilen, RRO, AIA, NCARB, CDT



As a forensic architect practicing in the US and specializing in the assessment of existing and design of new roofing and waterproofing systems, the author has encountered too many underperforming roof assemblies. These roofs have reduced service lives, often falling well short of the typical manufacturer's material warranty period of 20 years. See **Fig. 1** for an example of a typical underperforming roof. Why is this so?

Roof system designers often focus on one or two specific attributes while neglecting others. For instance, for projects with environmental goals or the need to accumulate credits, designers may quickly opt for a roof design with highly reflective surfaces or materials that are low in volatile organic compounds or free from red-list chemicals (that is chemicals that are not allowed for projects required to comply with the Living Building Challenge) However, they may not consider the ramifications of the climate zone where buildings are located or the temperature and dew point limitations of certain products during installation. In some cases, there may be a push to reduce installation costs, leading to the removal or downgrading of critical elements from proposed roof designs, most often cover boards, vapor barriers, or adhesives, in favor of peel-and-stick alternatives. Consequently, tested roof assemblies with predictable performance transform into untested and often non-code-compliant experiments. It is not surprising that such roof system designs tend to perform poorly over the long term and fail to provide good value from a life-cycle perspective, negating any cost savings realized during installation.



FIGURE 1. An underperforming roof.



FIGURE 2. Example of a low door threshold height limiting adjacent roof system insulation thickness.

A STRATEGY FOR BETTER-PERFORMING ROOFS

It is time to adopt a new strategy that encourages a balanced approach across all categories, leading to resilient roof assemblies that perform well over the long term. Achieving the right balance

is crucial in new construction, and it is essential for reroofing projects, where additional flexibility is often needed to accommodate conditions such as low curb and parapet heights, low windowsills and door thresholds (**Fig. 2**), and existing rooftop equipment and structural elements. A crucial first step in

creating balanced designs for low-slope roofs is to understand the minimum requirements for developing resilient roofing systems.

BUILDING AND RELATED CODES

Codes dictate the minimum requirements for design and construction. Since the inception of the International Codes, or I-codes, in 2000, the family of model codes that most US jurisdictions and some international locations adopt and amend to establish local and state construction codes, the strategy for establishing minimum requirements for low-slope commercial roof assemblies has remained virtually unchanged. Borrowing from older regional legacy codes, Chapter 15 of the *International Building Code* (IBC) includes the base requirements for designing low-slope roofs. Chapter 15 also includes references to Chapter 16 (structural requirements) of the IBC and to other I-codes (the plumbing and fire code). Relevant standards by ASTM International (formerly known as American Society for Testing and Materials), the Single-Ply Roofing Institute (SPRI), and the American Society of Civil Engineers (ASCE) Structural Engineering Institute are also referenced. The I-codes are updated through a hearing and committee process and are published on a 3-year cycle. The current version, as of this writing, is the 2024 edition, and those are the requirements discussed in this paper.

This web of provisions and referenced standards establishes the minimum requirements for designing and installing low-slope roof assemblies, with a focus on new construction. As indicated by the scope of the IBC, these requirements focus on providing a reasonable level of life safety for building occupants and protecting property from hazards. Additionally, they seek to provide a reasonable level of safety for firefighters and first responders during emergency operations.

Before proceeding, it is essential to understand a few key definitions. A roof assembly, as defined in the IBC, is a system designed to provide weather protection and resistance to design

loads. Roof assemblies are composed of the following two parts: roof deck and roof covering. The definitions of those terms that appear in Section 202 of the IBC are

- » **Roof Deck:** The flat or sloped surface constructed on top of the exterior walls of a building or other supports for the purpose of enclosing the story below or sheltering an area to protect it from the elements, not including its supporting members or vertical supports
- » **Roof Covering:** The covering applied to the roof deck for weather resistance, fire classification, or appearance

The term *roof covering* is commonly used in building codes. However, the author finds this term misleading, as it may lead one to believe that it refers only to the top surface of the roof, rather than encompassing all the layers of material and attachments above the roof deck. A more accurate term is *roofing system*. This term is defined in ASTM D1079-24, *Standard Terminology Relating to Roofing and Waterproofing*, as “an assembly of interacting components designed to weatherproof and typically insulate a building’s top surface.”

Why are these definitions important? Here are the key points to remember:

- » Roof assemblies must be tested according to standards referenced in the code to ensure installed roofs meet minimum requirements for fire and wind pressure resistance. This testing applies to complete roof systems and is specific to the type of roof deck used. For instance, roof systems that have been tested on concrete roof decks may exhibit different properties when tested on steel or wood decks due to differing thermal performance characteristics of specific deck types.
- » Roof assemblies must be designed to provide adequate drainage according to the methodologies outlined in building codes. This is essential to ensure the load of rainwater, referred to as *design rain load* in Section 1611.1 of the IBC, does not exceed the structural capacity of buildings during heavy storms. Insufficient

drainage capacity, especially in cases where emergency overflow drainage systems are either absent or undersized, can lead to significant water ponding on roofs as it awaits drainage.

You might think that the information listed above seems like a significant extension of the actual definitions, but they are indeed closely related. It is essential to understand that code definitions are not enforceable on their own. Most jurisdictions align their regulations for low-slope roofs with Chapters 15 and 16 of the IBC. These chapters outline the specific building code-related requirements applicable to roofs.

As mentioned above, the base requirements relevant for low-slope roof assemblies are established for new construction. For reroofing, the IBC includes a section that indicates reroofing projects must comply with requirements for new construction, with the following exceptions:

- » The minimum slope for roofs that are replacing existing roofs can be reduced from the ¼ in. per foot (6.35 mm per 30.48 cm) (2% slope) that is normally required for new construction, as long as positive roof drainage is achieved. *Positive roof drainage* is defined in Section 202 of the IBC as a design that accounts for deflections from all design loads and has sufficient additional slope to ensure that drainage of the roof occurs within 48 hours of precipitation.
- » Where positive roof drainage is achieved, a secondary (overflow) drainage system does not have to be added where none exists under certain conditions.

The limitations of these exceptions are discussed in a later section. In addition to reroofing exceptions typically noted in code, where the IBC is used as a base for code adoption (most US locations), some jurisdictions have a restoration code that addresses construction related to existing buildings. Often, the *International Existing Building Code* (IEBC) is adopted for this purpose, and for reroofing, Sections

706.2 and 706.3.1 of the IEBC contain requirements and exceptions related to low-slope roof assemblies that are similar to the IBC with the following additional requirements:

- » When roofing or rooftop equipment is replaced and new roof systems and/or rooftop equipment cause an increase in load of more than 5% to specific load-carrying structural building elements, affected structural elements are required to be evaluated and improved or replaced as necessary to carry the loads required by the current building code, and not for the code in force at the time the building was constructed.
- » In some instances, roof diaphragms resisting wind loads in high-wind regions may be required to be enhanced.

ENERGY CONSERVATION CODES

Traditionally, energy conservation codes have been developed separately from building and related codes. Most jurisdictions in the US have adopted the *International Energy Conservation Code* (IECC), which generally applies at the state level. The current version is IECC 2024, and the requirements discussed in this paper are based on it. This means the provisions are designed to be implemented across all state jurisdictions. However, some states permit local jurisdictions to establish more stringent requirements. In some instances, energy conservation standards may be adopted solely at the local level, even in the absence of a state requirement.

Before moving on, it is essential to understand a few more definitions:

- » **R-Value (Thermal Resistance):** The inverse of the time rate of heat flow through a body from one of its bounding surfaces to the other surface for a unit temperature difference between the two surfaces, under steady-state conditions, per unit area ($h \times ft^2 \times ^\circ F/Btu [m^2 \times k]/W$).
Note: The higher the R-value, the more resistance there is to heat moving through an assembly.
- » **U-Factor (Thermal Transmittance):** The coefficient of heat transmission

(air to air) through a building component or assembly, equal to the time rate of heat flow per unit area and unit temperature difference between the warm side and cold side air films ($Btu/h \times ft^2 \times ^\circ F [W/(m^2 \times k)]$)

- » **Solar Reflectance Index (SRI):** An indicator on a scale of 1 to 100 of the ability of a surface to return solar energy to the atmosphere.

Note: The higher the number, the cooler the surface will be when exposed to solar energy versus a surface with a lower SRI value, especially on a day without cloud cover.

- » **Prescriptive Path:** Demonstrating compliance with the IECC's commercial energy efficiency provisions by meeting or exceeding specific, detailed minimum low-slope-roof-related requirements in the code.

Note: This approach is most common and is the basis for the requirements discussed in this paper.

- » **Performance Path:** Also called *simulated building performance*, this is a process where proposed building designs are compared to standard reference designs to estimate relative energy use against baseline designs. Approved designs must achieve a specific improvement over baseline designs.

Note: This approach is most commonly used for new construction. Projects limited to a reroofing scope would not use this method to demonstrate code compliance.

The IECC has three principal requirements related to low-slope roof assemblies. The requirements apply to roof areas above conditioned space, defined as an area, room, or space that is enclosed within the building thermal envelope and is directly or indirectly heated or cooled. There is also an exception for roofs above spaces that use very little energy, as defined in the IECC.

For roof assemblies that meet the above requirements, Chapter 4 of the IECC includes the three principal requirements for commercial buildings:

- » **Minimum Thermal Resistance:** Low-slope roof assemblies must be insulated based on the location of the buildings. The IECC includes a US climate zone map with the southernmost locations in Climate Zone 0 and the most northerly areas in Climate Zone 8. Per the IECC, when roofs are insulated entirely above the roof deck, the minimum R-value for insulation must be between R-20 and R-35, with the higher minimum required R-value in more northerly zones. When roofs are insulated in any configuration other than entirely above the roof deck, the required minimum R-value range is R-38 to R-60.
- » **Roof Solar Reflectance and Thermal Emittance:** For buildings in Climate Zones 0 to 3 and for roofs above cooled condition spaces only, the sunward-facing surface of the roof system is required to have a minimum 3-year-aged solar reflectance of 0.55 and a minimum 3-year-aged thermal emittance of 0.75. Alternatively, the roof surface must have a minimum 3-year-aged SRI of 64.
- » **Air Barriers:** A continuous air barrier shall be provided throughout the building thermal envelope, defined as "the basement walls, exterior walls, floors, ceilings, roofs and any other building element assemblies that enclose conditioned space or provide a boundary between conditioned space and exempt or unconditioned space." For roof assemblies that are a part of the building thermal envelope, air barrier materials are required to be continuous, and construction details must be developed to allow for air barrier components of the roof and adjacent construction to be uninterrupted and/or connected in a way that does not interrupt the barrier to air flow.

In reroofing situations, Chapter 5 of the IECC contains an exception that exempts having to comply with the air barrier requirement where the scope of work does not also include alterations or repairs to the remainder of the building's thermal envelope for projects where the overall energy use of buildings does not increase as a result of changes that occur as part of projects.

DESIGNING ROOFS TO COMPLY WITH BUILDING AND ENERGY CODES

As someone who participates in the code development process, the author understands the challenge of avoiding unintended consequences. Committees of subject matter experts consider potential code changes, and it is not reasonable to expect each committee to immediately understand all possible ramifications of a change, especially in seemingly unrelated areas of the code.

The requirements related to low-slope roof assemblies are mature, meaning the structure of the related code sections and many of the provisions have been similar for decades. Significant changes often take multiple code cycles to be considered and ultimately approved.

An interesting aspect of the history of low-slope code requirements in the I-codes is that energy conservation provisions have been developed separately from the building and related code provisions without “pointers” between the two. A pointer is a reference in one part of the code that also directs a designer to related requirements in other parts of the I-codes.

For example, the following is a provision in Chapter 15 of the IBC. The pointers are shown in bold:

“1502.2: Secondary (emergency overflow) drains or scuppers.

Where roof drains are required, secondary (emergency overflow) roof drains or scuppers shall be provided where the roof perimeter construction extends above the roof in such a manner that water will be entrapped if the primary drains allow buildup for any reason. The installation and sizing of secondary emergency overflow drains, leaders, and conductors shall comply with Section 1611 of this code and Chapter 11 of the International Plumbing Code.”

See **Fig. 3** for an example where this has not been done.

The text discusses specific conditions outlined in the roofing chapter of the IBC. When these conditions arise, the



FIGURE 3. Example of a roof drain without a corresponding secondary (emergency overflow) drain or scupper.

section directs roof system designers to a related section in the structural chapter of the IBC and to a chapter in the plumbing code that contains requirements for addressing the issues identified in the roofing chapter. Without these references, the designer may not be aware of relevant information in other areas of code. In the author’s experience, this has been an issue with roof system design, as the promulgators of building codes have traditionally relied on pointers to make users aware of relevant code provisions outside of Chapter 15. Such pointers have not been added in the IBC for relevant IECC provisions. Similarly, users of the IECC are often unaware of roof assembly requirements beyond the IECC.

Beyond the lack of pointers, in the author’s experience, there has been a noticeable lack of coordination between the teams responsible for building code development and those focused on energy code provisions. This disconnect may stem from a traditional lack of understanding of each other’s issues that they are trying to overcome. As a result, when optimizing a roof assembly design for energy efficiency, it sometimes comes at the expense of compliance with building codes, and vice versa.

The lack of coordination also results

in negative consequences that extend beyond just ensuring code compliance. In the following sections, three examples will illustrate common challenges that often arise.

THE REROOFING THICKNESS PROBLEM

In reroofing situations, a common challenge is that replacement roof systems are often thicker than the roof systems being replaced. This is primarily due to the increased required minimum *R*-values for roof systems installed entirely above the roof deck, which have evolved through several cycles of energy code development. As a result, the minimum required *R*-value has become higher, necessitating thicker systems to comply.

Currently, the minimum required *R*-value for most of the US (Climate Zones 2 to 6) is *R*-25 to *R*-30. This equates to about 4½ to 5½ in. (11.43 to 13.97 cm) thick of polyisocyanurate insulation, plus other components and required roof system flashing heights. Roof systems installed 20 to 30 years ago often have thinner insulation, in some cases as thin as 1 in. (2.54 cm) or less. Additionally, many low-slope roof systems rely on tapered insulation to achieve the required ¼ in. per ft (5.35

mm/m) slope for new construction. In other words, a typical tapered insulation system gains 1 in. (2.54 cm) of thickness every 4 ft (1.219 m) of distance from a drainage point. It is not uncommon for such tapered systems to require up to 12 in. (30.48 cm) of thickness just for the insulation at points furthest from primary drain points, or a bit less if drains are spaced closer together. It is sometimes possible to insulate below roof decks, although the IECC requires additional thickness in this configuration, typically 6 to 8 in. (16.24 to 20.32 cm) of insulation thickness. However, it is not always an option to insulate below roof decks, especially if the original construction did not have under-deck insulation. When undertaking a reroofing project, adding additional thickness to insulation can pose several challenges. One of the main concerns is that increased insulation thickness occupies more vertical space than the existing roof system. This commonly leads to complications.

For instance, the heights of parapet walls are often designed based on original roof thicknesses. Additionally, access doors to roofs are typically positioned with their thresholds above original roof heights, where thicker roofs may exceed threshold heights. The same is true for certain window types with set windowsills. Other critical considerations include maintaining existing through-wall flashing outlets that drain moisture from walls, which must remain above neighboring roof surfaces to prevent water from draining into and wetting roofs, thereby creating interior leaks. Moreover, rooftop equipment, including curbs and supports, as well as louvers and gutter blocking, must be accounted for in relation to replacement roof systems. In many cases, it may not be feasible to adjust the heights of adjacent constructions to meet required roof system terminations and flashing heights required by roof system manufacturers as a condition for warranty coverage. The cost of modifying existing structures to accommodate these changes can, in some instances, exceed the expense of the reroofing itself.

The end result is often to use as thick an insulation layer as possible, but this often falls short of the required

insulation thicknesses for new construction. This may also necessitate reducing the roof slope to preserve enough vertical space for flashings. While building codes allow for reduced slopes in reroofing as long as positive roof drainage is maintained, achieving proper drainage can be challenging. Factors such as roof geometry, material deflection, rooftop equipment layout, and existing scupper heights can complicate this. Reduced slopes often lead to ponding water, which is undesirable for several reasons: it can be visually unappealing, cause staining after evaporation (this also reduces surface reflectivity), serve as a breeding ground for insects, and shorten the roof's service life. In extreme cases, significant ponding can lead to "ponding instability," compromising roof deck integrity and risking structural collapse. Thus, it is crucial for designers to carefully balance insulation thickness and roof slope to avoid these issues.

As the thickness problem is especially common, language was added to the current version of the IECC to address this issue. When the minimum insulation entirely above the roof deck, as required by the IECC, cannot be met due to limiting conditions, the following remedies were added to IECC Section C503.2.1:

- » Construction documents that include a report by a registered design professional or an approved source documenting details of the limiting conditions affecting compliance with the insulation requirements can be submitted to the code official having jurisdiction for approval.
- » Construction documents that include a roof design by a registered design professional or an approved source that minimizes deviation from the insulation requirements.

While the above remedies do offer a path where roof system designers can demonstrate code compliance when dealing with limiting conditions for adding additional insulation thickness, in the author's view, they fall short in three critical ways:

- » Pointers are not included to identify requirements in the IBC where slope is critical for achieving the required

drainage. As insulation thickness and slope are often interconnected, this oversight is significant.

- » Both remedies require registered design professionals (except for those jurisdictions that have approved alternative entities to serve this function, a relative few in the author's experience) to provide a deliverable, such as a report or construction documents, to code officials, who must then approve the proposed approach. Since most jurisdictions do not require a registered design professional to obtain a building permit for a roof replacement, this adds significant costs to a project, and the outcome does not guarantee a favorable result for the owner. The code language also lacks guidance for code officials on how to determine the validity of a particular approach. As a registered design professional specializing in roof system design for over 30 years, the author would like to point out that most of his peers do not specialize in roof system design and, as a result, may lack the experience to confidently address issues in this area. Additionally, many building code officials lack sufficient knowledge in roof system design to feel confident in determining whether a particular approach is adequate.
- » In the author's experience, many building departments, particularly in smaller jurisdictions, often lack the budget to have staff available to review and approve technical documents for roof replacement projects in a timely manner, or sometimes not at all. This issue is especially prevalent before a permit is applied for. The inability to know the approved insulation thickness for specific projects creates challenges, as this information is crucial for designing roof systems, typically well in advance of applying for a permit.

THE COOL-ROOF CONDENSATION PROBLEM

In Climate Zones 0 to 3 (southern US), the IECC requires a minimum roof solar reflectance and thermal emittance for roof surfaces above cooled conditioned spaces, as noted in a previous section. Roofs designed with such reflective

surfaces are sometimes called *cool roofs*. As we will see, there are certain situations where cool roofs are too cool and can cause condensation issues within roof assemblies or in spaces below such roofs.

The climate zone map included in the IECC was developed by US Department of Energy researchers at the Pacific Northwest National Laboratory and is based on heating and cooling degree-day data collected from weather stations. The border between Climate Zones 3 and 4 indicates where cool roofs are mandated in the IECC. This line extends from east to west, passing through southern Virginia, eastern North Carolina, several southern counties in Tennessee, most of Arkansas, Oklahoma, Texas, southern New Mexico, southern and eastern Arizona, a small southwestern corner of Utah, the southern tip of Nevada, and central and southern California. Mandates have also been enacted in more northerly jurisdictions, notably Denver and Chicago, which are both in Climate Zone 5. Alternatively, Tennessee, with some Climate Zone 3 counties, has moved away from cool-roof mandates to preserve flexibility in low-slope roof design.

The research most frequently cited when discussing cool-roof mandates was conducted over 20 years ago and involved roof assemblies that were insulated to levels significantly less than what is required today, typically *R*-8 and below, about three times less than IECC requirements for roofs in Climate Zones 3 and 4. At that time, the rationale for mandating cool roofing was that a white or high-albedo roof surface material would reflect a portion of the incoming solar radiation away from a building's roof before it could be transmitted to and absorbed by the building and place stress on internal cooling systems, resulting in energy and cooling cost savings. However, the potential for condensation issues with roofs was generally overlooked. In addition to energy cost savings, although not part of the IECC's scope, some proponents argue that cool roofs can help mitigate urban heat islands (UHIs), which are areas in cities that experience higher temperatures than their surrounding rural environments.

Recent studies on roof albedo conclude

that decisions by cities and building code governing bodies to mandate reflective roofing in certain climate zones have preempted economic and science-based individualized design decisions, predicated upon critical factors such as local geography, building use, or the roofing materials' carbon footprint.¹ Focusing on the reflectivity of roofing materials as a means of addressing the impacts of UHIs is misplaced and unproven. The article "An Updated Holistic Look at Old Assumptions: Insights from Three New Studies on Roof Albedo" further notes that all too often, mandates like those some US cities have been enacting regarding the use of cool roofs on all new construction and roof replacements limit the flexibility to consider other options by focusing too intently on one environmental attribute, in this case roof reflectivity, instead of taking a more comprehensive approach and considering the overall sustainability and resilience of the roof assembly.¹ Such restrictions limit the ability of roofing design professionals to use their education and training to design, specify, or recommend a particular roof membrane, and thereby prohibit them from implementing the best and most sustainable solution for the situation at hand. In the author's opinion, the ideal scenario would involve the code providing sufficient guidance and flexibility, allowing both code officials and designers to demonstrate and confirm compliance with the overall intent of the code. This collaboration would enable them to find solutions that balance the overall performance of buildings, especially in cases where adhering to individual code provisions could lead to negative performance consequences in other areas.

Mandates are especially problematic in reroofing situations, as discussed in the "The Reroofing Thickness Problem" section above, where the ability to add insulation to the roof system is limited. Often, in these situations, a warmer roof surface can help limit or prevent condensation where a cool surface cannot. Having the flexibility to utilize a warm roof surface in cooler months is especially important in Climate Zone 3 and the north. When roofs are sufficiently insulated, as has been

required in the I-codes since 2015, when minimum required *R*-values for above-deck roof insulation reached currently required levels after rising every code edition since 2006, recent research has demonstrated that the temperature of the roof surface has a minimal effect on cooling within many buildings in climate Zone 3 and most buildings in climate Zone 4 and north,¹ thereby negating the need to mandate a specific roof surface color or reflectivity. When roofs are less insulated, as is sometimes the case in reroofing situations, a darker color is often preferred, as this helps mitigate condensation potential within roof assemblies, as darker-colored roof surfaces promote downward drying, which is not a characteristic of cool roofs and such moisture accumulation can be cumulative.² See **Fig. 4** for an example of condensation damage below a white roof membrane.

Mandates for cool roofing have also been proposed as a solution to combat UHIs. However, a review of results in cities with long-term cool-roof mandates in Climate Zones 4 and 5 has indicated that these cool-roof mandates have not been effective in reducing UHIs.¹ Additionally, a study from Harvard University in 2024 presents data that suggest the energy from reflective surfaces does not disappear but is instead redistributed, leading to increased heating in less affluent areas.³ Also, a study from Stanford University in 2017 found that prominent UHI studies that advocate for the use of reflective roofing do not account for feedback of changes in local temperatures, moisture, and their gradients to large-scale weather systems.⁴ It also found that such studies cannot distinguish temperature changes in urban areas due to the UHI from temperature changes due to greenhouse gases, carbon dioxide domes over cities, cooling or warming aerosol particles, transmission or use of electricity, stationary or mobile combustion, or human respiration, which also occur in urban areas. Lastly, a study by the Institute for Atmospheric and Climate Science in 2015 shows that increasing land surface albedo, and not high roof reflectivity, preferentially cools hot extremes and that such cooling intensity is projected to increase in the



FIGURE 4. Example of condensation damage beneath a cool-roof membrane in Climate Zone 5.

21st century.⁵ In other words, unlike high roof reflectivity, the study found that increasing vegetative land (like urban tree canopy) does mitigate regional heating.

THE ROOF SYSTEM MATERIAL PROBLEM

When designing a roof assembly, several requirements must be addressed to ensure compliance with minimum building codes. In addition to these code concerns, roof system manufacturers have their own warranty requirements. Building owners may also need to meet criteria set by their insurance providers or adhere to environmentally focused guidelines to achieve institutional or voluntary goals. Furthermore, roofs frequently serve as platforms for various elements, including amenity decks, rooftop equipment, roof anchors, and solar systems (that is, photovoltaics or rooftop-mounted solar panels). This means that roof system designers must accommodate many factors in their designs.

The challenge is achieving the goals in owners' programs without compromising code compliance. It is important to remember that roof systems are composed of layers of materials and various attachment methods. Most jurisdictions require that

installed roof assemblies meet or exceed building code requirements, including minimum fire classification, drainage and overflow capacity, and wind uplift pressure resistance. Additionally, they must comply with energy conservation code requirements, which include a minimum *R*-value, air barriers that meet specified air permeance standards, and typically, reflective surfaces for buildings located in Climate Zones 0 to 3.

To comply with standard code provisions, roof system manufacturers test their product assemblies and can provide test reports as a method to demonstrate code compliance. Chapter 15 of the IBC outlines the required assembly testing standards and requires that roofs be applied in accordance with the applicable provisions of the code and the manufacturer's installation instructions. In practical terms, this means the code requires that the roof system manufacturers test every possible combination of products, a challenging proposition. The reality is that not every roof system manufacturer tests every possible material combination. Why is this an issue?

Diligent roof system designers confirm their designs during the design process with roof system manufacturers to ensure that testing has been conducted

using the specific materials and attachment methods proposed for the particular roof deck types being used. This confirms that the resulting roof assemblies meet or exceed the required wind uplift pressure calculated for projects. The same principle applies for fire classification. The following common situations often complicate things:

- » Many projects, particularly those related to public work, require an "open specification" for roof system designs. This means that the acceptable design must allow for multiple manufacturers to participate. For roof system designers, this entails a verification process with various manufacturers to confirm that testing has been conducted to support the proposed designs. However, the fees typically paid to roof system designers often make this verification process challenging.
- » Many projects undergo a process to reduce costs, often referred to as value engineering. During this process, proposed roof system components may be modified or removed. Additionally, during the summer months or periods of supply chain stress, certain components may become scarce or unavailable, leading to the consideration of alternatives. As a result, the system that is ultimately installed may differ from the original design that underwent thorough review. In my experience, the as-built construction sometimes does not receive adequate evaluation for code compliance, particularly regarding wind uplift pressure resistance and fire classification.
- » In an effort to comply with sustainability goals, sometimes products are considered for environmental reasons without fully considering the impact on building-code-related requirements and the associated referenced testing requirements.
- » According to a 2025 report by investment bank Brown Gibbons Lang & Company, reroofing projects account for 80% of roofing work in the US. Most reroofing projects are designed and permitted by

contractors since most jurisdictions do not require design professionals to sign and stamp permit applications for these projects. In my experience, the level of expertise among roofing contractors varies greatly, particularly regarding their understanding of code-related issues. Additionally, building departments sometimes do not review reroofing permit applications with the same rigor as they do for new construction projects.

MOVING TO A BALANCED APPROACH

The three examples presented in the previous sections highlight the complexities involved in designing roof assemblies to meet minimum code requirements. The challenges observed in these examples could be addressed more easily if building codes and energy conservation codes were fully integrated. There are at least three improvements that need to be made urgently, as implementing these changes would likely enhance the resiliency of roof assemblies without increasing construction costs, since most jurisdictions already include these requirements in their codes:

- » Pointers should be added in Chapter 15 of the IBC that alert roof system designers to roofing-related provisions in Chapters 4 and 5 of the IECC and vice versa.
- » The remedies outlined in Chapter 5 of the IECC, which address situations where code-mandated

levels of above-deck roof insulation are required for reroofing projects, should be expanded to reference Chapter 15 of the IBC. This would identify the minimum drainage requirements necessary for effective roof design. Tapered insulation is frequently used to create slope as part of a storm drainage strategy, and the most effective roof assemblies achieve an optimal balance between slope and thermal resistance without compromising either element.

- » Another important improvement to the remedies outlined in Chapter 5 of the IECC would be to give roof system designers the flexibility to specify lower-SRI roof surfaces when necessary to address potential condensation issues. This is especially relevant for reroofing projects where it is not feasible to provide code-mandated roof insulation. Additionally, consideration should be given to buildings with high internal relative humidity, since condensation is more likely to occur during the winter months in areas that use cool roofing.

Such clarifications and additional commentary within the code would be immensely helpful for roof system designers. Building code officials, in my experience, also appreciate such guidance, especially in areas outside their area of expertise and experience. This is certainly relevant, as most code officials do not have a roofing background.

FINAL THOUGHTS

Integrating building and energy conservation codes is just the first step towards achieving resilient roof assemblies. As new information becomes available, it is crucial for everyone involved in the built environment to remain open to considering the latest practices, products, and technologies. We should incorporate science-based minimum requirements into codes and standards, properly referenced to relevant sections elsewhere in the I-codes. One area in this discussion that exemplifies this evolution is cool roofing. Research referenced in this paper indicates that mandatory reflective roofing has not delivered the anticipated benefits over the past 25 years. Recent data also suggest that the advantages of cool roofing are best realized when applied selectively, particularly for certain building types, especially in Climate Zones 0 to 2. Considering this, the mandated use of roofs with reflective surfaces in Climate Zones 3 to 8 seems outdated and inappropriate.

Lastly, these suggested improvements to model codes have another profound benefit. As model codes are the starting point for most jurisdictions, improved language, pointers, and flexibility will be distributed to all jurisdictions as part of the adoption process. Jurisdictions will not have to find balance in their codes; the balance will come to them, and better, more resilient roof assemblies will be the result.

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Structural Design for Steep-Sloped Roofing Systems

ABSTRACT

In sloped roof construction, understanding and defining the load path between the roofing system and the roof structure for the in-plane component of gravity loads can be complicated. Vented roofs, metal roofs, and roofs with snow retention devices are examples of roofing systems for which a well-thought structural load path is instrumental in delivering gravity forces into the base building structure. Despite the importance of completing this load path, design teams and contractors often overlook its design. By not seriously considering and evaluating the load path during the design phase, we also miss the opportunity to properly detail the structural penetrations through the building enclosure. Consequently, failing to address the in-plane gravity load path during the design phase can result in unintended discontinuities in the building enclosure, thermal bridging, reduction in thermal performance, and an increased risk of condensation at these crucial structural connections.

This paper explains when and why the structural design of steep-slope roofing systems is essential and provides design considerations, including an in-depth review of the coordination required between structural and enclosure designers.

LEARNING OBJECTIVES

- » Review the common and unique scenarios in which structural blocking is required for sloped roofing systems.
- » Discuss the load path between the roofing system and roof structure in systems requiring blocking and evaluate detailing options that provide a competent load path while minimizing negative impact on the building enclosure.
- » Summarize how to detail structural penetrations through the air, water, vapor, and thermal enclosure barriers.
- » Identify techniques to maintain and calculate the proper roof ventilation around structural blocking.

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INTRODUCTION

In this paper, the authors hope to impress upon the reader the importance of coordinating the structure and enclosure of steep-sloped roofs. Unlike with flat roofs, components of a steep-sloped (3:12 slope or greater) roof must continually resist the in-plane, i.e., “sliding,” component of forces imparted on them by gravity. The structural solutions to restrain this movement range from simple to complicated, and the design responsibility for this feature often falls between the cracks, as the architect, engineer of record, delegated design engineer, and contractor could all foreseeably be responsible.

Simply including the proper structure to resist the in-plane components of gravity loads is not necessarily sufficient to resolve the issue. The design team must balance the structural requirements with the potential impacts to the enclosure. For example, how will the team detail the continuity of the four barriers (air, vapor, thermal, water) around a structural feature like roof edge blocking? Structure that impedes ventilation or interrupts insulation may also increase the risk of ice dams or condensation within the roof system.

STRUCTURAL APPLICATIONS TO RESIST IN-PLANE GRAVITY FORCES IN STEEP-SLOPED ROOF CONSTRUCTION

Structural components can be used in a wide variety of configurations to support individual roofing elements or to complete the load path of the roof system as a whole. In this section, we summarize the common instances where coordinated structural components are required to resist

in-plane gravity-induced sliding forces in steep-sloped roof systems. This paper does not address the structural components that resist uplift forces imparted on roofing systems by wind, though the structural components utilized to resist sliding forces can also be part of the load path that resists wind uplift forces.

In sloped roof construction, all roofing components installed above the roof structure must be secured to the structure in a way that resists the constant pull of gravity. The steeper the slope of the roof, the greater the gravity-induced sliding force parallel to the plane of the roof. Lightweight roofing installed directly to the structure, such as lightweight asphalt shingles fastened to plywood sheathing, resists the in-plane sliding component of gravity loads through shear in the nails fastening the shingles to the sheathing. Heavy roofing assemblies on steep-sloped roofs can produce a significant in-plane gravity sliding force on individual fasteners. Thick roofing assemblies apply their sliding force on the individual fasteners farther from the roof sheathing and can introduce significant eccentric loading on the fasteners. Common heavy assemblies include clay and slate roof tiles. The eccentric sliding force is exacerbated when the roofing assembly requires insulation or an air gap (or both) between the roof cover and the roof structure. This typically requires longer fasteners, but these eccentric sliding loads can cause fasteners to fail in bending or by rotating within the structural substrate. The gravity-induced sliding forces associated with these systems must be resisted by structural blocking. This structural

blocking can take the form of roof edge support, continuous structural support, intermittent blocking, or ridge blocking, which transfer the sliding shear from the level of the roofing to the roof structure and eliminate the eccentric loading on typical individual roofing fasteners. These four types of structural support are defined below:

- » **Roof edge support** (“heel blocking”) – in-plane loads are collected along the length of the slope and delivered into the roof structure at the eave.
- » **Continuous blocking** (“sleepers”) – deliver in-plane forces to the roof framing continuously along the slope.
- » **Intermittent blocking** – in between approach, collecting in-plane forces and intermittently delivering the forces to the roof framing along the slope. This can vary from close and evenly spaced blocking (smaller more distributed forces) to a few discrete lines of blocking across the slope (larger forces).
- » **Ridge blocking** – similar to heel blocking, but the loads are collected at the ridge via tension of the roofing material. This blocking is typically used for standing seam, and other “hung” sheet metal roofing systems. For hung roofing systems that are insulated and/or ventilated above the roof structure, some combination of ridge blocking and the other blocking types is required, along with careful detailing to understand whether the load paths are in parallel or sequence.

Although steep-sloped roofing assemblies are commonly associated with low-rise wood-framed houses, they can also be used in commercial and institutional construction, such as

the example shown in **Fig. 1**. Figure 1 provides an example of a clay tile roof system over a vented nail base where the in-plane component of the gravity load of a 35-foot-long length of roofing is supported at the eave with an assembly extending from the edge of the structural slab. **Fig. 2** shows an in-progress view of the structural edge support assembly.

Snow Retention Systems

Snow retention requirements can vary depending on the climate zone and jurisdiction in which a building is designed and constructed. In some cases, an owner may voluntarily elect to retain snow to protect building occupants, pedestrians, or personal property (e.g., parked vehicles).

The type of snow retention system selected will affect how these snow-induced sliding forces travel through, or bypass, the structural elements supporting the gravity-induced sliding forces of the roofing. Snow retention systems, such as the continuous rail system and its supporting structure which passes through the elevated roofing system depicted in **Fig. 2** extend above the roofing surface and can impart significant eccentric loads on the roof structure when retaining snow. The designers must provide a competent load path between the snow retention

system and roof structure and must ensure that the roof structure can support the concentrated loads imparted by the snow retention system as well as the increased loads due to the retained snow. Additionally, the designers must ensure that the structure required to resist loads imparted by snow retention systems does not compromise the effectiveness of the building enclosure. For example, snow retention systems installed on a standing seam metal roof may need to be clamped to the standing seams or adhered to the flat metal between seams to avoid penetrating the roofing. This requires the designers to ensure that the anchors connecting the metal roofing to the ridge blocking are adequate to support the increased in-plane loads from snow.

HOW DOES COORDINATION OF STRUCTURAL SUPPORTS WITH ROOFING ELEMENTS AFFECT THE BUILDING ENCLOSURE?

Each of the structural solutions introduced above potentially interferes with the building enclosure system. Careful coordination and integration of the

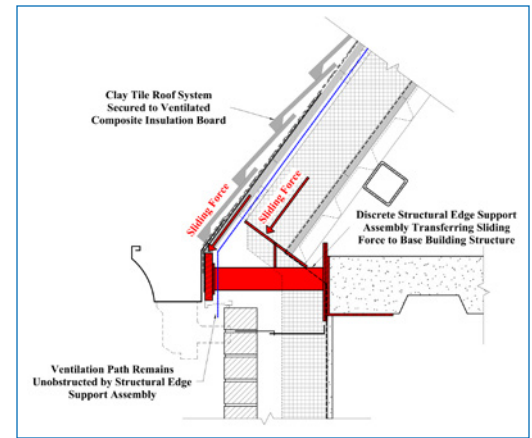


FIGURE 1. Roof edge support.

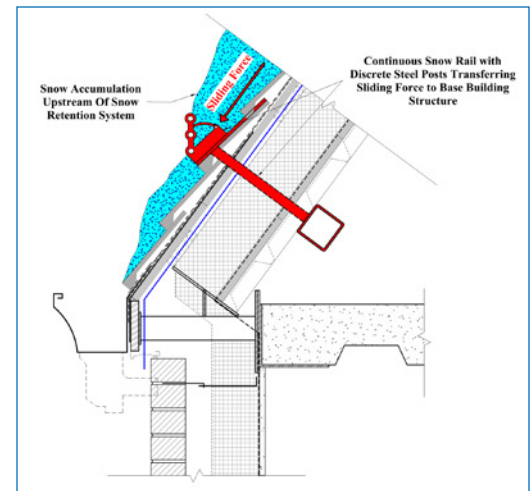


FIGURE 3. Snow retention support.



FIGURE 2. Roof edge support in progress.

selected structural solution with the desired enclosure system is important for a successful design.

Condensation, Air, and Moisture Management

Controlling the buildup of moisture in the form of condensation within a roof system is paramount to providing a durable and long-lasting roof. Section 1202.2.1 of the 2021 International Building Code requires that enclosed attics and enclosed rafter spaces formed where ceilings are applied directly to the underside of roof framing members shall have cross ventilation for each separate space by ventilation openings protected against the entrance of rain and snow.¹ Section R806 of the 2021 International Residential Code contains similar requirements.² Blocking and bridging shall be arranged so as not to interfere with the movement of air. An air space not less than 1 inch shall be

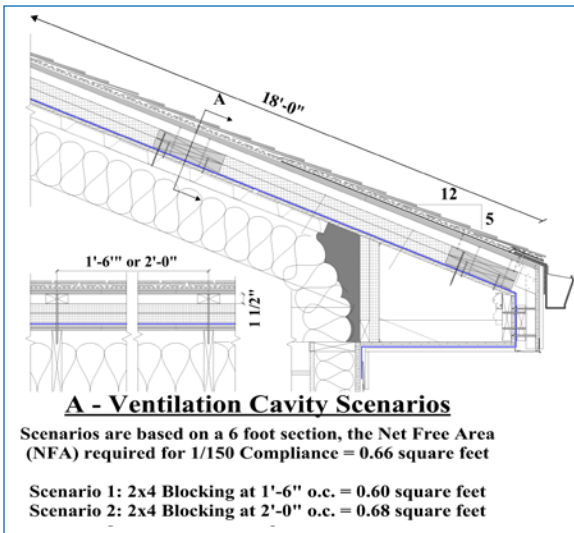


FIGURE 4. Ventilation scenarios.

provided between the insulation and the roof sheathing. The net-free ventilating area shall be no less than 1/150 of the area of space ventilated. In certain cases, the net-free ventilating area can be reduced to 1/300.

The code requires that blocking be arranged so as not to interfere with ventilation, but in most cases, some interference can be expected. **Fig. 4** shows an intermittently supported roof system above a large attic space. Figure 3 includes two scenarios, each containing 2 x 4 sleepers at different spacings. In this example, sleepers at 2 feet o.c. satisfies the 1/150 code requirement. If a tighter spacing is required, the net-free

ventilation might not meet the 1/150 code requirement, requiring the designer to increase the ventilation air gap; re-evaluate the support blocking layout or material, introduce mechanical ventilation; or select a roof system that does not rely on ventilation.

Despite the existence of many industry documents repeating the 1/150 and 1/300 ratios, this is an arbitrary number that should not be misinterpreted as an exact science or a universal technical necessity. William B. Rose, a research architect at the University of Illinois at

Urbana-Champaign, studied this topic exhaustively, and we encourage the reader to review his published literature.^{3,4}

Condensation Control and Ice Dams

Ice dams form when heat loss through the roof melts snow on the roof although exterior temperatures are below freezing. The meltwater flows to the cold eave overhang where it refreezes. This ongoing process causes ice to build up and create a dam, eventually preventing upslope meltwater from draining off the roof, as depicted in **Fig. 5**.

The most effective way to control ice dams is to keep the roof deck cold enough to prevent snow from melting,

which can be accomplished in a few ways, one of them being ventilation beneath the roof deck. Two common designs for vented roofs include cold attics and vented compact roofs. Adequately sized eave and ridge vent openings are required for ventilation to function properly in preventing ice damming.

The net-free ventilation requirements discussed in the prior section are not intended to prevent ice damming and are antiquated, arbitrary ratios from 1942, as discussed in detail in the referenced Rose articles. We typically base our analysis of effective attic ventilation on methods developed by Wayne Tobiasson's 1998 research with the Cold Regions Research and Engineering Laboratory (CRREL), modified by the authors to account for the flow caused by thermal forces with guidance from Chapter 25 of the ASHRAE 1997 Handbook of Fundamentals.^{5,6}

To highlight the importance of proper ventilation, **Fig. 6** shows the performance of a roof system with adequate ventilation on the same campus on the same day as Photo 2 after ventilation repairs accounted for the increase in heat loss due to mechanical equipment within the attic space. In addition to improving insulation, reducing HVAC heat loss in attic spaces and meticulously air sealing between the interior conditioned



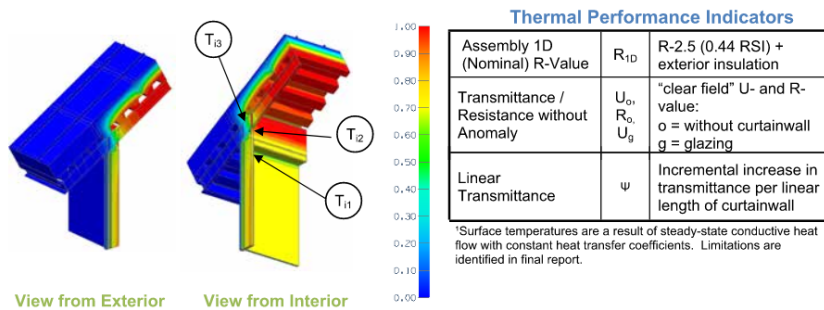
FIGURE 5. Ice dams and icicles resulting from insufficient ventilation.



FIGURE 6. Sufficient ventilation, resulting in negligible ice dams or icicles.

Detail 10.2.4

Exterior Insulated Sloped Metal Roof with Metal Sub-Girts (24" o.c.) Supporting Standing Seam Metal Roof and Curtain Wall – Roof to Wall Intersection with Through Wall Structural Beam and Continuous Through Wall Structural Metal Deck



View from Exterior View from Interior

Nominal (1D) vs. Assembly Performance Indicators

Base Assembly Roof				Roof to Wall Linear Transmittance		
Roof Insulation 1D R-Value (RSI)	R_{1D} ft ² ·hr·°F / Btu (m ² K / W)	R_o ft ² ·hr·°F / Btu (m ² K / W)	U_o Btu/ft ² ·hr·°F (W/m ² K)	R ft ² ·hr·°F / Btu (m ² K / W)	U Btu/ft ² ·hr·°F (W/m ² K)	Ψ Btu/ft ² ·hr·°F (W/m ² K)
R-36 (6.34)	R-38.5 (6.78)	12.4 (2.18)	0.081 (0.46)	2.7 (0.48)	0.369 (2.10)	0.679 (1.177)

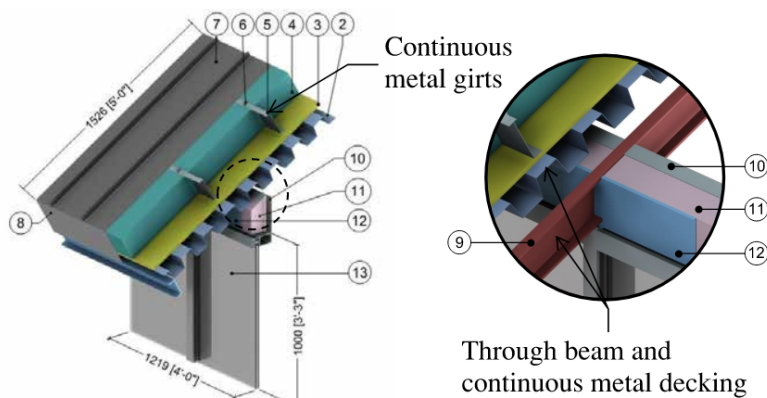


FIGURE 7. Derated roof assembly.

space and the roof system can help to eliminate the risk of ice damming.

Thermal Bridging

Thermal bridging has long been the focus of condensation risk mitigation and is still an important consideration to designers when reviewing the thermal performance of a roof system. Regional jurisdictions, such as Massachusetts, where the authors typically practice, require thermal bridging to be accounted for when calculating the U -factor of certain facade components. The accounting of thermal bridging in U -factors is commonly referred to as "derating." The 2024 *International Energy Conservation Code (2024 IECC)* codifies derating facade systems and will be required once states eventually

adopt this code.⁷ The authors predict that derating roofing systems will be codified in the near future.

Figure 7 is referenced from Detail 10.2.4 of the *Building Envelope Thermal Bridging Guide* and provides an example of two thermal bridges to be considered in our steep-sloped roof assembly: a clearfield nonthermally broken roof support and a linear thermal bridge consisting of a through beam and continuous metal decking.⁸ When using nonthermally broken continuous metal Z-girts at 24 in. o.c. to support an insulated steel-sloped roof assembly, an R -36 roof assembly is reduced to R -12.4. When we consider the linear thermal bridge at the roof edge support, the linear transmittance is 0.679 Btu/ft²·hr·°F.

The continuous metal Z-girts create a significant reduction in the thermal performance of the roof. Thermally improved materials, such as thermal spacer blocks, fiberglass, or even wood, when compared to metal can improve the effective R -value of the roof. Appendix A of ASHRAE 90.1-2022 also provides various tables with precalculated assembly U -factors to assist with design and detailing.⁹ Although not directly related to the subject of this paper, **Fig. 8**, referenced from Detail 10.2.5 of the *Building Envelope Thermal Bridging Guide* shows how a thermally broken roof edge support system can reduce the linear transmittance by nearly half when compared to the nonthermally improved detail shown in Fig. 7.

DESIGN TIPS

When possible, the most structurally efficient method of resisting in-plane components of gravity loads in steep-sloped roofs is to provide continuous, regularly spaced structural elements such as steel z-girts or wood strapping parallel to the roof slope, extending between eave and ridge. These elements evenly distribute the in-plane gravity sliding forces, including the eccentricity described above, over the length of the roof slope, primarily in shear. Once in-plane forces are delivered to the surface of the roof structure, the roof diaphragm is typically capable of distributing to the roof framing. **Fig. 9** shows continuous steel z-girts parallel to the slope of the roof completing the load path between roofing elements and the roof structure. Note that the girts do not interfere with the ventilation of the roof assembly, nor are the girts a significant contributor to the derating of the roof assembly, as the insulation layer is installed below deck; thermal bridging in this design occurs at the main structural steel supports but not at the z-girts. Continuous above-deck insulation would theoretically provide better thermal efficiency but will be impacted by thermal bridging at the structural elements that resist shear through the thickness of the insulation.

Continuous structural elements parallel to the slope of the roof are preferable to structural elements that are discrete or continuous and perpendicular to the

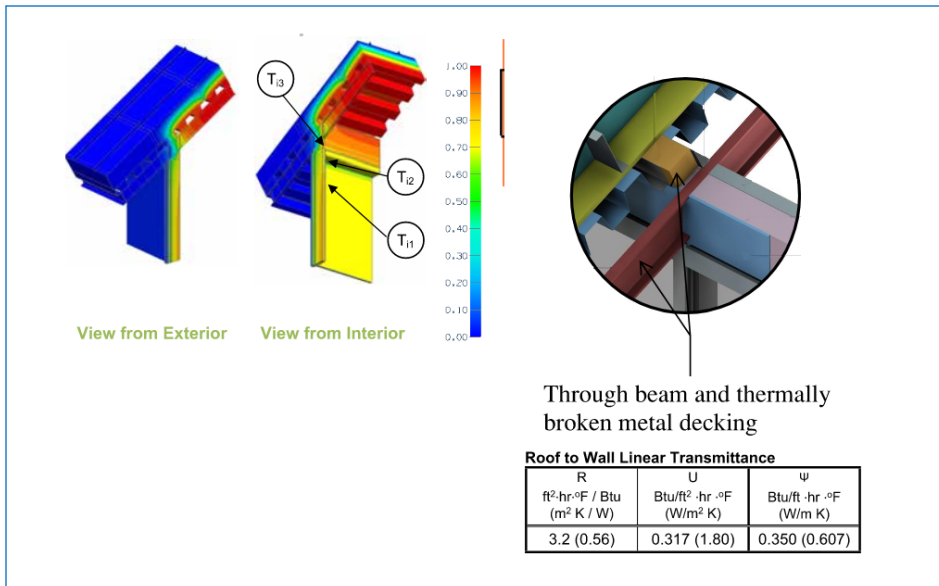


FIGURE 8. Thermally improved roof edge.

slope of the roof, which can produce substantial concentrated moments and shears that components of the underlying roof structure, such as plywood sheathing or steel roof deck, may not be adequate to resist. In retrofit projects, the designers may need to add new members or strengthen existing structural elements. In new design projects, the designers may have more flexibility to align roofing support structure with roof framing members to avoid concentrated loads on the midspan of roof sheathing or metal deck. However, it still may be necessary to reduce roofing support structure spacing to minimize concentrated load effects.

When reviewing how the roof structural support affects the building enclosure, consider the following items as part of your review and adjust the structural support components or enclosure strategy accordingly.

Roof Ventilation

- » Does my roof system require roof ventilation to reduce the risk of ice damming or condensation? Identifying whether you have a compact roof system or a ventilated roof system is the first step.
- » Does my structural support system interfere with my ventilation path? Is this the point where my net free ventilation area is the smallest?

Review the net free ventilation area against the code requirement and the authors' recommended analysis for attic ventilation to confirm that the design meets code and reduces the risk of ice damming.

Thermal Bridging

- » Do my structural supports interfere with the clearfield performance of my roof system? While not currently required by code in most jurisdictions, soon the code may require designers to calculate and derate the composite *U*-value of roof systems.
- » Does my structural support create a linear thermal bridge? In some jurisdictions, the linear thermal bridging must be accounted for as part of the energy code compliance path. Existing published thermal models or prescriptive table values (e.g., *Building Envelope Thermal Bridging Guide* or ASHRAE 90.1-2022) may be available for project use, or custom thermal models may need to be developed based on the complexity of the thermal bridge support.
- » Does my structural support create a

thermal bridge that creates a risk of interior condensation or exterior ice damming? If it is apparent that the thermal bridge may cause ice damming (e.g., transfers enough energy to melt snow at eaves) or cause condensation (e.g., transfers enough energy to reduce interior temperature below the dewpoint), thermal modelling and further analysis may be required.

Air and Water Barrier Continuity

- » Does my structural support penetrate through my air and water barriers? If our support system is penetrating our air and water barriers, consider the following list of design considerations to help maintain continuity and reduce the risk of air penetration and water leakage.
- » Reduce the penetrations: Can the supporting elements be "sized up" to increase the spacing and thus reduce the number of penetrations?
- » Penetration geometry: Can round, closed structural shapes be used? These are often easier to flash and allow for the use of a metal draw band that can provide uniform compression on flashing membranes.
- » Flashing height: Whether the penetration is going through a vertical or horizontal portion of air and water barrier, you need to have enough space for the air and water barrier to lap onto. Review the membrane product requirements and locate the

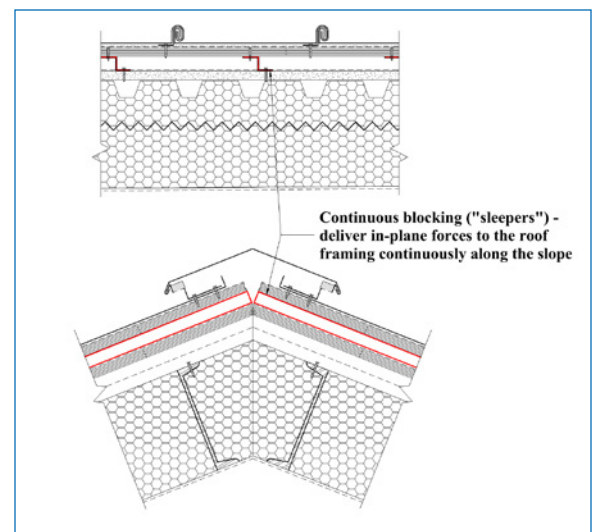


FIGURE 9. Continuous sleepers parallel to roof slope.

penetrations so that proper flashing height or length can be provided.

- » Fasteners: Perhaps the only “structure” needed is a tremendous number of fasteners? Even with a “self-healing” membrane, some air leakage through fastener penetrations can be expected, and this air leakage can add up. If achieving a high degree

of airtightness is the project goal, the authors recommend bedding all fasteners that penetrate the air and water barrier with sealant.

CONCLUSION

In steep-sloped roof construction, it is necessary to provide a competent

load path between the roofing system and the roof structure for the in-plane component of gravity loads. The design of the structure comprising this load path should be addressed early in the design phase so that the design team may account for potential impacts on the four barriers of the building enclosure (air, vapor, thermal, water).

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Retrospective Embodied Carbon Facade Study: A Retrospective Perspective

ABSTRACT

When initially approaching embodied carbon and the corresponding research, professionals are often overwhelmed by a plethora of resources, making the process difficult to navigate. This presentation will review a completed facade embodied carbon study to highlight potential variabilities within the initial lack of parameters. A brief systematic breakdown of stage-by-stage calculations for retrospective building projects will be used as a basis for discussion focusing on the impact of each stage, realism of the results, and inherent variabilities or uncertainties.

A series of in-depth microstudies were explored to analyse tools and factors used throughout the manual calculation process, setting lessons learned for future professionals. An understanding of the inherent uncertainties between the manual calculations and online toolkits is critical and will be explored to highlight the impacts of project specific EPDs and utilization of embodied carbon performance tools such as EC3 for guiding methodology and its reliability.

Ultimately, this presentation will provide attendees with a more refined approach to managing embodied carbon studies, equipping them with the tools to streamline future retrospective assessments and enhance carbon-conscious decision-making.

LEARNING OBJECTIVES

- » Describe the research decisions made throughout the embodied carbon calculation process to streamline studies and make analyses more accessible.
- » Evaluate tools and steps toward holistically completing facade embodied carbon studies.
- » Identify different calculation methodologies such as manual or online tools and their inherent variabilities.
- » Evaluate the applied process from the perspectives of facade engineers and the establishment of communication between various stakeholders, to then manipulate the process for future studies from varied AEC perspectives.

SPEAKER



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Aria Mascall is currently a facade engineer at Buro Happold in Los Angeles, California. She recently graduated with honors as the valedictorian of her class in the department of civil and architectural engineering, receiving a bachelor of science in architectural engineering and a minor in sustainable built environments from the University of Arizona. Stemming from her childhood in Powell Butte, Oregon, her passion for innovative and critical design fosters a disposition for resilient and sustainable developmental practices. Studying location-advantageous design theory allowed her connection to wilderness to flourish and deepened her desire for time spent with Mother Nature.



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Embodied carbon (EC) has become the “talk of the town” in the construction industry and rightfully so. New sustainability initiatives aim to address the impact of EC in new and retrofitted construction, addressing challenges of understanding EC in fields such as building enclosure consulting. For example, Boston set a precedent with its standard to achieve net-zero carbon emissions.¹

Each module within a building’s life cycle assessment (LCA), from material extraction through construction and ongoing use to end-of-life building disassembly, contributes to the building’s carbon footprint. To track the output, a LCA can be divided into two overarching classifications: embodied and operational carbon. EC encompasses the carbon emissions associated with the up-front (A1–A5), in-use maintenance (B1–B5), and end-of-life (C1–C4) modules of a building, whereas operational carbon classifies all carbon expended during the operational use (B6–B7) of the building (Fig. 1).²

This paper focuses on the manual calculations completed for two case studies documenting the EC of product and construction modules of their corresponding primary facade systems. Facades constitute approximately 25% of EC within a building, as Benke and coauthors published.³ This illustrates how impactful facade systems are to the overall EC of a project, outlining the cruciality of retrospective research to determine precedents for future early EC-conscious design decisions (Fig. 1).

Global warming potential (GWP) is used to track EC, using kilograms of carbon equivalent (kg CO₂e) as the metric.⁴

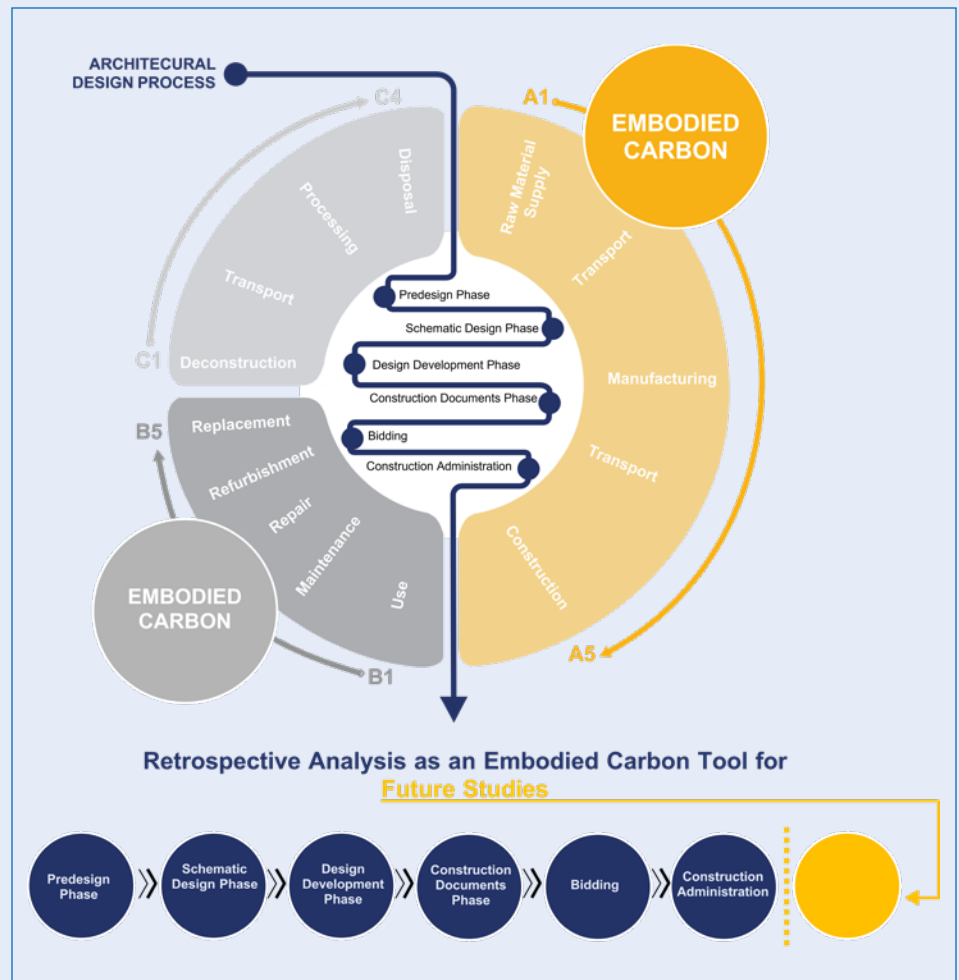


FIGURE 1. Embodied carbon project life cycle showing alignment architectural design phases. Areas in yellow are the focus of this paper with cradle-to-gate phases in a retrospective analysis.

Although greenhouse gases other than carbon dioxide (CO₂) contribute, their impact is reported in terms of GWP relative to CO₂. Typical LCA’s provide final EC values in kg CO₂e/m² gross internal floor area (GIA), whereas EC calculations for facades apply to the vertical area of study. Hence, facade EC studies are provided in units of

kg CO₂e/m² in facade surface area (FSA). The facade form factor is the ratio of FSA to GIA units:⁵

$$FFF(m^2) = \frac{FSA (m^2)}{GIA (m^2)}$$

EQUATION 1. All results presented in this research will be provided in FSA units.

TABLE 1. Façade system types in the case studies and the relative area of each compared to the entire building façade area for each case study

	Façade System	Façade System Breakdown
Case Study 1	Glazed Curtainwall Panel System with Thin Brick Masonry	58%
	Glazed Curtainwall Panel System with Prefinished Aluminum Truss	15%
	Glazed Curtainwall Panel System with Prefinished Aluminum Horizontal and Vertical Members	24%
	Metal Panel Rainscreen	3%
Case Study 2	Glazed Curtainwall Panel System	23%
	Glazed Curtainwall Panel System with Metal Panel	43%
	Metal Panel Rainscreen	28%
	Lobby Storefront	6%

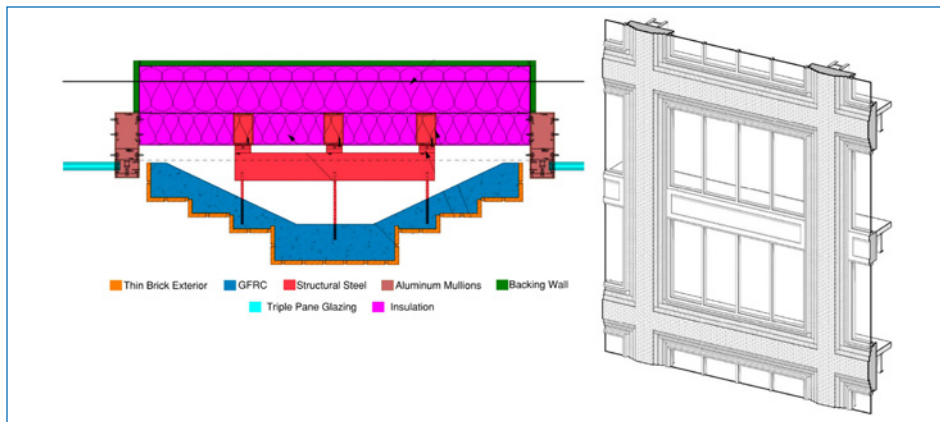


FIGURE 2. Scope of analysis for case study 1. Note: GFRC = glass-fiber-reinforced concrete.

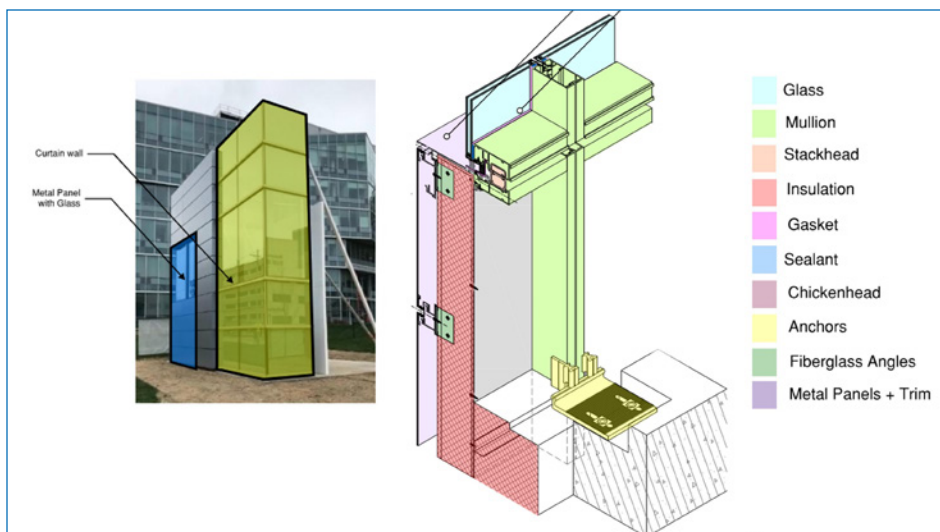


FIGURE 3. Scope of analysis for case study 2.

RELEVANCE OF RETROSPECTIVE STUDIES

The timing of an EC study can significantly impact the accuracy of results and actionability. Early in a project, while systems are in development, there's often insufficient information to accurately calculate EC. Even after system selection, the components differences—like manufacturer, size, and material—add variability. As the design progresses and product selections are refined, the data improves. Since product selections are often finalized in later design phases, monetary restrictions limit actionable design changes based on EC results.

An EC study can also be conducted after a project has been completed. Retrospective studies can provide valuable information for future projects, enabling more proactive design, research, and decisions by improving early design system comparisons and procurement processes. Retrospective studies are the focus of this paper.

RETROSPECTIVE CASE STUDY BUILDINGS

Two retrospective EC studies were completed in 2023 and 2024. The calculation methodology for both studies identified building system assemblies per **Table 1**, compiled EC information for most components, and manually calculated the total EC averaged out per square meter of the building.

The first case study involved a commercial building in Boston, which featured four typical façade systems. This EC study focused on the glazed curtainwall panel system with thin brick masonry, as this façade system encompassed most of the vertical area of the façade (**Fig. 2**).

The second case study examined an educational building in Missouri. The building enclosure primarily featured glazing and metal panel systems, and the study investigated the most prominent wall types: large shop-fabricated sections (i.e. mega panel units with metal and glazing), and curtainwall units (**Fig. 3**).

TABLE 2. Workflow for modules A1–A3, selected metrics

CASE STUDY 2 CURTAINWALL	FU	Density	Face Area	Weight	EC per panel	EC per m2 of panel
Component	[FU]	[kg/m ³]	[m ²]	[kg]	[kgCO ₂ /panel]	[kgCO ₂ /m ²]
Glass	m ²	2,500.00	7.33	465.16	436.59	59.48
Anchor	kg	2,700.00	0.00	2.04	26.91	3.67
Anchor Attachment	kg	2,700.00	0.01	0.24	3.18	0.43
Anchor Attachment 2	kg	2,700.00	0.00	0.44	5.76	0.78
Backpan	kg	7,850.00	0.00	49.12	135.57	18.47
Sealant - regular	m ²	1,500.00	0.00	1.88	28.51	3.88
Sealant - thicker top seal	m ²	1,500.00	0.00	0.27	4.17	0.57
Sealant - spandrel midspan	m ²	1,500.00	0.00	0.37	5.56	0.76
Gasket	kg	400.00	-	0.52	0.66	0.09
Insulation	m ²	128.00	8.32	108.25	29.97	4.08
Mullion Vertical	kg	2,700.00	0.00	25.51	336.75	45.88
Mullion Horizontal Between Spandrel	kg	2,700.00	0.00	14.05	185.44	25.26
Mullion Horizontal Top of Unit	kg	2,700.00	0.00	21.21	280.00	38.15
Mullion Horizontal Bottom of Unit	kg	2,700.00	0.00	8.70	114.80	15.64
TOTAL					1,593.87	217.15

Note: EC = embodied carbon; FU = functional unit.

EC CALCULATION PROCESS

Modules A1–A3: Product Stage

For the case studies, the environmental product declarations (EPDs) were primarily used for A1, A2, and A3 calculations. In retrospective EC studies, shop drawings, submittals, and specifications are used to identify products for which EPDs are needed. In case study 2, investigators obtained majority of the information directly from the curtainwall manufacturer. This expedited the process as the bulk of the

facade scope was owned by one entity rather than multiple manufacturers.

To ensure the most up-to-date information, it is advisable to use data from submittals for component-focused dimension calculations, such as those in **Table 2** and **Table 3**. While generalized industry EPDs are available in various databases, the study’s effectiveness depends on project-specific EPDs. In retrospective studies, it is recommended to use product-specific data as façade systems have been predetermined. Although detailed

TABLE 3. A1–A3 calculation metrics

Metrics	Units
EC per function unit	kgCO ₂ /FU
Density	kg/m ³
Thickness, width, height/length	m
Face area	m ²
Volume per panel	m ³
Weight	kg
EC per panel	kg CO ₂ /panel
EC per area	kg CO ₂ /m ²

Note: The calculation takeoff methodology involves a variety of units, due to the varied declared/functional units provided by EPDs per product type. For example, insulation is measured in vertical area per RSI = 1, whereas glass is measured by weight. This is one of the several parameters set out by the Product Category Rules (PCR) to ensure that similar products are assessed comparably. EPD units vary by product type, but the end goal is to calculate a unified measurement of EC for a representative area. When calculating EC, it is important to determine whether imperial and metric units of measurements are used for accurate conversions in comparisons, shown in **Table 4**.

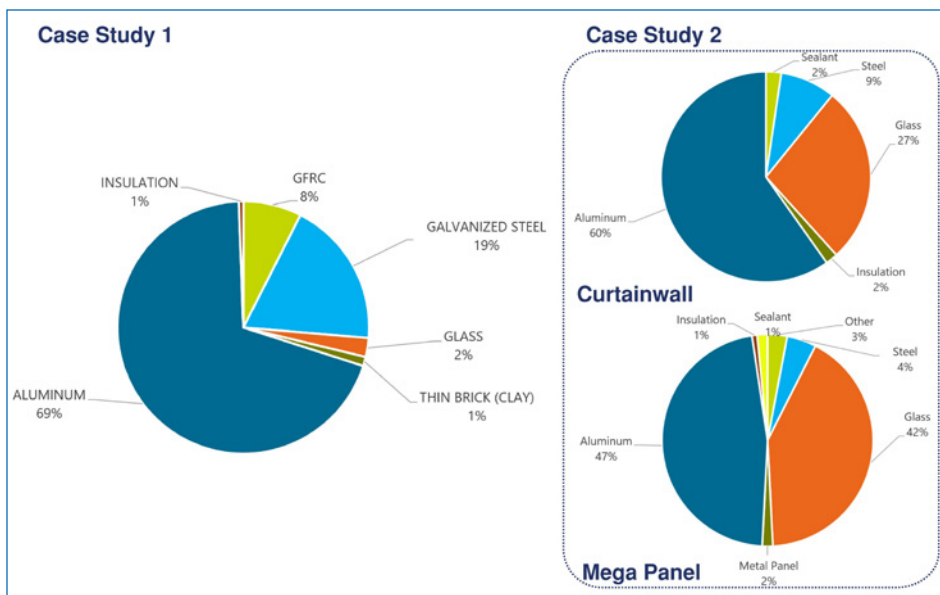


FIGURE 4. EC contributions by material type of facade system materials from case studies 1 and 2. Note: GFRC = glass-fiber-reinforced concrete. Note: EPDs are an international standard for measuring GWP as laid out by the internal standard ISO 14025 as to streamline the process towards factual environmental claims.

quantity and product information is available, project manufacturers might not have EPDs, limiting the study through early decisions. Therefore, early engagement with manufacturers is crucial to streamline future EC studies, especially for high-impact materials such as aluminum, demonstrated per the breakdown in **Fig. 4**.

To further track the GWP of specific materials, a sensitivity study was conducted for the metal mega panel in case study 2. The materials were grouped depending on the source of the EPD’s, as product-specific, partial, or industry-wide. **Fig. 5** shows that 43% of the total EC was calculated using project-specific EPDs, i.e. glass and insulation, which accounted for 91%

TABLE 4. A1–A3 result comparison by material type for Case Study 2 curtainwall and mega panel

Case Study 2 Metal Panel + Glass (kgCO ₂ e/m ²)								
Materials	Sealant	Glass	Aluminum	Metal Panel	Insulation	Steel	Other	Total
Total	4.13	109.37	131.22	4.21	2.08	11.78	0.09	262.88

Case Study 2 Curtainwall (kgCO ₂ e/m ²)								
Materials	Sealant	Glass	Aluminum	Metal Panel	Insulation	Steel	Other	Total
Total	5.21	59.48	129.81	–	4.08	18.47	0.09	217.14

Note: kg CO₂e (e = equivalents)

of the total material volume. Initially, this representation of project-specific information might seem adequate. However, material volume and EC are not proportional. For instance, aluminum is only 2% of the material volume, but due to its carbon intensity, it had the highest impact (47%) on the facade system’s EC. This illustrates the importance of assessing the need for project-specific EPDs based on the types of materials used, not the volumes of those materials.

Additionally, all materials in project systems need to be considered in EC analyses. For example, the metal panel system in case study 2 used project-specific EPDs, but these EPDs did not include the coatings. The EC impact of the coatings was derived from industry-average EPDs. Combining the EPD information provided the most accurate representation for EC given the available data.

**MODULE A2/A4:
TRANSPORTATION EMISSIONS**

During this phase of the retrospective research, investigators communicated directly with fabricators, manufacturers, and installers to collect data about transportation emissions. The distinction between these parties was critical towards the assignment of modules. Manufacturing includes the process of creating products from raw materials while fabrication is the more intricate process focused on the assembly from those pre-made components. Since the

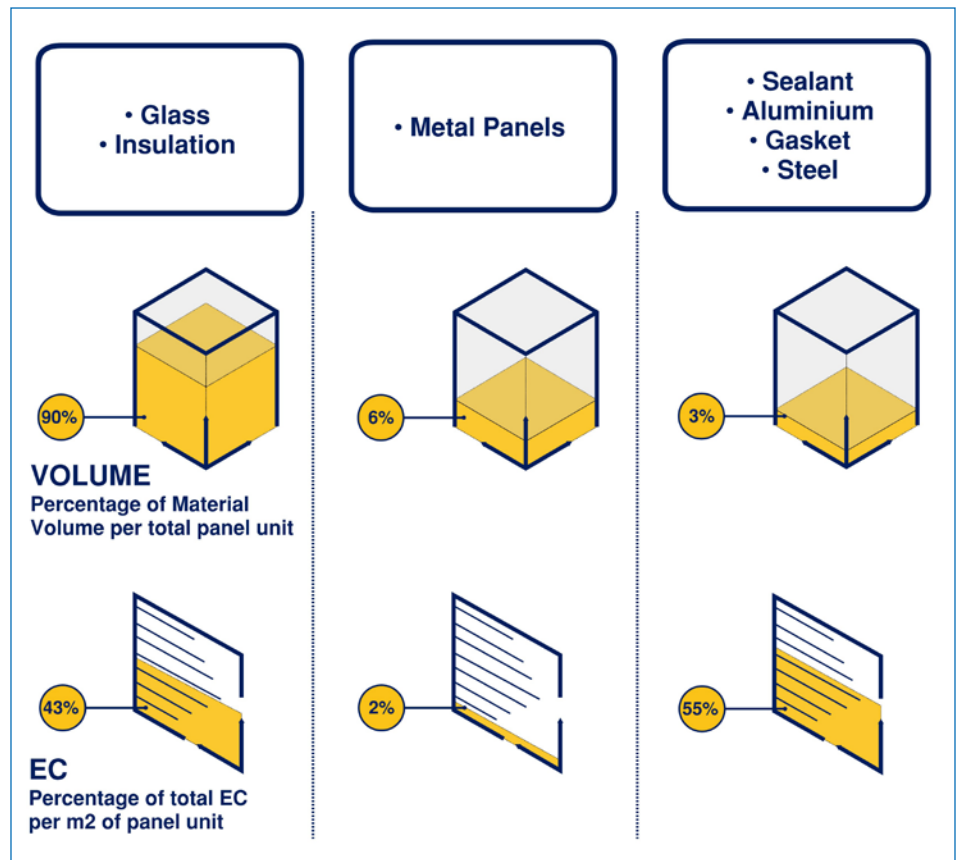


FIGURE 5. Sensitivity study of material volume to embodied carbon (EC) for Case Study 2. Material volume and kg of carbon dioxide per m² are not proportional.

work had already been completed, it was possible to gather information regarding material sources, direct transportation routes, panel weights, and transportation modes.

With the material’s pathway information for both case studies, the formula below was used for the necessary calculations:

$$A4 \text{ Emission} = \text{Material Weight} * \text{Transportation Distance (TD)} * \text{Transportation Emissions Factor (TEF)}$$

EQUATION 2. Transportation emission calculation equation.⁵

METHODOLOGY A

For case study 1, all materials were sourced within the Eastern United States, except for glass. The installers indicated that two fabricators were involved, with one being a combined manufacturer/fabricator: the site where the GFRC was manufactured to assemble the steel backup system and brick. Therefore, the calculated transportation-related EC emissions were broken into two separate modules: A2 and A4, instead of combining all results into the A4 module. The transportation emissions from each manufacturer to both the GFRC manufacturing/fabrication site and the whole panel fabrication site were calculated in A2, whereas A4 included transportation emissions from the panel fabrication site to the project site (Fig. 6). This division into two modules maintained clarity between transport emissions in the product development and construction modules as the path to site was not a consistent linear path for all materials. The transportation emissions calculation for A2 did not include any emissions that were previously calculated within the EPDs; rather, the calculated A2 results represent transportation emissions to additional product development sites.

METHODOLOGY B

In case study 2, transportation emissions were all grouped in module A4, considering the step between the manufacturer and project site in the Construction Process Stage of the LCA (Fig. 1). All materials were locally sourced and prefabricated elements. These elements were tracked in their transportation from manufacturer's site to fabrication site before finally moving to the project site, following a more linear path. The manufacturing and fabrication sites were distinctly separate, and all the emissions for materials traveling to the manufacturer were accounted in the EPDs under A2. The prefabricated mega panel units were assembled at a fabrication site instead of transporting construction ready components directly to the project site for on-site assembly. These factors drove the decision for all

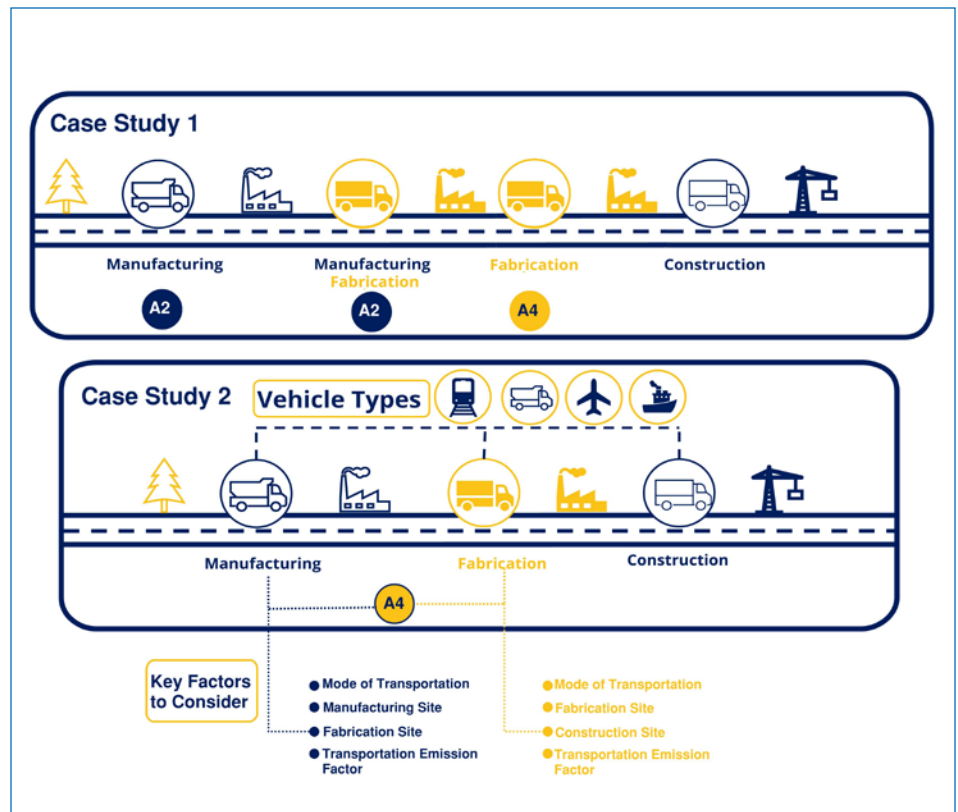


FIGURE 6. Methodologies A and B categorization for determining transportation embodied carbon emissions after manufacturing.

TABLE 5. Example of assumed mode of transportation A4 embodied carbon (EC) emissions for the curtainwall in case study 2. Reported values include TEF reported in Centre for Window and Cladding Technology (CWCT) from the Royal Institution of Chartered Surveyors (RICS)⁵

Case Study 2 Curtainwall						
		Material Type	Sealant	Glass	Aluminum	Insulation
TEF values ASHRAE 240P (draft)	A4	Components to Manufacturing				
		kgC02e/m2	0.01	9.73	1.27	0.45
	A4	Manufacturing to site				
		kgC02e/m2	0.01	2.72	0.42	0.63
Total A4 EC per m2						15.24
CWCT RICS	A4	Components to Manufacturing				
		kgC02e/m2	0.01	9.72	1.27	0.45
	A4	Manufacturing to site				
		kgC02e/m2	0.02	3.11	0.48	0.72
Total A4 EC per m2						15.78
Mixed Datasource 2023	A4	Components to Manufacturing				
		kgC02e/m2	0.01	12.09	1.58	0.56
	A4	Manufacturing to site				
		kgC02e/m2	0.02	3.38	0.52	0.79
Total A4 EC per m2						18.95

Note: Values above indicate the discrepancies between the different sources. Studies to always be completed using reputable sources—examples include RICS.⁶ It is understood that ASHRAE 240P is in its draft standard but as they are United States based values it was used as a comparative framework.

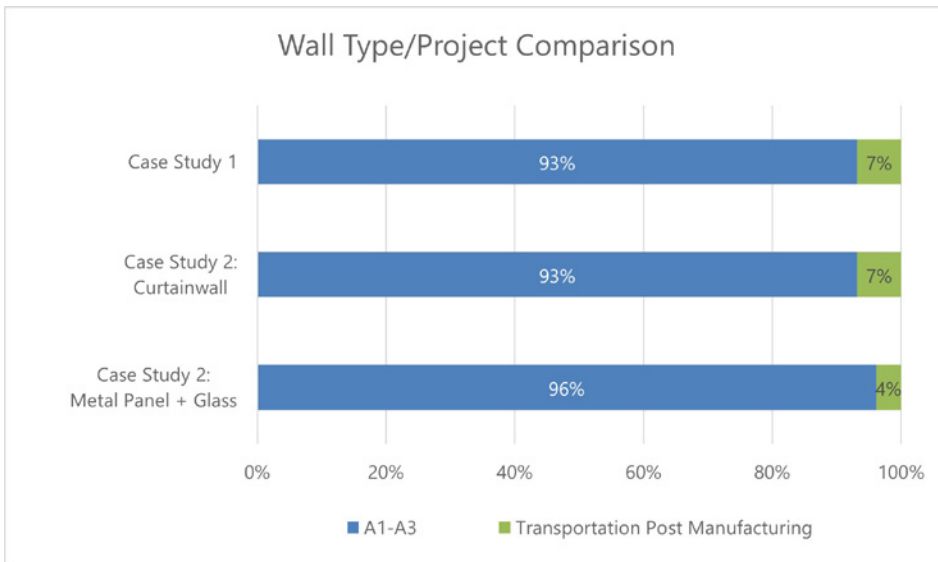


FIGURE 7. Comparison of embodied carbon during product and post-manufacturing transportation modules.

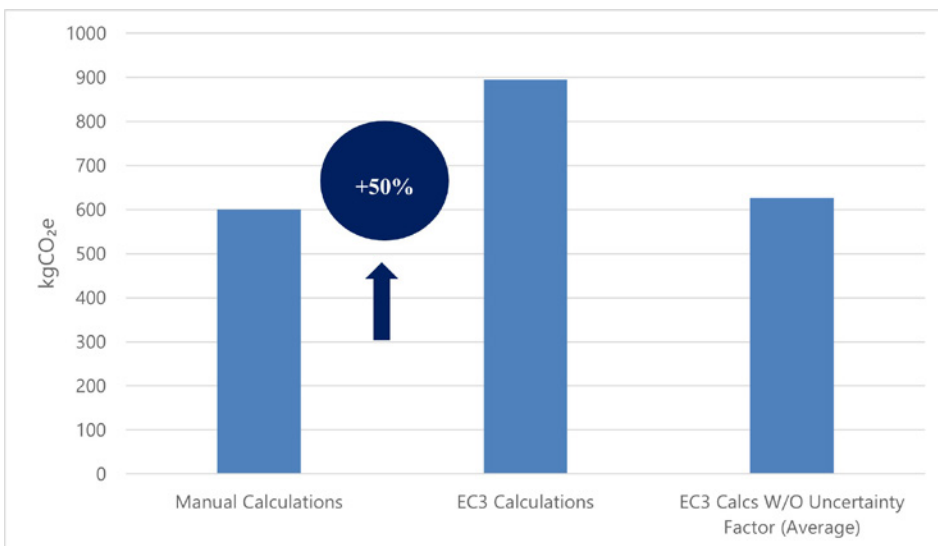


FIGURE 8. Comparison of embodied carbon results calculated manually and using EC3 software with and without an uncertainty factor applied. Note: EC3 URL - <https://www.buildingtransparency.org/tools/ec3/>.

transportation EC emissions from any components traveling to the fabrication site in addition to the travel to project site to fall under A4 (Fig. 6).

The Transportation Emission Factors (TEFs) used in the case studies were the most up-to-date values available at the time of calculation.⁵ However, as is typical with continued research development, TEF values can be updated outside of the baseline. The transportation emission results recalculated utilizing varied TEF values

decrease by about 20% (Table 5). The difference in TEF values can be attributed to vehicles becoming more efficient, datasets representing different regions, and more.

The final calculated ratio of EC for the product and transportation modules was similar in both case studies (Fig. 7). The development of typical percentages can be a part of future research; to be used to expedite future project-specific EC studies. The development of communication lines

with fabricators and installers through this retrospective process was vital, as both provided specific material and transport information. The collaborative work environment fostered accuracy and efficiency during the analysis.

MODULE A5: CONSTRUCTION AND INSTALLATION

In module A5 the methods for obtaining these construction and installation values can differ. Analysts can use online tools such as Embodied Carbon in Construction Calculator (EC3) tool, or perform manual calculations based on fuel consumption or project cost for site activity EC emissions as recognized by the Centre for Window and Cladding Technology (CWCT) in section 2.2.4 Inputs for module A5: construction/installation.⁵ Due to available information calculations based on project cost may be more prevalent for concept phases with limited accuracy. Calculations based on fuel consumption, though limited to the accessibility of quantifiable data, avoid double counting emissions of offsite prefabricated elements (e.g., counting the factory fabricated panels in A3 and then counting them again in A5 in association with project cost).

Major challenges can arise during this A5 module analysis because the industry lacks appropriate, consistent tracking systems to document energy expenditures in the work of contractors and installers. While tracking the type of fuel is possible, obtaining accurate information on fuel-use duration and machine's fuel-use intensity can be difficult, leading to inaccurate data. Therefore, it is suggested not to include EC emissions in A5 until the industry widely accepts a consistent system to accurately track emissions. This approach aligns with a benchmark recently published by the Carbon Leadership Forum in their 2025 CLF WBLCA Benchmark Study, which excluded A5.⁷

ONLINE TOOL MICROSTUDY (EC3)

A microstudy was conducted to reanalyze the results from case study 1 utilizing the EC3 tool (Fig. 8). As

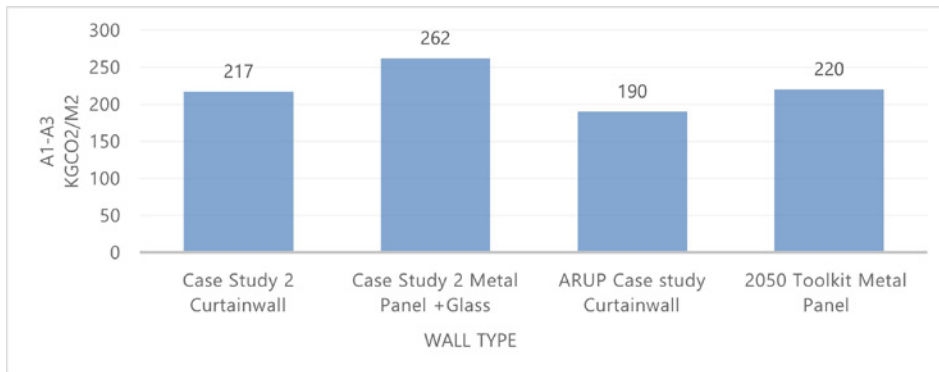


FIGURE 9. Comparison of industry baselines for embodied carbon associated with different wall types in modules A1, A2, and A3.¹⁰

published by Carbon Leadership Forum who establishes the EC categorization and assessment methods for the EC3 tool, EC3 “is a free and easy-to-use tool that allows benchmarking, assessment and reductions in EC, focused on the upfront supply chain emissions of construction materials.”⁸ The resulting EC calculated by the tool was substantially higher than that calculated manually; however, the breakdown between material types was proportional. This difference can be attributed to EC3’s calculation methodology.

EC3 establishes two boundaries for the GWP calculation: a conservative estimate representing the 80th percentile and an achievable target representing the 20th percentile. It applies uncertainty factors to each GWP representing the percent increase from its median to its 80th percentile impact value compiling multiple uncertainty groups (e.g., product, manufacturer, facility, supply chain, batch), accounting for any variabilities to represent the conservative estimate as described in the paper EC3 Uncertainty General Methodology.⁹ The use of these uncertainty factors is an important common practice, especially in early project stages, to account for variabilities within available information or differences in PCR development, with guides such as the one published by the CWCT calling it a scale up factor.⁵

To understand the impact of the uncertainty factors on EC3’s results, each factor was researched and

averaged. EC3’s results were divided by this average to reverse-engineer the calculations. The results without uncertainty factors were similar to those derived with the manual calculations. While online tools such as EC3 are useful for providing conservative values or showing preliminary differences between material choices, the available information within the database and the calculation methodology must be considered. It is suggested to use online tools as a resource in the early stages of a project when specific information is limited.

BUILDING A BASELINE

While retrospective studies are limited to existing developments, they serve as a valuable tool for building a dataset (Fig. 9). There are available baselines that compare the EC impacts of different systems, one example being Arup’s “Carbon Footprint of Façades: Significance of Glass.”¹⁰ However, these baselines are often simplified and do not account for atypical prefabrication, so retrospective studies remain essential sources of information.

Retrospective analyses can provide supplemental data utilizing tools like the LCA BHoM Toolkit to facilitate early-design studies.¹¹ The LCA Toolkit operates within the open-source Buildings and Habitats object Model (BHoM) to integrate the iterative modeling process with GWP data, allowing easy transfer of retrospective results to future early design studies.

CONCLUSION

Retrospective studies support improvements in environmental outcomes by leveraging accurate, project specific data to reduce EC in future construction projects. To correctly analyze the upfront EC in facade systems, analysts need consistent, evidence-based, and accessible carbon calculation methodologies for every stage of a building’s life cycle, including retrospective studies. The case studies underscore the importance of obtaining project-specific EPDs, having a nuanced understanding of transportation emissions, acknowledging the limitations within A5 construction data, and benchmarking contributions for future studies. Manual and software-based calculations demonstrate that both approaches have inherent limitations but can complement each other when used strategically. The development of a standardized, accessible, and transparent system for tracking EC will help building-enclosure consultants and other professionals bridge the gap between data complexity and actionable sustainability strategies, leading to better decisions for current and future EC developments.

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Failure Is Not an Option: Water Vapor and Healthcare Building Enclosures

ABSTRACT

Understanding water vapor, vapor drive, air leakage, and condensation in new and existing healthcare/humidified buildings (in northern climates) is vital to maintain building construction integrity, indoor air quality, and occupant health. This paper explores common causes of condensation and water accumulation issues specific to healthcare facilities from a technical building enclosure perspective. Common past performance issues, design considerations to alleviate those issues, and testing protocols prior to construction to validate the performance of the proposed enclosure system design will be discussed. In addition, this paper will cover upcoming energy code changes that directly impact condensation risk potential and energy code path decisions.

LEARNING OBJECTIVES

- » Identify three key factors that contribute to condensation in healthcare/humidified facilities.
- » Describe three major enclosure design considerations to help prevent condensation.
- » Reflect on examples of poor condensation control and successful mitigation strategies.
- » Discuss how current and forthcoming energy codes affect air leakage, thermal performance, and early design decision-making processes for building enclosures.

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CONDENSATION FUNDAMENTALS

Condensation is the conversion of vapor to liquid. Think of a glass of cold iced tea on a hot summer day or your bathroom mirror after a shower. For the purposes of this paper, we will explore water vapor contained in air, which has a limited moisture-holding capacity that is based on temperature. As the air temperature increases, its capacity for water vapor also increases. When air is saturated with water vapor at its maximum capacity, the relative humidity (RH) is 100%. "Relative" humidity is relative, as its value is dependent upon temperature. If 100% RH air is heated, the relative humidity decreases, therefore increasing its capacity for additional grains of moisture. If it is cooled, the excess moisture in the air condenses.

When considering the moisture content of air (that is, the number of individual grains of moisture contained by a pound of dry air) as a constant and temperature as a variable, the dew point can be calculated. The dew point is the temperature at which air of a constant moisture content reaches 100% RH and begins to condense excess moisture. Dew point can be calculated using online tools, formulas, or a psychrometric chart.

Considering an example interior winter setpoint of 70°F (21.1°C) and 20% RH, that same air would reach 100% RH at 27°F (-2.8°C). This means that any substrate that maintains a temperature at or below 27°F (-2.8°C) and is in contact with interior air will form condensation. Preventing moisture from reaching these substrates is essential.

If continuous, impermeable air and vapor barriers are not present, moisture

will migrate through the enclosure assemblies via mass air transit or absorption through permeable components. Note that there are varying degrees of material permeability, but for this discussion, we are referring to any material that allows the transfer of water vapor through its full thickness.

DRIVERS OF CONDENSATION FORMATION IN BUILDING ENCLOSURES

The risk of damage due to elevated humidity and condensation is present, to some degree, in all buildings. Some buildings are at greater risk than others, and a building's risk is largely dependent on the surrounding climate and the use of the building (that is, expected relative interior humidity).

In hot climates, condensation risk is related to hot, humid air from the exterior bypassing the air barrier (or moisture migration through permeable substrates) and condensing on cooler interior surfaces. In an extreme example, such as a controlled environment (refrigerated warehouse) building in Florida, the air and vapor barrier is typically placed at the far exterior side of the enclosure to allow all structure and insulation to be placed inboard, therefore preventing exterior air, which would almost always be warmer and more humid, from entering the enclosure. In Klein & Hoffman's experience, even a 1/4 in. (6 mm) hole in the air barrier of a controlled environment building can result in a block of ice on the interior the size of a small car.

In cold climates, we encounter the same behavior, with the only difference being that the heat and humidity is elevated

on the interior. The design response to this is to place the air and vapor barrier inboard of the thermal control layer. Another extreme example would be a natatorium in Alaska. In this example, the design challenge would be to provide an enclosure that accommodates a continuous air and vapor barrier that can consistently stay above the dew point.

For all climates and building types between the examples noted above, we rely on climate information from sources such as the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), building usage information provided by the building owner or mechanical engineer, and computer modeling to assess the risk of condensation in building enclosures.

Any level of condensation in building enclosures that results in damage to a substrate constitutes a failure. If the presence of moisture due to condensation remains on organic surfaces for too long, this failure may be compounded by organic growth. These failures stem from either faulty design or installation and are always due to improper placement of one of the four control layers (air, water, vapor, or thermal), or a discontinuity in one or more of these control layers. Note that a discontinuity of a control layer could represent either a physical gap or an insufficient property, such as permeability or *R*-value.

When designing, careful thought must be given to maintaining continuous control layers as necessary to resist moisture transport to substrates that cannot maintain temperatures above the dew point. Ample detailing must be included to clearly define each control layer, especially at enclosure system transitions.



FIGURE 1. Frost buildup on the interior face of precast concrete.

When specifying systems, components, and materials, the same consideration must be carried through when determining attributes such as vapor permeability, adhesion, and durability.

When installing, it is of paramount importance that the installer understand the function of each part and piece contributing to the control layers and how they relate and transition to adjacent systems.

CONSEQUENCES OF POOR CONDENSATION CONTROL IN HEALTHCARE FACILITIES

Healthcare facilities are required to operate with elevated humidification, typically offering a minimum humidification of around 30% RH in patient rooms for the health and comfort of the occupants. In other spaces, such as intensive care units, neonatal intensive care units, or surgery rooms, the interior humidification may exceed 50% RH. This elevated minimum humidification assists in the recovery of patients with respiratory illnesses and helps to reduce transmission of diseases.

However, this elevated minimum humidification results in design challenges for facilities located in cold climates. The elevated minimum humidification results in condensation that forms at a higher temperature, which means that enclosure components are more susceptible to damage at an increased number of days per year if the control layers are not designed and installed properly. The long-term exposure to elevated humidity and/or the formation of condensation within the

enclosure system (inboard of the water control layer) can result in corrosion of structural components. Water damage to substrates such as wood and gypsum board is also likely as the condensate begins to drip. Additionally, if the substrate is below freezing, the condensation may turn to frost (**Fig. 1**), which can build up over time. Once the substrate temperature rises, the frost that built up inside the enclosure is susceptible to quickly melting, often resulting in symptoms that resemble heavy leakage from the exterior. Think of defrosting an old freezer.

The risk of organic growth, associated with elevated moisture within the enclosure is especially concerning in healthcare facilities (**Fig. 2**). Considering the havoc this organic growth can wreak on healthy human bodies when aerosolized, this effect is amplified on patients who already suffer from other ailments. Complications due to mold encountered during a hospital stay could mean the difference between life and death for many patients. According to the Centers for Disease Control and Prevention (CDC), “mold outbreaks can occur in healthcare facilities causing severe illness and death among patients. Two common types of healthcare-associated invasive mold infections include mucormycosis and aspergillosis. Depending on the organism and patient characteristics, death rates can be more than 50%.”¹

According to data from the US Fire Administration (a division of the Federal Emergency Management Agency), an average of approximately five people are

killed in institutional building use fires each year, out of a total of approximately 3,000 people killed in building fires per year.² Note that institutional buildings also include prisons, assisted-living facilities, and group homes. The CDC has estimated that at least 7,000 US citizens die each year due to fungal/mold infections, with more than 75,000 hospitalizations.³ Based upon this documented risk factor, the same amount of consideration should be given to moisture control in the enclosure as is given to fire prevention in buildings.

DESIGN CONSIDERATIONS TO MITIGATE CONDENSATION FORMATION WITHIN THE ENCLOSURE

Effective condensation control begins with a clear understanding of the project’s climate, interior use, and the required temperature and humidity setpoints. Good enclosure design avoids common pitfalls like thermal bridging and discontinuities in control layers, especially at system transitions.

A helpful design tool is the “pencil test”—tracing each control layer through a detail without lifting the pencil—to verify continuity. However, designers must also consider out-of-plane transitions (for example, splices or terminations) and address material compatibility and long-term durability to ensure performance across all conditions.

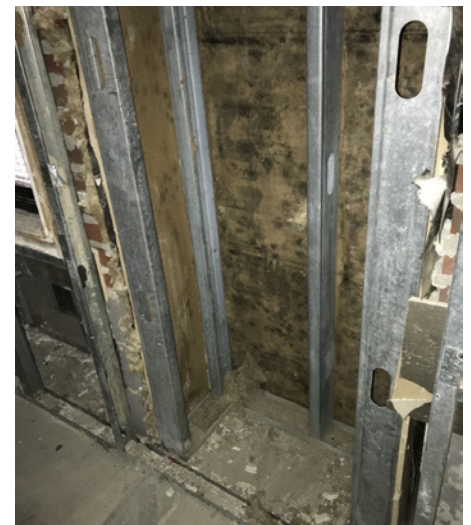


FIGURE 2. Organic growth at the interior face of the exterior sheathing within a neonatal intensive care unit space.

INVESTIGATION STRATEGIES FOR EXISTING BUILDINGS AND EXAMPLES OF POOR CONDENSATION CONTROL

Performing an initial visual review while utilizing a few rules of thumb is generally a good place to start an investigation. This will set the basis for the investigation and inform what additional investigation techniques may be prudent for each scenario.

Review the construction documents and the physical area for other visible factors, such as moisture or frost buildup, potential organic growth, a visible lack of air/vapor barriers, or even thick window coverings that are tight to the window opening, which may prevent interior air from warming the underlying window surfaces.

Thermography may be utilized to review the area for potential thermal bridging. Results from this effort are typically more conclusive on days that are nearest to the exterior design temperature. However, as thermal transfer is generally a linear relationship, thermal imaging results can often be interpolated (for illustration purposes) to determine the approximate interior surface temperature at the exterior design temperature. If the anatomy of the exterior enclosure is known, thermal modeling software such as THERM can also be utilized as an illustration tool to indicate areas of potential thermal bridging.⁴

Temperature and humidity dataloggers are useful tools for measuring ambient air within different locations, such as inside the wall, on the windowsill (Fig. 3), within an affected room, within a non-affected room, within the interstitial space, at the exterior, etc. These devices, paired with surface temperature thermocouples, placed at areas of suspected or known condensation development, will provide a detailed account of the hygrothermal profile of each area within an investigation (Fig. 4).

Confirm heating, ventilating, and air-conditioning (HVAC) system operation is within the intended parameters established when the building was constructed, as it relates to the enclosure design. We often observe that condensation within the enclosure is



FIGURE 3. Temperature and humidity datalogger on a windowsill.

a result of the HVAC system operating outside the original parameters set for the building or the building automation system's humidity sensors having drifted out of calibration.

SUCCESSFUL MITIGATION STRATEGIES FOR EXISTING BUILDINGS

Mitigation strategies range widely but generally consist of either eliminating thermal bridges, adding (or subtracting) insulation, ensuring control layer continuity at transitions, adding heating devices, or adjusting the interior temperature and humidification setpoints.

The elimination of thermal bridges often requires the replacement of enclosure components, such as glazing system components or anchorage. If adding or subtracting insulation, care should be taken to confirm associated thermal and hygrothermal modeling. Note that the ideal location of air and vapor control layers may shift based on the location of the thermal control layer, and this displacement should be considered and accommodated.

When weighing options to add heat to the enclosure, note that there are both active and passive strategies. A passive approach could include adding a heat sink to the interior surfaces (Fig. 5). Note that this passive approach does reduce the thermal efficiency of the enclosure and should be closely reviewed for compliance with the energy code. The active approach to adding heat to the enclosure includes installing heat trace elements where needed. This method is often effective but requires design assistance from an electrical engineer, needs replacement over time, and uses energy.



FIGURE 4. Thermocouple datalogger leads at the surfaces of an insulated glass unit and mullions.



FIGURE 5. Testing of added heat sinks at a four-way glazing system intersection.

ENERGY CODE CHANGES THAT AFFECT YOUR PROJECT

As the energy codes head towards net zero, condensation prevention becomes more difficult. The three main items in the latest energy codes that directly impact the condensation potential of your project are continuous air barrier, thermal bridging, and envelope backstop. Note that the code iteration in effect for your project is dependent on your state or municipality, and the current energy codes, as they become adopted, may have a very significant impact on the enclosure design.

Continuous air barriers have been a requirement of the energy codes for multiple cycles, but the latest energy codes (the 2024 *International Energy Conservation Code* [IECC] and ASHRAE 90.1-2022) have been updated to provide even more specific requirements. The updates aim to assure that a continuous air barrier is not only designed and detailed properly but also installed as designed. In addition to more robust documentation requirements, the 2024 IECC clarified language that requires most new projects to perform whole-building air barrier testing. ASHRAE 90.1-2022 still allows the choice between whole-building air barrier testing and a design and installation verification program.^{5,6} There is a significant difference between the two, which should be taken into account when the project team is deciding on the appropriate energy code compliance path at the beginning of a project. For example, whole-building air barrier testing may be appropriate for a small, stand-alone retail building. In this case, testing could occur before the cladding is installed, allowing the air barrier to be accessed if any deficiencies are discovered. In contrast, a large hospital would likely benefit more from a design and installation verification program, as

testing would be logistically difficult and large-scale repairs would be infeasible.

Both the 2024 IECC and ASHRAE 90.1-2022, for the first time, include prescriptive thermal bridging requirements or a calculation method with limits addressing balconies, floor intersections, cladding support, parapets, vertical fenestration, and structural elements.^{5,6}

The aim of the energy codes is to reduce the number of thermal bridges within a building and ensure that significant thermal bridges are adequately accounted for when using energy modeling for performance-based compliance.

The days of your typical multifamily high-rise with window-wall glazing and exposed concrete slab edges or balconies are over.

It must be noted that the energy code's treatment of thermal bridging is driven by the energy transfer, heat loss or gain, through the thermal bridges and does not directly address condensation risk. For example, the prescriptive vertical fenestration section limits the alignment of the wall insulation with the plane of the exterior face of glass. This follows the general design rule that the fenestration thermal break should be in line with the wall insulation. However,

it does not dictate the actual detailing, which may require THERM simulation to evaluate condensation potential.

ASHRAE 90.1-2022 introduces an envelope backstop that limits how much envelope performance can be traded off against HVAC and lighting in performance-based energy modeling.^{5,6} Previously, envelope components could underperform as long as the building's overall energy model exceeded baseline performance, often relying on high-efficiency systems to compensate. However, because the envelope lasts the life of the building—unlike replaceable HVAC and lighting—this approach creates long-term inefficiencies. To address this, the 2022 update limits envelope trade-offs to 15% over the base envelope performance factor for multifamily, hotel/motel, and dormitory buildings and 7% for all other types. This change limits the use of low-performance systems like curtainwalls, pushing designers toward designs utilizing a mix of different cladding systems. More transitions between material systems increase the risk of condensation and bulk water intrusion if not properly detailed. As this is specific to ASHRAE 90.1-2022, it is important to consider during early energy code path decisions.

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Drainage Efficiencies of Fiber Cement Panels

ABSTRACT

Building codes now prescribe minimum drainage spaces for distinct cladding types. The intent is to facilitate efficient release of water that has penetrated beyond the cladding. Compliance can also be achieved with drainage efficiencies that are proven through testing in accordance with ASTM E2273, Standard Test Method for Determining the Drainage Efficiency of Exterior Insulation and Finish Systems (EIFS) Clad Wall Assemblies. One prevailing assumption is that gap size and drainage efficiency are inexorably linked. However, this notion is challenged by the advent of drainage wraps and other products offering smaller yet efficient drainage spaces. This paper examines drainage efficiencies of full-scale test walls configured with fiber cement panels and gap depths of 10 mm or 1.5 mm. Key considerations, including variances in water application rates and the effects of moisture absorption at drainage interfaces, are discussed. The fate of residual water within the drainage space is further explored with hygrothermal simulations for multiple North American climates.

LEARNING OBJECTIVES

- » Discuss methods, criteria, and limitations of ASTM E2273.
- » Define the relationships between drainage gap size, drainage efficiency, water absorption, and water application rates.
- » Describe key factors that influence drainage efficiencies in standardized testing and real-world conditions.
- » Interpret the need for optimized gap size based on climate and proposed wall type.

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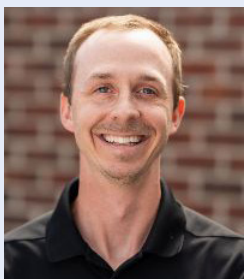
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FIGURE 1. Material degradation due to cladding leaks and poor drainage.

Drainage is a fundamental requirement for proper moisture management of non-barrier wall assemblies. The need for drainage stems all cladding systems leak, whether by design, defect, or the natural weathering of enclosure components. The purpose of drainage is to reduce moisture storage loads, which must be otherwise addressed by much slower processes such as diffusion, capillarity, or evaporation. When the assembly does not drain effectively, moisture may exceed the assembly's storage capacity, leading to degradation and a shortened service life (**Fig. 1**).

A traditional view is that water migrating beyond the cladding is managed by one or more drainage planes, gravity, and a means for unobstructed water egress. In this simplified model, the primary drainage plane is served by building papers or water-resistive barriers (WRBs). The notion of free drainage implies that water flows without impediment in response to gravity alone. This does not occur when cladding is interfaced tightly against the drainage plane.^{1,2} Some form of interstitial space is therefore necessary; however, there is little agreement on the minimum size and configuration of drainage spaces. Furthermore, current methods for evaluating the benefits of drainage focus largely on drainage efficiency—the ratio of water expelled from the system to the total amount of water applied. The fates and effects of undrained water are rarely considered and poorly understood.

DRAINAGE SPACE

A drainage space is often referred to as a capillary break, a layer of air that serves to decouple cladding materials from the primary drainage plane. To achieve a perfect decoupling and free drainage, the air space must be sized to prevent water from spanning the gap. Historically, a gap size of 3 mm (1/8 in.)

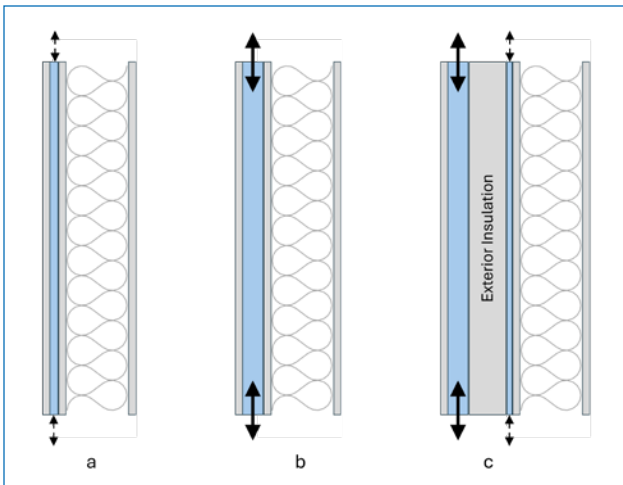


FIGURE 2. (a) Conventional drainage wall; (b) ventilated rain-screen wall; and (c) insulated rain-screen wall.

reflected the limits for capillary suction. Drainage spaces greater than 6 mm ($\frac{1}{4}$ in.) exceed water's ability to bridge the gap due to the interplay between surface tension and gravity. Accounting for dimensional tolerances achieves what is arguably the most widely cited minimum space, 10 mm ($\frac{3}{8}$ in.).³

Air gaps smaller than 3 mm ($\frac{1}{8}$ in.), or those otherwise occluded and discontinuous, create constrained or even tortuous paths that are resistant to free drainage. Such spaces rely on head pressure to achieve a desired downward flow. Along these constrained or blocked occluded paths, water may pool or it may be potentially absorbed by building materials, increasing the likelihood of detrimental effects.

Despite seemingly sound rationales for large capillary breaks, research has demonstrated effective drainage can be achieved with much smaller spaces. For example, a study by Straube and Smegal showed that gaps that are less than 1 mm (0.04 in.) may drain even when the space is discontinuous or ill defined, such as interfaces formed between two layers of building paper.⁴ The same study demonstrated that gaps ranging from 1 to 9 mm (0.04 to 0.35 in.) offer ample drainage for various cladding types. Results such as these show that a perfect decoupling of the cladding and drainage plane is not necessary. Within the context of modern drainage testing, small spaces work because water within them is pushed by head pressure from

drainage walls have all the components of a rainscreen wall, including cladding, an air space, a drainage plane, and means for water egress. In essence, a drainage wall is a type of rainscreen with limited or negligible ventilation. Drainage walls also lack the ability to appreciably moderate pressure differences, especially when configured with constrained spaces (<3 mm [$\frac{1}{8}$ in.]

Ventilation within drainage walls relies largely on natural convection or the buoyancy effect. To some extent, air is also exchanged with the exterior environment as air leakage occurs whether by intent or at imperfections in assembly construction. Ventilation rates for unvented drainage cavities typically range from 1 to 5 air changes per hour (ACH).⁵ Ventilation increases as drainage spaces become larger and are coupled with exterior air via intentional vent openings. Vented rainscreens provide ventilation rates ranging from 10 to 50 ACH, whereas ventilated rainscreens are designed to vent at rates of 100 to more than 1000 ACH.⁵⁻⁸

Differences between drainage walls and rainscreens become more obscured when walls are configured with exterior insulation. By placing an insulation layer over the WRB, an interface is formed that necessitates drainage. Thus, a drainage space and a rainscreen space may coexist within the same assembly. A vented or ventilated space typically occurs outboard of the insulation, and a primary drainage space is formed

above while being pulled by gravity from below.

DRAINAGE WALLS VERSUS RAINSCREENS

Drainage walls and rainscreens are multicomponent enclosures that share the function of removing water that enters beyond the cladding. The former does so with drainage, and the latter incorporates both drainage and appreciably greater ventilation. Most

behind the insulation. The principles discussed herein are therefore applicable to conventional drainage walls as well as insulated rainscreens (Fig. 2).

BUILDING CODE REQUIREMENTS

Drainage requirements for exterior cladding first appeared in the 2006 editions of the International Residential Code (IRC), in Section 703.1, and the International Building Code (IBC) in Section 1403.2.^{9,10} These early mandates did not specify the means for drainage nor the performance criteria necessary to fulfill the requirements. Model building codes have since refined the drainage requirements for distinct cladding types. For example, the 2009 edition of the IBC included prescriptive drainage requirements for exterior insulation and finish systems (EIFS), as follows:¹¹

EIFS with drainage shall have an average minimum drainage efficiency of 90% when tested in accordance with the requirements of ASTM E2273 and is required on framed walls of Type V construction, Group R1, R2, R3 & R4 occupancies.

Similarly, in 2021, the IBC included specific drainage requirements for stucco based on sheathing type and climate zone.¹²

In Moist (A) or Marine (C) climate zones, water-resistive barrier shall comply with one of the following:

1. *In addition to complying with Item 1 or 2 of Section 2510.6.1, a space or drainage material not less than 3/16 inch [4.76 mm] in depth shall be applied to the exterior side of the water-resistive barrier.*
2. *In addition to complying with Item 2 of Section 2510.6.1, drainage on the exterior side of the water-resistive barrier shall have a minimum drainage efficiency of 90% as measured in accordance with ASTM E2273 or Annex A2 of ASTM E2925.*

The 2021 edition of the IRC included language that is essentially identical to that contained in the 2021 IBC.¹³ These requirements remained unchanged for 2024. It should be noted that both IBC and IRC have options for drainage compliance based on

drainage efficiency, not gap size per se. Furthermore, neither of these model codes addresses ventilation criteria for the drainage space.

Several North American jurisdictions stipulate specific dimensions for drainage spaces. For example, the National Building Code of Canada requires a 10 mm ($\frac{3}{8}$ in.) capillary break behind cladding materials.¹⁴ Exception is granted if omission of the gap does not adversely affect the performance of the wall assembly. The 10 mm gap is further prescribed as being vented, but there are no criteria for specific ventilation rates or drainage efficiencies.

Jurisdictions also may accept alternative materials that offer minimum drainage but do not necessarily meet the code-prescribed gap dimensions. Since 2014, the Oregon residential code has required a $\frac{1}{8}$ in. (3 mm) drainage space between exterior veneer and the WRB.¹⁵ This requirement is waived for WRB products that meet a minimum 75% drainage efficiency when tested in accordance with ASTM E2273.

ASTM E2273

Standard testing of drainage efficiency is performed in accordance with ASTM E2273, Standard Test Method for Determining the Drainage Efficiency of Exterior Insulation and Finish Systems (EIFS) Clad Wall Assemblies.¹⁶ First published in 2003, this standard was originally devised to assess drainage efficiencies of EIFS with drainage. ASTM E2273 has since been adopted as the standard means for evaluating a wide array of drainage systems, including drainage wraps. Other drainage materials such as entangled meshes, formed/textured sheets, and formed battens are evaluated according to Annex A2 of ASTM E2925; the annex methods are substantively identical to those described by ASTM E2273.¹⁷

The ASTM E2273 test method introduces water into a slot fault positioned at the upper portion of a prescribed 4 ft x 8 ft test assembly. Water is applied by means of two calibrated nozzles at a rate of 106 g/min (0.106 L/min [0.23 lb/min; 3.6 fl. oz/min]) over the course of five 15-minute spray intervals. At each interval, water is collected at the base of

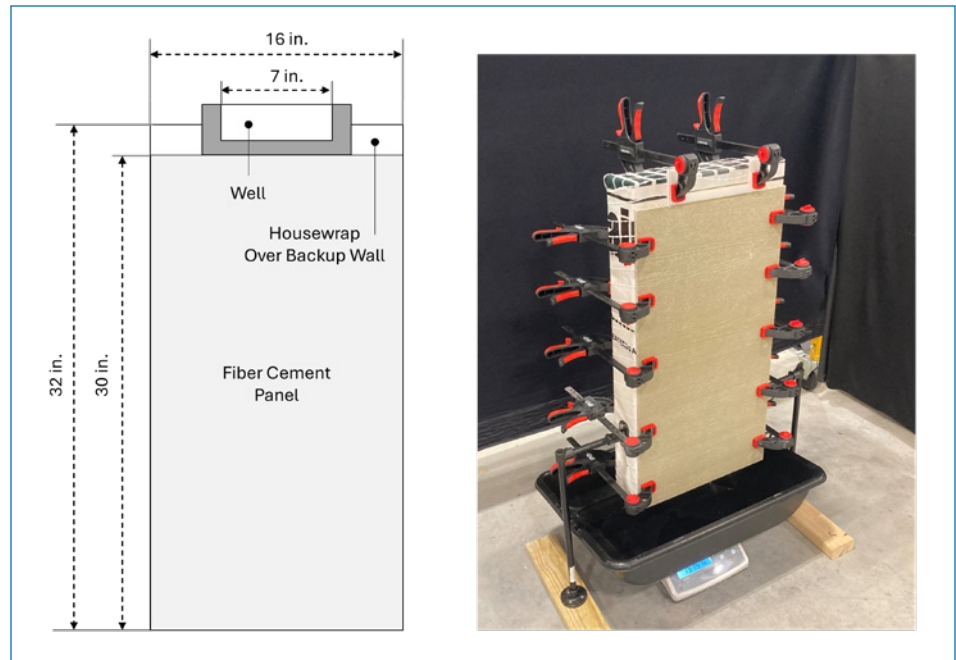


FIGURE 3. Benchtop drainage assembly. *Note: 1 in. = 25.4 mm.*

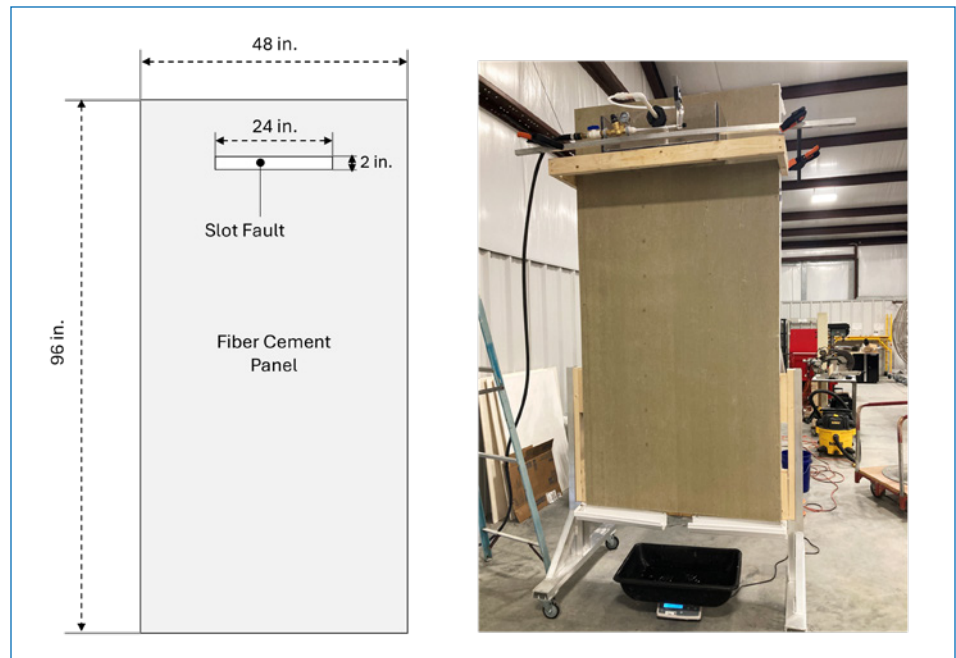


FIGURE 4. Full-scale drainage assembly. *Note: 1 in. = 25.4 mm.*

the test assembly and weighed. Water collection is continued for 60 minutes following the completed 75-minute application. Efficiency is reported as a percentage based on the ratio of drained water to the total water applied.

STUDY DESIGN

The study reported herein had three primary objectives. The first was to compare drainage efficiencies of walls

clad with fiber cement panels having 1.5- or 10-mm (0.06 or 0.375 [$\frac{3}{8}$] in.) capillary breaks. Drainage testing incorporated benchtop and full-scale assemblies evaluated in accordance with ASTM E2273. We chose medium-density fiber cement panels based on their simple planar interface, potential for water absorption, and common use in residential and commercial construction. Selected gap sizes represent typical reliefs of drainage wraps (1.5 mm) and

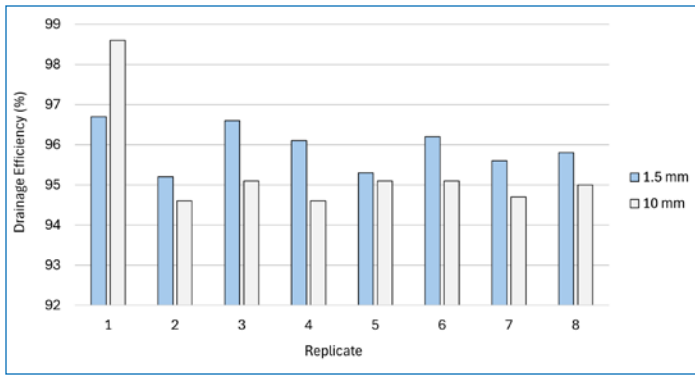


FIGURE 5. Drainage efficiencies of benchtop assemblies. Note: 1 mm = 0.039 in.

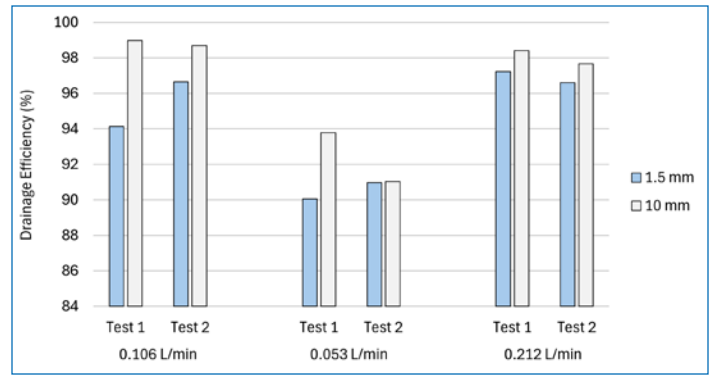


FIGURE 6. Drainage efficiencies of full-scale assemblies. Note: 1 mm = 0.039 in.

conventional practices involving larger drainage spaces (10 mm).

Our second aim was to evaluate potential water absorption by fiber cement panels that interface with drainage spaces. Here, we relied on two approaches, including static ponding and gravimetric measurements of panels used in our benchtop studies.

Lastly, we sought to compare wetting and drying potentials of fiber cement panels configured with the same gap sizes used in our drainage studies. These analyses used one-dimensional hygrothermal simulations for the purpose of determining the effects of climate and gap size on overall wall performance.

DRAINAGE EFFICIENCIES

Test assemblies used in this study are illustrated in **Fig. 3** and **4**. Both assembly types were factory-primed 5/16-in. (7.9-mm) fiber cement panels installed over code-accepted WRBs, 3/4 in. (19 mm) oriented strand board (OSB) sheathing, and 2 in. x 4 in. (51 x 102 mm) wood framing. Selected drainage spaces of 1.5 and 10 mm (0.06 or 0.375 [3/8] in.) were achieved with either a commercially available drainage wrap or 10 mm vertically applied high-density polyethylene (HDPE) battens. For benchtop testing, cladding was clamped to the backup wall to facilitate removal and weighing of cladding panels. Full-scale assemblies employed cladding fastened in accordance with the manufacturer’s installation instructions.

The benchtop apparatus was scaled to one-eighth of the standard test

assembly. Water application rates were also reduced accordingly to approximately 0.014 L/min (38 fl. oz/min). Three different flow rates were employed for full-scale testing, including the standard rate of 0.106 L/min (3.6 fl. oz/min), 0.053 L/min (1.8 fl. oz/min; 50% decrease), and 0.212 L/min (7.2 fl. oz/min; 100% increase). Small-scale testing involved 8 test replicates for each drainage gap and the single-flow condition, for a total of 16 tests. Full-scale testing employed 2 replicates for each drainage space and each flow rate, for a total of 12 tests.

Drainage efficiencies for the eight benchtop replicates are summarized in **Fig. 5**. No significant differences were observed for the two gap conditions, which yielded efficiencies ranging from 95% to 98%. Mean drainage efficiencies for the 1.5-mm and 10-mm (0.06 and 0.375 [3/8] in.) gaps were 95.9% and 95.4%, respectively. Approximately 23 to 77 g (0.8 to 2.7 oz) of water remained within the test assemblies either as water adhered to drainage surfaces or as water absorbed by the fiber cement panels.

Full-scale testing employing standard flow conditions revealed drainage efficiencies that were unchanged from those determined by our benchtop studies (i.e., 95%–98%). In **Fig. 6**, we report drainage efficiencies for each replicate and corresponding water application rate. Both gap conditions met the minimum 90% drainage criteria set by ASTM E2273 for all three flow conditions. In most instances, the 10-mm (3/8-in.) battens offered only minor improvement over the 1.5-mm (0.06-in.) drainage wrap.

Our results further show that flow rates and corresponding head pressures play important roles in wall drainage. For example, drainage efficiency was reduced to approximately 91% when water application rates were decreased by half; this finding was due largely to reduced head pressures. Any further reduction would likely result in test failures, especially for smaller gaps. When the application rate was doubled, drainage efficiencies remained unchanged from those determined under standard flows. We therefore expect that a further increase in flow will result in little or no difference as efficiency approximates 100%. This finding supports the premise that current standards favor displacement (i.e., head pressure) over the dynamics of space, surface tension, and gravity (i.e., free drainage). As flow rates increase, the effects of displacement are more pronounced. Conversely, the quotient of stored water is diminished.

Lower drainage efficiencies resulting from reduced flow rates are consistent with findings obtained from our prior unpublished work. When application rates for 1.5-mm (0.06-in.) gaps were reduced from 0.106 to 0.01 L/min (3.6 to 0.34 fl. oz/min), drainage efficiencies decreased to approximately 63% to 84%. Based on these earlier findings and the results presented herein, we conclude that lower flow rates are more challenging and are therefore less likely to meet standard drainage criteria. The application rate employed by ASTM E2273 most likely reflects the near-minimum displacement necessary to reliably achieve 90% efficiency, regardless of gap size.

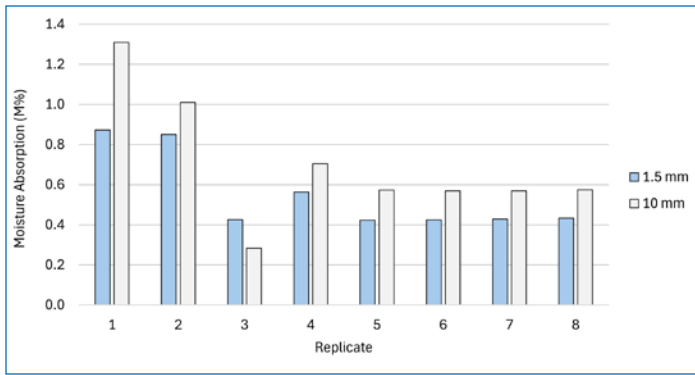


FIGURE 7. Water absorption by fiber cement panels. Note: 1 mm = 0.0394 in.

Reduced application rates are also more indicative of real-world conditions.

For example, Boardman and Glass demonstrated infiltration rates of 0 to 0.028 L/min (0 to 946.8 fl. oz/min.) for vinyl siding under pressure differentials ranging from 17 to 48 Pa (0.002 to 0.007 psi).¹⁸ Even lower infiltration rates have been shown for EIFS installed with intentional cracks (0.007–0.008 L/min at 0 Pa [0.24–0.27 fl. oz/min at 0 psi]).¹⁹ Curtainwalls exhibit infiltration rates of 0.05 to 0.07 L/min at 0 Pa (1.7 to 2.7 fl. oz/min at 0 psi) and 0.069 to 0.077 L/min at 600 Pa (2.33 to 2.6 fl. oz/min at 0.09 psi).²⁰ Under low pressure differentials, the only conditions that exceed 0.106 L/min (3.6 fl. oz/min) are those associated with extreme fault conditions, open-jointed claddings, or absorptive claddings such as stucco and brick.²¹

WATER ABSORPTION

These findings, as well as those of others, show that 100% drainage efficiency is not possible as some quantity of water is always stored within the system.^{1,4} Unreleased water remains as films or droplets adhered to drainage surfaces. Water is also absorbed by interfacing materials. In these evaluations, the WRBs and HDPE battens were not absorptive, leaving only the fiber cement cladding as the sole absorptive material.

Benchtop studies showed that approximately 5% of the applied water was stored within test assemblies, equating to 53 g (1.9 oz) or 171 g/m² (5 oz/yd²). Of the undrained portions, 18% to 85% (10–45 g [0.4–1.6 oz]) was

absorbed by fiber cement panels, representing 0.28% to 1.32% on a panel weight basis. A more conservative estimate was obtained with static ponding tests, which demonstrated 2% water absorption over 2.5 hours—the period corresponding to drainage testing and the associated 60-minute post-flow collection.

Panels installed over the drainage wrap absorbed less water than panels installed over the 10-mm (³/₈-in.) battens (Fig. 7). This outcome was unexpected due to tighter interfaces associated with the 1.5-mm (0.06-in.) gap. We attribute this discrepancy to differences in drainage patterns as well as selective water absorption at untreated panel edges. For the 10-mm gaps, the applied water flowed freely across a limited surface area corresponding to the width of the application well. As a result, there were continuous exposures near the center of each test panel. In contrast, the drainage wrap dispersed water into smaller, discrete streams; thus, panel surfaces were less prone to repeated or continuous exposure.

Untreated cut edges of benchtop panels also served as routes for water absorption. For tests involving 10-mm (³/₈-in.) battens, water application wells were slightly offset outward, increasing edge exposure and hastening water absorption. Considering these findings, cut edges in full-scale assemblies were primed to comply with the manufacturer’s installation instructions.

Fastener penetrations in full-scale assemblies served as another route for localized water absorption. This condition was particularly apparent for walls configured with the drainage wrap where water bridged the gap at fastener shanks (Fig. 8). In contrast, fasteners applied through the 10-mm (³/₈-in.) gaps also penetrated the HDPE battens and were therefore partially sealed.

HYGROTHERMAL ANALYSES

The efficacy of drainage, in terms of overall wall performance, is best gauged not by the amount of water forced into an orifice and subsequently expelled but rather by the fate of water that is left undrained. The assumption that a 10-mm (³/₈-in.) space is inherently superior to a 1.5-mm (0.06-in.) space is invalid; in fact, the same amount of water is stored regardless of gap size. Likewise, the belief that a 10-mm space is better vented is also flawed; venting is substantively improved only when the assembly is designed and constructed to do so—a condition not required by building codes.

To further test the efficacy of gap size, we performed one-dimensional hygrothermal modeling to simulate wetting and drying within drainage gaps. Although this type of modeling does not directly evaluate the dynamics of water drainage, it does assess the effects of moisture infiltration behind the cladding as fractions of wind-driven rain. In this manner, the infiltration loads simulate water applied into the slot fault of a standard drainage test. The influence of gap size and assumed ventilation rates can be assessed in relation to climate and building orientation.

We used the computer software model WUFI® Pro 7.0 to perform 5-year simulations for 15 climate locations.



FIGURE 8. Water absorption at fastener penetrations.

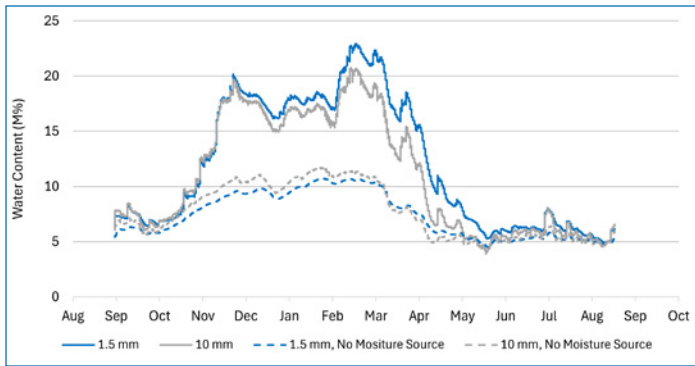


FIGURE 9. Water content of fiber cement panels for a typical simulated year in Vancouver, British Columbia. *Note:* 1 mm = 0.0394 in.

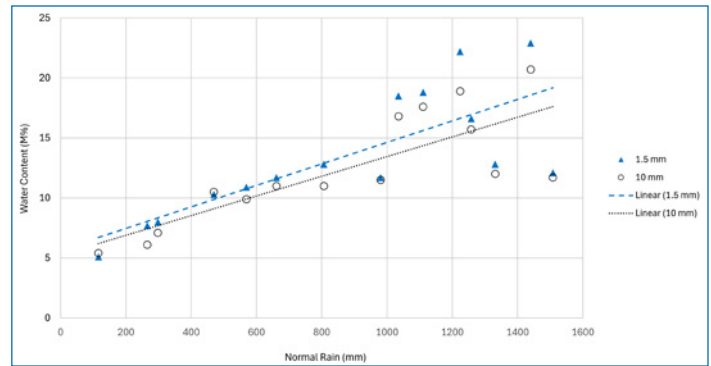


FIGURE 10. Peak water content of fiber cement panels. *Note:* 1 mm = 0.0394 in.

Analyses assumed a low-rise building with a framed wall enclosure configured with 5/16 in. (7.9 mm) fiber cement cladding, 1.5- or 10-mm (0.06 or 0.375 [3/8] in.) air gaps, polyolefin house wrap, and 1/2-in. (12.7-mm) plywood sheathing. The remaining wall assembly included 5 1/2-in. (139.7-mm) batt-filled stud cavities and 1/2-in. interior gypsum. An interior vapor retarder was incorporated where appropriate for a given climate.

Boundary conditions were assigned the default surface transfer coefficient for interior air films; whereas wind-dependence was selected for exterior surfaces. Absorptivity was designated as 0.6 without radiative overcooling. Additional diffusion resistance was modeled as latex paint applied to exterior and interior boundaries.

Rain loading was calculated according to ASHRAE Standard 160, *Criteria for Moisture-Control Design Analysis in Buildings*, using the building height option of <10 m (32.8 ft).²² Building orientation was varied based on climate location and prevailing wind directions, with the intent of demonstrating worst-case scenarios for wind-driven rain loads. Corresponding exposure and deposition factors were 1.0 and 0.5, respectively.

In accordance with ASHRAE 160, assumed moisture infiltration within the drainage space was simulated with a total wind-driven fraction of 1%. This fraction was further segregated into two equal portions (0.5%) applied to the WRB and interfacing fiber

cement. This approach accounts for the fact that water is deposited onto both surfaces—a condition demonstrated by drainage testing for both gap sizes. Free water saturation was selected as the source term cutoff, relegating unreleased moisture to assumed drainage. Ventilation rates for the 1.5- and 10-mm (0.06 and 0.375 [3/8] in.) air gaps were 1 ACH and 20 ACH, respectively. The chosen air change rates reflect the model's lower limit for cavity walls (1 ACH) and the upper limit for vented spaces (20 ACH). The rate of ventilation for the 10-mm gap represents a generous assumption, as assemblies built to code generally lack the necessary vent openings to achieve this rate.

Interior climates were modeled as simplified sinusoidal curves with temperature variances of 20°C to 22°C (36°F to 39.6°F) and 40% to 60% relative humidity. Exterior climates were modeled as ASHRAE Year 3. It should be noted that key materials, including the cladding and plywood sheathing, were partitioned as two layers to better resolve the density-dependence of predicted moisture contents, which were ultimately converted to, and expressed as, mass percent.

Preliminary analyses showed that drainage-gap performance was best measured by water content within the interfacing layer of fiber cement. Furthermore, outcomes for all climates and both gap conditions revealed no evidence of moisture accumulation in other material layers. Although cladding moisture levels was largely

influenced by exterior conditions, they were also notably affected by infiltration loads placed directly against the interior cladding surface. Moreover, such loads result in short-term and long-term moisture storage that is not accounted for by exterior climates alone. For example, in **Fig. 9**, we compare simulated moisture contents for assemblies with and without applied moisture infiltration. The 1% infiltration load clearly affects wall performance more than gap size and assumed ventilation rates.

Fig. 10 presents peak moisture contents for all 15 climates as a function of corresponding normal rain. These outcomes demonstrate that moisture content is moderately correlative with total rainfall ($R^2 = 0.60$ [1.5 mm] and 0.64 [10 mm]). Of particular interest was the finding that gap size and corresponding ventilation rates had limited influence on overall wall performance. In most instances, the primary determinants were climate or the mere presence of moisture infiltration (**Fig. 9, 10**). The influence of gap dimension was more pronounced for marine and cool humid climates that receive greater than 1000 mm (39 in.) of rainfall annually. In these instances, the results support the use of larger drainage gaps with higher ventilation rates.

CONCLUSION

This study highlights several important outcomes and limitations concerning drainage testing. First, we conclude that small drainage spaces such as

1.5 mm drain as well as larger gaps when evaluated in accordance with ASTM E2273. This premise holds true even at the reduced water application rate. We assert that the standard flow rate specified by ASTM E2273 is too high, as doubling it yields no substantive change and reducing it by half lowers drainage efficiency for both gap conditions. The standard reflects a bias toward higher drainage efficiencies that are obfuscated by the influence of displacement and predicated on the perception that 90% efficiency indicates better performance. In other words, a benchmark of 90% is perceived more favorably than one of 80% even though the lower application rate yields the same moisture storage. A proposed flow rate of 0.035 L/min (1.18 fl. oz/min)—or one-third of the flow rate employed by ASTM E2273—would better represent infiltration resulting from real-world fault conditions. Furthermore, most buildings experience a wide range of defects over the course of their service lives; some yield higher infiltration rates whereas others may yield significantly lower rates. It would seem obvious that a standard should account for smaller, more common faults yielding lower infiltration loads rather than larger ones that are arguably less common and notably less rigorous.

Water absorption by the interfacing cladding can markedly influence drainage efficiency. Our research shows that moisture absorption by fiber cement panels accounts for up to 85% of the stored moisture or roughly 4% of the total applied water. Although this moisture appears to be safely stored in all but the most extreme climates, this conclusion may not hold true for other types of claddings or other test conditions. Research into methods for further reducing moisture absorption may be worth pursuing to improve drainage and cladding durability.

Mandates for 10-mm ($\frac{3}{8}$ -in.) gaps are fundamentally flawed if criteria for minimum ventilation rates are not also prescribed. As shown here, expectations that 10-mm gaps drain and dry substantively better than smaller gaps are not necessarily correct even when higher ventilation rates are assumed. In some instances, significant improvements in moisture control require a ventilated space—a condition not required by model building codes. Our results support the prevailing thought that buildings in marine or cool, humid climates would benefit from larger, effectively vented drainage gaps. However, for most climates, it is the mere presence of moisture, not the size of the drainage space, that

determines whether a wall will sustain water-related damage.

Lastly, our findings expose an important conundrum in modern design practices. While model building codes and jurisdictions embrace drainage mandates, they do not adequately address the interface between exterior insulation and the drainage plane (**Fig. 1c**). A larger drainage gap, or one that is notably ventilated, would compromise thermal performance. If mandates assume that walls are best served by larger vented spaces, how do we justify much smaller spaces between exterior insulation and the drainage plane? No matter how much water is addressed by the outboard rainscreen, the primary drainage space is the one adjacent to the WRB—the point from which walls are flashed and the last resort for preventing air-induced intrusion. Drainage at the insulation-WRB interface is best managed by small drainage gaps that drain effectively while preserving thermal performance. The 1.5-mm (0.06-in.) space can effectively achieve this objective. Further research is therefore necessary to better understand drainage efficiencies and drying potentials in spaces that are thermally isolated from the outboard rainscreen cavity.

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Development and Experimental Design of a Novel, Low-Carbon, Industrialized Below-Grade Wall Retrofit Method

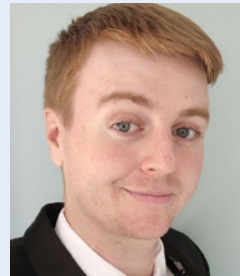
ABSTRACT

Deep retrofits require the renewal of the entire building enclosure to enhance both resilience and thermal performance. Natural Resources Canada's (NRCan's) Prefabricated Exterior Energy Retrofit (PEER) project has developed prefabricated panels for rapidly retrofitting above grade wall assemblies –an approach well-suited for renewing occupied housing. However, with basements in these units also being occupied, there is a need for a complimentary, industrialized solution to retrofitting below grade wall assemblies from the exterior. NRCan has developed a concept for a novel, exterior below grade wall retrofit approach that aims to reduce material costs, labour and site disruption, while also improving drainage, and reducing waste and material emissions compared to the current best practices. This innovative method involves hydrovacuum excavating a narrow 6–12" wide trench, spray-applying a water proofing membrane and backfilling using free-draining insulating materials (such as perlite or foam glass aggregate) to provide both insulation and drainage. This presentation will provide the schematic design of the retrofit system, associated construction (paired with a panelized above grade retrofit), an analysis of the thermal performance and embodied carbon emissions, preliminary material properties and a suitability assessment of perlite, and an experimental design to evaluate system performance.

LEARNING OBJECTIVES

- » Summarize the benefits of below-grade wall retrofits when an exterior approach is required (versus insulating from the interior) and understand current practices in cold climates.
- » Discuss alternative materials, such as foam glass aggregate and perlite, including their properties, availability, cost, and considerations for below-grade applications.
- » Describe the steps involved in a novel "excavationless" approach to foundation retrofitting.
- » Explain the experimental design presented and effectively solicit feedback from peers and stakeholders.

SPEAKER



Hamish Pope, PhD
Advanced Building
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Hamish Pope is an advanced building envelope specialist at Natural Resources Canada, where he works on Canmet's building envelope research projects. His research is on improving industry confidence in novel, high-performance building envelope assemblies and prefabricated approaches to rapid retrofit. Additionally, his research focuses on requirements for industrialized retrofits and on existing and novel low-carbon building materials.

NONPRESENTING AUTHORS



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Mark Carver is a research and design project lead at CanmetENERGY National Resources Canada and a member of the buildings and renewables group. He leads NRCan's Prefabricated Exterior Energy Retrofit project. His research interests include net-zero energy and passive homes and building enclosures, prefabrication, climate-resilient buildings, and low-carbon design and construction. Carver is passionate about making high-performance design, construction, and renovation mainstream. He and his family put a heritage home in Ottawa's Lebreton Flats neighborhood through the deep retrofit wringer. They recently moved to the suburbs and have even more ambitious plans to retrofit their 1970s bungalow to near net-zero.

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Brock Conley is a research engineer with CanmetENERGY. He joined after

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**Jeff Armstrong,
BArchTech, MArch**

Principal
Cold Climate
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Jeff Armstrong has designed and built energy-efficient

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BACKGROUND/INTRODUCTION

Natural Resources Canada's (NRCan's) Prefabricated Exterior Energy Retrofit (PEER) research and development project has developed prototype prefabricated panels for rapidly retrofitting above-grade wall assemblies.¹ Deep retrofits may also involve renewing the below-grade wall system to improve water management and thermal performance as well. A below-grade retrofit can be approached from the interior or the exterior. While both approaches have their merits, interior retrofits can be challenging to implement in occupied housing, and if the basement is finished it would involve the removal of those finishings. Exterior retrofits allow occupants to remain in their home during the retrofit, but there are added costs related to excavating and landscaping. NRCan is undertaking a research project to develop and experimentally evaluate new approaches to exterior below-grade retrofit that seek to reduce labour, cost and embodied carbon while improving thermal performance and resilience of existing buildings. This paper presents one of those concepts, and an experimental design.

There are four ways to insulate a new foundation wall. From the exterior, from the interior, from the center, or from both the exterior and interior (in the case of insulate concrete forms). When retrofitting however, the only practical options are insulation from the interior or the exterior. When the basement is unfinished and the walls are bare, it is simplest and most cost effective to insulate from the interior. However, this can reduce the ability of the basement walls to dry to the interior, which can lead to mold growth and damage to the finishings. Especially in cold climates, it is not recommended to retrofit from the interior, unless changes are also made to the exterior to improve drainage and ensure that moisture will not be an issue.^{2,3}

Exterior below-grade wall retrofits typically involve several key steps to ensure proper insulation, water management, and structural integrity. For a typical below-grade retrofit, the steps are as follows (**Fig. 1**):⁴

1. **Site Preparation:** Underground utilities are located and protected.
2. **Excavation:** The foundation perimeter is excavated, ideally down to the footings, but never below. The trench must be wide enough to work in and properly shored to avoid collapse. Grade the bottom of the excavation to slope at least 5% away from the foundation.
3. **Surface Preparation:** Clean the foundation wall with a wire brush or pressure washer. Re-parge (apply a thin layer of mortar to protect the foundation) / repair cracks as necessary.
4. **Waterproofing:** Install a waterproofing material (membrane, spray or fluid applied) from grade to footing, including the cold joint between the footing and wall. Seal all penetrations and laps. An airgap / dimpled geomembrane is considered best practice as it

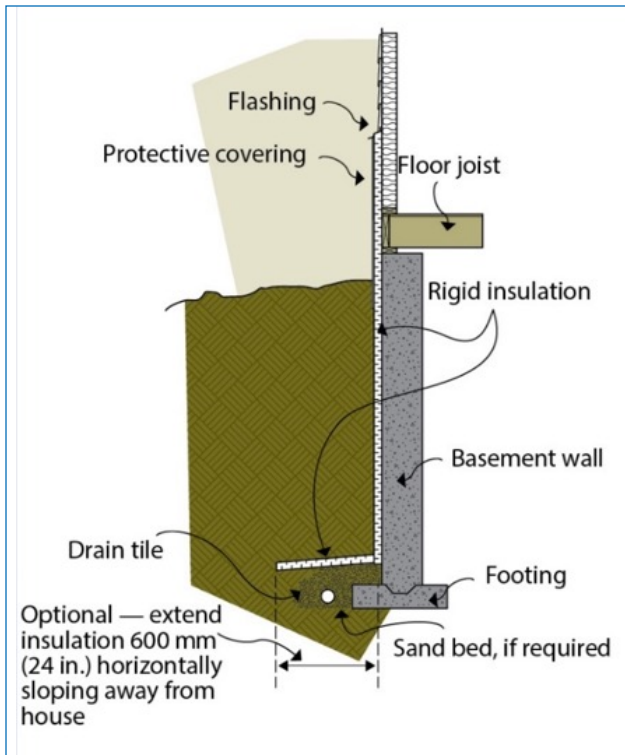


FIGURE 1. Exterior foundation insulation.⁴

reduces hydrostatic pressure and provides a secondary drainage plane. Terminate the waterproofing material appropriately.

5. **Insulation:** Install a non-moisture-sensitive rigid insulation on the wall. Typically, XPS or mineral wool boards are used for this application.
6. **Drainage:** Check the conditions of the drain tile and repair if needed or install a new drain tile at the low end of the foundation skirt, ensuring it slopes to a daylight outlet or storm water collection. If using rigid perforated pipe, the holes should face downward from the bottom of the pipe.
7. **Backfilling:** Backfill the excavation to within 4 inches of the finished grade with free-draining backfill. Install a drip trench adjacent to the foundation wall, separated from the backfill/soil with a durable filter fabric (geotextile).

Asphaug et al conducted a literature review of foundation design for countries with cold climates. It was recommended in many of the European countries to slope the exterior grade away from the building to improve drainage.⁵ All countries recommended installing a drainage layer consisting of backfill and/

or draining insulation. The European countries recommend >200 mm (~8 in.) of mineral backfill (or insulation material with the same capacity), whereas Canada only requires >100 mm (~4 in.) or >19 mm [0.75 in.] mineral fibre insulation.⁶ Each country recommended using a drainage pipe (with varying requirements for size and placement), with some recommending the use of a geotextile. Each country recommended a water-repellent capillary breaking layer (such as a dimple membrane, water-repellent treatment, or bituminous membrane) located on the exterior of the wall or the insulation. Each

country recommends insulation, with its thickness, type, vapor permeance, and location varying. The consensus is that the wall should be allowed to dry to the exterior and that better airtightness is preferred.⁵

Pallin researched the risk of hygrothermal performance of various building retrofits.⁷ For below-grade retrofits, the paper recommends digging down to expose the below-grade wall. If any damage is detected (cracks, damaged drainage pipe, etc.) it needs to be repaired prior to the retrofit. Drainage and insulation boards (such as XPS or mineral wool with a dimple membrane) are then installed on the walls' surface, a geotextile (landscape fabric) is installed over the board, and the removed material is filled back in. The dimple membrane provides improved drainage, reduced capillary suction of ground water, outward drying of the wall, and the insulation provides improved thermal performance. The geotextile keeps ground materials from entering the board and compromising its properties. Likewise, a flashing on the top of the board ensures no material or bulk water enters the board from the top. An important consideration is that the high exterior water pressure may cause

water to drain toward the exterior wall. If the interior temperature of the building is lower than the soil temperature, then drying will occur inward rather than outward, which may cause durability issues such as moisture accumulation, damage to interior finishes, etc.

Mosiman et al conducted research into alternative exterior foundation options that reduced cost and minimized the disturbance to the exterior. One of the methods they suggested was the use of a hydrovacuum to dig a trench at least 4 in wide to allow the installation of waterproofing and insulation materials.² The hydrovacuum operator interviewed had dug small trenches for foundation retrofits in the past and saw no issues with digging a trench at least 4in wide and up to 7 ft deep. One of the benefits of this method would be that it could go around some of the obstructions at the surface that may be more difficult to remove/replace.

One reason to retrofit a building is to reduce operational carbon emissions by improving the thermal performance and airtightness of the structure. It is also important to ensure that this reduction in operational carbon emissions is not exceeded by the upfront embodied carbon emissions from the materials and processes used. It is important to choose materials and methods that have a lower embodied carbon. It is, however, worth noting that foundation retrofits may be required to improve durability and to prevent water infiltration, which may cause expensive damage and require a larger-scale retrofit to fix. By preventing this damage early, it can help to increase the service life of the building.

GOAL

NRCan sought to develop novel exterior foundation retrofit approaches that achieve the following outcomes:

- » Reduce labour and site disruption compared to traditional practice;
- » Improve drainage compared to rigid foam plastics;
- » Reduce waste and embodied carbon for the whole system; and
- » Improve the thermal performance of the below grade walls



FIGURE 2. Hydrovac trench example.

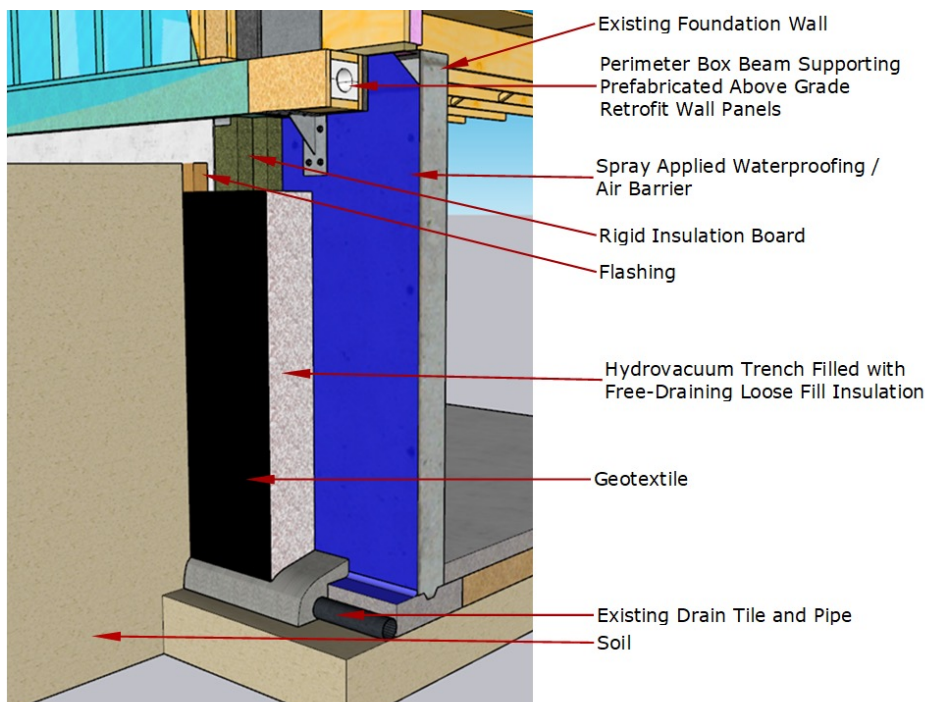


FIGURE 3. Novel foundation retrofit approach.

NOVEL APPROACH

NRCan's idea consists of using a hydrovacuum (hydrovac) for excavation. Hydrovacuums work by having an operator spray pressurised water into the soil to break up the soil and create a slurry, which is then sucked up into the hydrovacuum. This process minimizes risk of damage to the structure,

especially when compared to a more traditional excavator. The process also involves the use of pressurized water, which would clean the foundation and make identifying cracks or defects much simpler. There is a cost premium for the specialized equipment and crew required to perform hydrovac excavation, and there is often also a fee

required to handle and dispose of the excavated soil, as it could be mixed with contaminated soil. Normally new soil or fill would be needed to replace the excavated earth.

The proposed plan would be to hydrovac a roughly 6–12" (15–30cm) wide trench (**Fig. 2**). If there is obvious damage to the foundation it can be repaired at this point. More soil may need to be removed locally to provide safe access for working below-grade. Otherwise, all work is performed at grade. A spray-applied waterproofing membrane is then applied onto the foundation wall, and a geotextile is installed along the perimeter face of the trench. The trench is then backfilled using free-draining loose fill foam-glass or perlite aggregate to provide both insulation and drainage below grade. When this approach is combined with an above grade retrofit, a perimeter box beam can be installed to prep for prefabricated above grade retrofit wall panels. The top of the loose fill insulation under the box beam is then protected with rigid insulation board (such as semi-rigid mineral wool), and the remainder of the loose fill insulation is protected with flashing. If no above grade wall is being installed, then the entire thickness of the trench would need to be flashed to keep debris from entering the loose fill insulation. **Figure 3** illustrates this idea.

This approach reduces labour requirements as excavation can be completed quickly by a single individual. Since the backfilling process is necessary regardless, using a granular insulation material improves thermal performance without needing the time and labour required to install rigid board insulation. As the trench that is being excavated is rather thin, and no workers will be going down into the trench, it improves the safety and reduces the time and materials required to shore up or grade the trench.

From the literature, it is clear that adequate drainage, insulation, and waterproofing is important for long term durability and thermal performance. The spray applied waterproofing can accomplish the waterproofing requirements. Including a geotextile all around and flashing at the top can help to keep foreign material from degrading

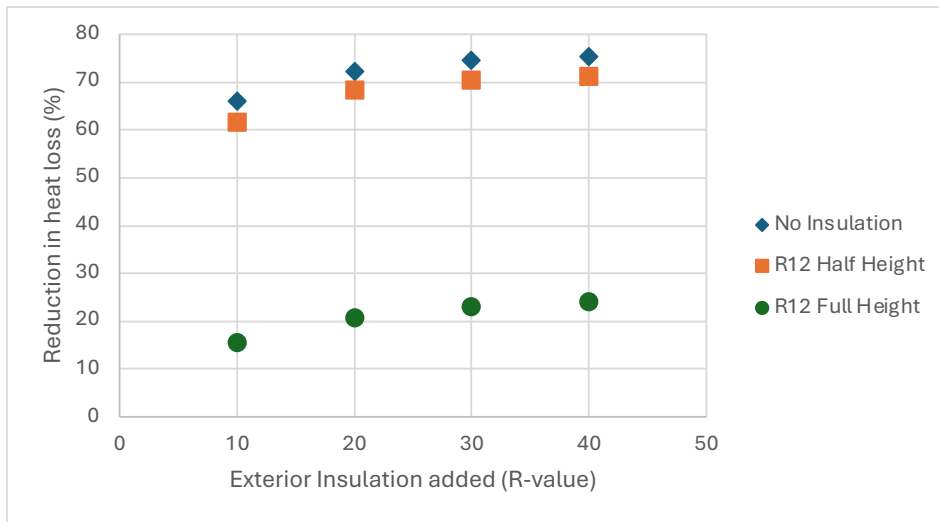


FIGURE 4. Heat loss reduction through exterior insulation.

the performance of the insulation and drainage material. The insulation and drainage thicknesses minimums proposed in literature are exceeded in this design. This will improve the drainage and thermal performance of the below grade walls significantly when compared to the pre-retrofit state.

THERMAL PERFORMANCE AND ENERGY USE REDUCTION

Loose foam glass has an R -value of 1.7/in.⁸ (Glavel), and Perlite has an R -value of 2.5/in.⁹ By adding 6" (15cm) or 12" (30cm) of loose fill insulation the total R -value added is R10.2–R20.4 and R15.0–R30.0 for foam glass and perlite respectively. As was found with Asphaug, drying is improved when the insulation thickness of the exterior is thicker than the interior, so adding this insulation to the exterior is more beneficial than adding a similar level to the interior.¹⁰

In order to determine the impact of adding insulation to a building, models of various residential buildings were created in HOT2000. The buildings were modeled with typical construction from the various code changes in Canada, which include zero insulation, 50% of the basement wall insulated to R -12, and full height insulated to R -12 on the exterior. These buildings were then modelled with varying amounts of below grade insulation added, from adding R10–R40 exterior insulation. The change in annual heat loss through the foundation was calculated and the results can be found in **Fig. 4**.

It can be seen that with adding insulation, there is a huge benefit to increasing the amount from near zero to some nominal value, which is why there is a large jump to over 60% for the No Insulation case. The reduction in heat loss (%) for R12 Half Height case is

similar to the No Insulation case, as the thermal bridging that occurs when half of the foundation wall is left uninsulated reduces the overall R -value of the insulation to under R -1. For the case with R12 Full Height the percentage improvement is lower because the wall was already performing better. As more insulation is added the performance of all scenarios only increases by another 10%. This would indicate that the thickness of the insulation should be balanced based on cost, functionality, and carbon emissions payback.

EMBODIED CARBON

To compare various options the functional unit for embodied carbon shall be $\text{kgCO}_2\text{e}/\text{m}^2$ ($\text{lbCO}_2\text{e}/\text{ft}^2$) of wall area. The traditional approach includes installing XPS or mineral wool boards below grade to improve the thermal performance of the below grade walls. The novel approach includes adding several inches of foam glass or perlite aggregate to the exterior of the below grade walls. The embodied carbon values for adding R10 or R20 of the material is presented in **Table 1**. The embodied carbon of the novel approach can be less than that of the traditional approaches while achieving a similar or better thermal performance if foam glass is used, however if perlite is used the embodied carbon emissions would be higher than the traditional approach.

MATERIAL PROPERTIES

Thermal Performance

When loose fill insulation is used below grade, there is a high likelihood

TABLE 1. Comparison of the embodied carbon of various below grade options^{8,9,11,12,13,14}

Material	R -value/in.	Embodied carbon			
		At R -10 (RSI 1.76)		At R -20 (RSI 3.52)	
	($\text{ft}^2 \cdot ^\circ\text{F} \cdot \text{h}/\text{Btu}/\text{in}.$)	($\text{kgCO}_2\text{e}/\text{m}^2$)	($\text{lbCO}_2\text{e}/\text{ft}^2$)	($\text{kgCO}_2\text{e}/\text{m}^2$)	($\text{lbCO}_2\text{e}/\text{ft}^2$)
Extruded polystyrene	5.0	8.6	1.76	17.3	3.54
Mineral wool	4.2	9.7	1.99	19.4	3.97
Foam glass	1.7	3.2	0.66	6.4	1.31
Perlite	2.5	12.5	2.56	25.0	5.12

TABLE 2. Perlite samples

Size	Condition	Density		Moisture content
		kg/m ³	lb/ft ³	
GR. 6 (finer)	Dry	100	6.2	0 %
GR. 4 (coarser)	Dry	120	7.5	0 %
GR. 4 (coarser)	Fully saturated	260	16.2	117%

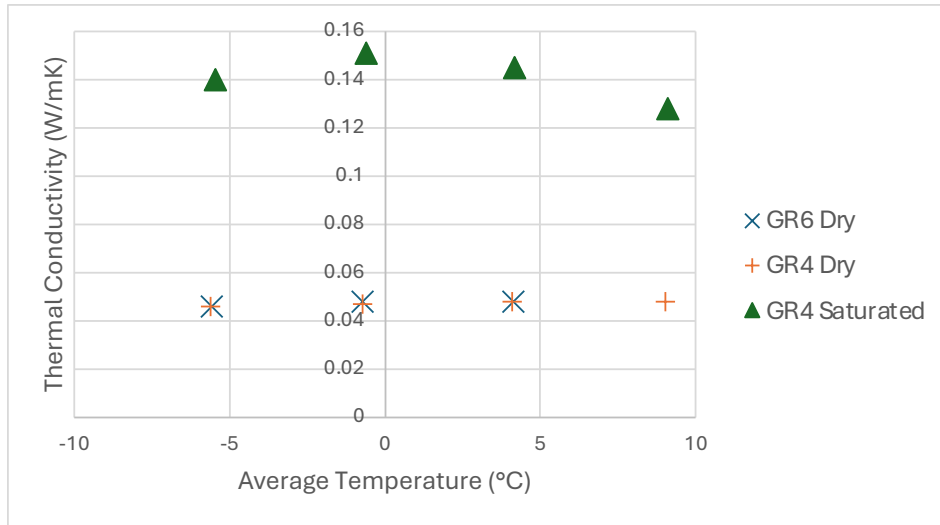


FIGURE 5. Thermal conductivity of perlite with respect to temperature.

that it will trap some moisture in the voids between the aggregates and within the pores of the individual aggregates themselves. To determine the thermal conductivity and *R*-value at different moisture contents, a set of tests were devised to measure the thermal properties of the perlite at dry conditions, at 100% humidity conditions, and at fully saturated conditions. The perlite did not retain a significant amount of moisture when exposed to 100% humidity, so the thermal performance would be the same as the dry conditions. A table outlining the size, density, and moisture content, is presented in **Table 2**, and the thermal conductivity values are shown in **Fig. 5**.

The two different perlite grades had very similar thermal conductivities, with an *R*-Value/in of around 3 (RSI/25mm of 0.52). When the sample was wetted, the performance dropped to around R 1/in (RSI/25mm of 0.18). The thermal conductivity remained relatively consistent for all samples throughout

the different temperatures tested.

PROPOSED EXPERIMENTAL DESIGN AND NEXT STEPS

As one of the major concerns with a foundation wall is the accumulation of water which may lead to degradation or water infiltration, it is important that the infill material has adequate drainage. If there are any drainage issues, it could cause water to infiltrate into cracks or defects in the existing foundation wall. Stagnant water would also be a concern if the water was completely blocked and unable to drain at all.

One way to determine if there is significant risk involved with the proposed foundation retrofit would be to compare the drainage capacity of the proposed design to the existing code minimum. A lab scale apparatus can be built to simulate a foundation with 19 mm (0.75 in.) mineral fibre insulation, and another to simulate a foundation with the proposed novel approach with perlite or foam glass. A set amount of

water would be introduced into each sample, and the time taken for the water to drain would be compared.

For more confidence on the performance of the novel approach when compared to more traditional approaches, a lab scale pilot on a real foundation wall would be required. Different sections of the foundation could be retrofit with foam glass, perlite, mineral wool, and XPS to compare cost and installation, as well as the thermal and drainage performance. If this pilot were successful, installing the novel foundation retrofit on a real-world building and monitoring its performance would be the next step.

CONCLUSION

- » Exterior insulation added below grade is beneficial both for improving the thermal performance and drying potential of the below grade wall.
- » The novel approach introduced in this paper provides a simplified way to improve drainage while simultaneously improving the external insulation, all while minimizing the amount of excavation needed.
- » The improvement on heat loss reduction is most impactful for older buildings without any full below grade insulation (either interior or exterior).
- » The embodied carbon of the proposed options are within the same magnitude as the traditional options for the same thermal performance. Foam glass fill had a lower embodied carbon and perlite fill had a higher embodied carbon when compared to the incumbent materials.
- » The results of the thermal testing on perlite fill show that it is a good insulator, however when water is allowed to collect between the aggregate the thermal performance drops significantly. It will be important to determine how long the drying process is to determine how often the perlite would have the reduction in thermal performance.
- » Options for experimental design to gain confidence with the novel approach were proposed.

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Enclosure Rehabilitations: Using a Collaborative and Holistic Process to Maximize Value

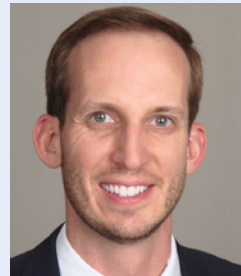
ABSTRACT

Rehabilitation of existing building enclosures offers technical designers the opportunity to optimize building performance while bridging the owner's goals and providing value for the owner. This paper outlines the benefits of early-stage planning and communication, with an integrated holistic approach implemented throughout the predesign phase. For a technical designer, the amount of effort should be maximized in the predesign phase in order to maximize overall project value. Key tasks from the predesign phase are outlined. These include forming a team, identifying urgent issues and long-term goals, developing an owner's project requirements, investigation, and site assessment. To conclude the predesign process, documentation that summarizes and materializes the findings and details of the predesign phase is also discussed, as are the design and construction phases. Roofing case studies, including dead load and wind uplift calculations, are used to exemplify the benefits of placing emphasis on the predesign phase to increase value for the owner.

LEARNING OBJECTIVES

- » Identify key strategies to drive a design process that maximizes owner value, including a robust predesign phase.
- » Explain how to work with owners during a predesign phase to establish project goals before beginning the design.
- » Discuss important technical intricacies to be considered as part of building enclosure rehabilitation projects using a roof replacement case study that considers current and future code requirements and industry standards.
- » Identify key design criteria and construction phase tasks to help bridge the gap between the owner's goals and completed construction.

SPEAKERS



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Rick Ziegler is a principal at Stantec with specialized expertise in the design and rehabilitation of building envelope systems. His work encompasses building assessments, forensic investigations, facade and roof design, specification development, and construction administration. Ziegler has a collaborative approach, working closely with project teams to guide assembly design, system selection, and performance evaluation.



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Amy Huynh is a building science engineer at Stantec. Huynh has worked on a variety of projects, including building envelope consulting, building rehabilitation projects, building envelope commissioning, and building condition assessments. Huynh also has an interest in energy modeling, with experience in three-dimensional finite element analysis thermal modeling. Huynh's approach supports the delivery of high-performing, resilient building systems.

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As a technical leader, Stéphane Hoffman leverages Stantec's building

science team's expertise in enclosure design, facade engineering, and building analytics to assist our clients in delivering high-performance buildings. Hoffman's blend of experience in building science, engineering, and architecture guides his balanced approach to building enclosure design, blending scientific analysis with an understanding of aesthetics. He is particularly adept at providing innovative design concepts and construction alternatives that provide value by improving durability and increasing energy efficiency. His work experience covers a wide range of building types with a mix of new construction, enclosure rehabilitation, and historic restoration projects.

INTRODUCTION

Rehabilitation of existing buildings presents unique opportunities for project teams. An effective and collaborative process for rehabilitation designs can add substantial value for the owner by bridging the gap between their project goals and construction, at a cost within their budget. We all likely have our own ideas for how value is defined, but ultimately, it is the owner and/or end user who defines value.¹ The role of an enclosure designer is to help achieve the performance the owner wants to experience as a user that aligns with their vision. Achieving excellence in building envelope design requires the technical designer to mindfully consider various factors that may influence the final design. This paper outlines essential tasks throughout the predesign phase of enclosure rehabilitation projects, with specific examples taken from recent roof replacement projects.

PREDESIGN

The predesign stage is foundational to a successful overall building envelope design (and, by extension, the construction of such). Throughout the project schedule, the majority of the effort and analysis for the designer takes place during the predesign stage, with decreasing effort during design and construction (Fig. 1).

The predesign phase requires an in-depth review of the project requirements and existing documents, a site assessment, working with the owner to align their goals with existing conditions, and consideration of local building codes and insurance requirements. There are certain tasks that must be considered in the predesign stage, as incorporating them

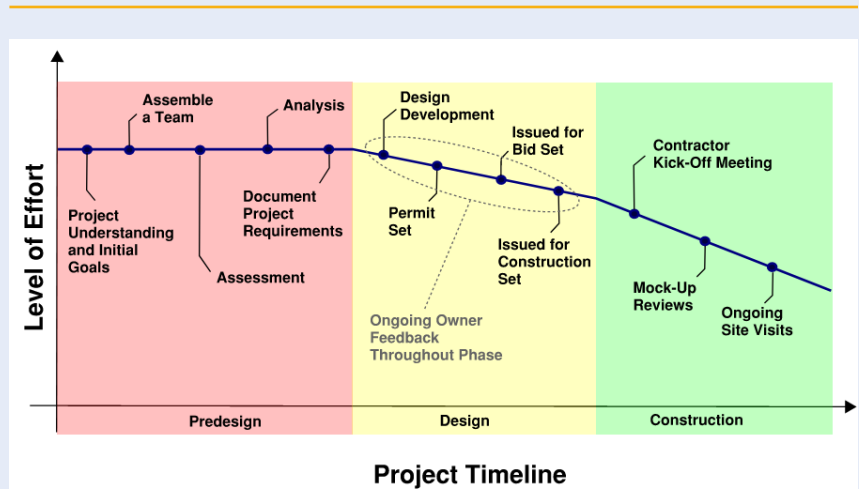


FIGURE 1. Proposed project approach demonstrating early predesign phase effort to maximize project value.

later in the design phase can result in costly changes and delays in the final design. There are several tasks that are important to complete in the predesign stage, and they are summarized below:

- » Create a technically diverse and experienced team
- » In-depth understanding of the owner's immediate problems and long-term goals
- » Building investigation or assessment to identify the existing conditions and causes of performance problems

At the conclusion of the predesign phase, it is recommended to provide a deliverable that summarizes the findings, sources of the problems, remaining service life, and conceptual options that address the immediate problem and applicable holistic goals within the context of building performance, maintenance, operational limitations, and applicable code/insurance requirements (Fig. 2).

BRINGING THE TEAM TOGETHER

Project teams can benefit from technically diverse teams. Enclosure rehabilitation projects are often led by enclosure specialists but may benefit from a multidisciplinary team including architects, mechanical/structural

engineers, energy engineers, and historic preservationists. Working on a diverse design team can be helpful in achieving an integrated design approach that considers a broad range of investigation with design options that identify opportunities that may be more holistic.

Project Example #1:

During a recent roof replacement project, the new roof assembly added approximately 10 lb/ft² (49 kg/m²) compared to the original, which exceeded a 5% increase in the dead load (according to the 2021 International Existing Building Code [Section 706.2], any increase in the dead load of more than 5% shall be replaced or altered as needed to carry the gravity loads²). With structural engineers on the team, the existing structure was assessed and confirmed to adequately support the additional weight. The engineers also verified that the increased load did not adversely affect the building's seismic performance. If a structural engineer had not been on the team or consulted in the predesign phase of the project, the team would have had to consider potential structural upgrades during the design phase after the design scope and initial construction budgets were established.

FROM URGENT ISSUES TO LONG-TERM VISION

Many projects are initiated by a request from an owner for a relatively immediate problem. These problems can vary and are often related to water intrusion, durability, remaining service life, material failures, air leakage, or condensation. In many cases, the owner or facilities manager has unsuccessfully attempted to resolve the issues on their own through maintenance or by retaining contractors directly. They often have an opinion of the reason for the failure; however, the consultant needs to perform the appropriate observations and testing to accurately diagnose the problem.

Rehabilitation focused on resolving an immediate problem may present an opportunity for a holistic project that improves the overall building performance. For the majority of building assets, existing building performance is far behind current energy code requirements. Existing buildings need to be upgraded beyond the simple measures performed in recent years for further improvements in overall energy performance and lowering carbon emissions. However, building owners are faced with the challenge of balancing financial constraints with aesthetics and energy efficiency goals. Rehabilitations that include system replacements are sometimes extensive enough that broadening the scope to assess and improve overall energy performance may balance the project to be financially feasible. The building industry has recognized the need to improve existing building performance and has introduced several standards that address this topic, such as the American Society of Heating, Refrigerating and Air-Conditioning Engineers' (ASHRAE's) ASHRAE 227P, *Standard Method of Test for Determining the Performance of Air-to-Air Energy Recovery Ventilation Equipment*, and LEED v5 Building Operations and Maintenance.³ Whether the building envelope improvements are initiated by a building certification system or a deep energy retrofit, there are generally two paths to approaching improved performance: prescriptive

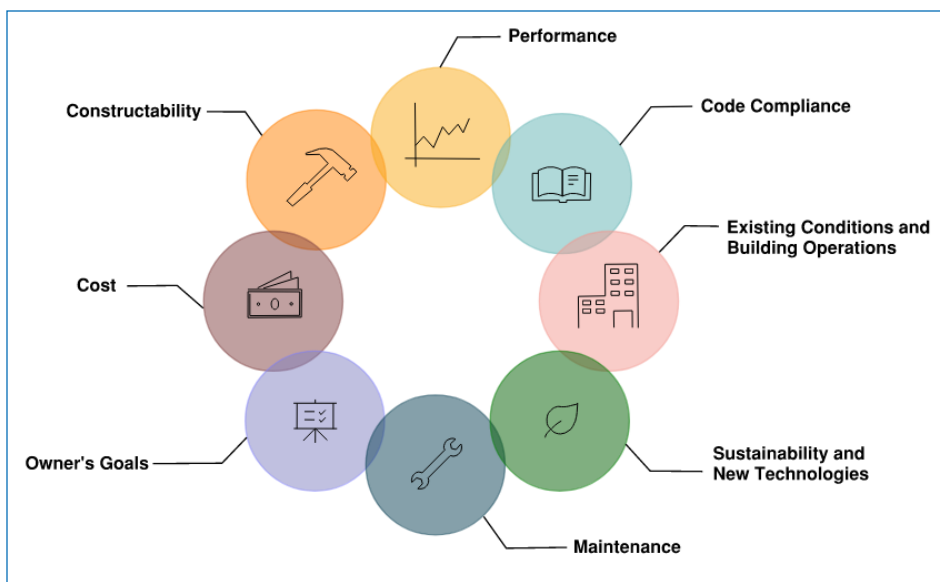


FIGURE 2. Diagram showing potential considerations during a project rehabilitation project. Considerations should be reconciled based on the project requirements to align the project scope with the owner's vision

or building-specific analysis. The prescriptive approach is based on the requirements of the local building codes and/or a certification program developed by LEED or ASHRAE.

DEVELOPING THE OWNER'S PROJECT REQUIREMENTS

The project requirements may be obtained directly or inferred from ongoing discussions with the client. There are straightforward factors, such as climate considerations and budget constraints, that should be discussed, but there are likely unknown factors that the client has not yet materialized. As a technical designer, it is important to formulate effective questions that may assist the client in shaping what their goals for building function and performance are that can be implemented in the design. The aim is to deliver a rehabilitation project that fulfills its intended purpose in the simplest and most efficient way possible.

Project Example #2:

After ongoing roof issues on a relatively new roof of a laboratory facility in a hurricane region, the owner elected to move forward with a replacement. Based on previous experiences with other facilities that were insufficiently resilient during hurricanes, the owner had a general sense that they desired a reliable and climate-resilient roof assembly that would mitigate the risk of operational downtime due to storm events. After a review of background documents and ongoing discussions with the owner to understand their short-term and long-term goals, we outlined the following initial items that formed the owner's project requirements:

- » *New roof with multiple layers to increase the redundancy and mitigate the risk of punctures resulting in roof leaks*
- » *Balancing of the heating, ventilating, and air conditioning system to reduce the building over-pressurization from 0.3 in. (0.76 cm) of water to 0.05 in. (0.13 cm) of water*
- » *Inclusion of an air/vapor barrier at the roof deck to improve building*

airtightness and improve uplift capacity⁴

- » *A fully adhered roof membrane system and air barrier resulting in an assembly that resists "billowing" that was previously observed due to the internal pressurization*
- » *Roof uplift design to resist high-wind events*
- » *Evaluation of the deck attachment to the structure to account for the additional uplift pressures due to the enclosure modification*
- » *Redesign of mechanical curbs and equipment attachment with the addition of hurricane cables to resist design wind forces*
- » *Addition of rooftop mechanical equipment and penetrations*
- » *Design and attachment of copings and edge metals that adequately resist the design wind pressures*
- » *Addition of sealants at the precast parapet panel-to-panel sealant joints to provide air barrier continuity*

After identifying the initial project goals, the designers can complete the assessment and investigation to document existing conditions prior to starting the design. Note that after the assessment was completed in Project Example #2, the owner's project requirements were clarified with additional specificity and included other items that were identified during the assessment.

INVESTIGATION AND ASSESSMENT

For a rehabilitation project, a basic understanding of existing conditions can be determined from a review of existing design documents. A site assessment is required regardless of existing documents being reviewed, as undocumented changes occur over the lifespan of a building. During the site review, the designer should be mindful of barriers that could restrict the design or result in scope change, and they should report those to the client promptly. The depth of on-site investigation should be balanced with the project scope and specific conditions.

Some industry standards exist for enclosure assessments and investigations, such as The Masonry Society's TMS 1700-17, *Guide for Condition Assessment of Masonry Facades*, or ASTM E2128, *Standard Guide for Evaluating Water Leakage of Building Walls*, and they can be referenced to create the assessment approach.^{5,6} Regardless of the type of problem, testing is often performed to confirm the issue. Proceeding with a repair project without first confirming the sources of the problems with testing and analysis often results in wasted efforts through unsuccessful attempts at resolving the issue. An accurate diagnosis and repair that effectively resolves the issue is critical. A consultant must rely on their experience and judgment to develop an assessment and investigation scope that is reconciled with the potential project and corresponding costs. For example, in typical scenarios it would not be prudent to spend more time and money investigating the problem than repairing it. One major consideration is the number and location of exploratory openings, which are relied on to understand the existing conditions to mitigate the risk of unknown conditions during construction. An experienced team can work with the owner to identify the scope of openings that is reconciled with the project scope and the owner's tolerance for risk during construction.

After identifying the causes of immediate problems, the team can progress towards a more holistic assessment, if needed, based on the owner's requirements. The industry has recently gained access to more nondestructive tools and quantitative analysis techniques. If overall energy usage is a consideration, the typical quantifiable variables include effective thermal performance and air leakage. A combination of field evaluation and modeling can be used to determine effective thermal performance, accounting for thermal bridging.

As the project transitions from the assessment to end the predesign phase, documentation is typically developed with a report. This documentation should consider the following:

- Existing conditions:** A thorough description is important to document to understand the potential rehabilitation options and outcomes. The existing conditions often justify the options presented but can also be used to identify the practical limitations of potential options.
- Options to solve urgent problems:** If the consultant was retained to identify the source of an urgent problem, there may be several options available for consideration. The options typically include a conceptual description of the repair approach, sketches, and advantages and/or disadvantages. It is important for the consulting team to have an intimate knowledge of material and product performance to accurately describe the outcome. Some typical assembly or product considerations are as follows:
 - Anticipated life span and performance of materials used in similar climates and applications
 - Technical and practical performance outside of limited manufacturer’s test data as established through in-house testing or practical experience
 - Unique or innovative products or concepts that should be considered
- Generate outcomes that affect broader/peripheral goals, such as overall building performance, that consider the following:
 - Overall energy performance
 - Maintenance and/or durability
 - Certifications for existing buildings

- Impact to occupancy/operations:** Most buildings are going to be occupied during the rehabilitation project; therefore, the rehabilitation scope should consider the impact to occupants.
- Building code or owner’s insurance requirements:** The applicable code and insurance requirements should be considered and reconciled with the project rehabilitation options. For new systems where current code requirements apply for replacement of existing systems, it is also recommended to review future code requirements that may have been incorporated to address previous limitations or failures.
- Costs:** Typically, at the predesign stage, rough order-of-magnitude cost estimates are helpful to facilitate an informed decision.

Project Example #3:

After identifying the initial project goals at the onset of the project, an assessment was completed to document existing conditions. The following highlights considerations that require coordination with the owner based on the project requirements and existing conditions:

- » Two roof assembly options were provided to the owner—single ply and modified bitumen—along with advantages and disadvantages. The design team worked with manufacturers and contractors to determine approximate costs. The owner elected to proceed with a two-ply modified bitumen roof assembly. The membrane was to be fully adhered (torch-applied) to resist “billowing,” as previously mentioned.

- » The laboratory spaces inside the building required precise regulation of interior temperature and relative humidity. It was the owner’s intent that the building would be occupied during construction. The roof area was relatively large, and removing all of the insulation during construction could diminish the ability to sufficiently regulate the interior conditions. The design team performed an analysis to determine that only portions of insulation up to 500 ft² (46.5 m²) could be removed at a time, and the contractor would need to coordinate and sequence their work accordingly.
- » The roof uplift pressures were calculated during the predesign phase to identify potential assemblies (that is, tested systems) and to evaluate the deck for the uplift pressures. The owner’s insurer did not have specific requirements; however, the design team included calculations in accordance with Factory Mutual Loss Prevention Data Sheet 1-29, Roof Deck Securement and Above-Deck Roof Components, for comparative and informational purposes (Table 1).⁷ At the design team’s recommendation, the owner proceeded with the code and 2.0 safety factor for the design approach.⁸

DESIGN AND CONSTRUCTION

Due to the effort spent during the predesign phase on the assessment and analysis, the development of the design can be simplified and focused on representing the project requirements.

Project Example #4:

The design included a detailed set of specifications and drawings that reflected

TABLE 1. Approximate comparative uplift pressure on Project Example #3

Zone	Code minimum		Code with 2.0 safety factor		Factory mutual	
	(lb/ft ²)	(kg/m ²)	(lb/ft ²)	(kg/m ²)	(lb/ft ²)	(kg/m ²)
Field interior	-41	-200	-82	-400	-180	-879
Field exterior	-63	-308	-127	-620	-270	-1,318
Perimeter	-80	-391	-160	-781	-345	-1,684
Corner	-105	-513	-211	-1,030	-450	-2,197

the direction of the predesign phase. After a pre-bid meeting, bidding, and bid review, a contractor was selected. Mock-ups were used at all critical phases/systems, including the following:

- » Metal deck enhancement (fasteners installed to secure the deck to the structure below)
- » Substrate board installation, including verification of the attachment to the deck based on the manufacturer's tested assembly
- » Installation of the roof air/vapor barrier and interface with the wall, including the precast parapet sealant joint installation to improve air barrier continuity

- » Insulation and cover board installation, including adhesive pattern and spacing
- » Installation of the roof membrane base ply and cap ply
- » Parapet wood blocking, underlayment, and coping

In the previous example, since the designer and the contractor worked together through each initial installation of every component, they were able to reconcile the intended installation with actual construction. After an initial approved mock-up, the contractor was aware of the design intent and standard of quality to carry out throughout the project.

CONCLUSIONS

In conclusion, successful enclosure rehabilitation projects hinge on a thoughtful, user-oriented approach that aligns experience and technical expertise with the owner's goals and budget. By considering both performance-driven parameters and broader client needs in the earliest stages of design, enclosure professionals can deliver solutions that are not only durable and efficient but also add specific value to the owner. The examples provided from recent roof replacement projects illustrate how a collaborative and integrated design process during the predesign phase can set the foundation for long-term project success and end-user satisfaction.

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Effective Design Strategies for Natatorium Enclosures: Insights from a Real-World Case Study

ABSTRACT

Participants will develop a comprehensive understanding of the potential risks involved in designing roof and wall assemblies over pools and other corrosive environments. This session will cover effective design strategies to mitigate moisture damage by managing air, temperature, and vapor control. Key roof assembly elements—such as metal decking, fasteners, air/vapor barriers, and insulation—will be discussed in detail. Finally, these principles will be applied in a case study, covering the full project life cycle from concept and design to application, inspections, and handover.

LEARNING OBJECTIVES

- » Explain how moisture intrudes and affects roof/wall assemblies over pools and caustic environments.
- » Summarize the typical materials of construction, and advantages associated with material selection in roof and wall assemblies.
- » Identify the functional performance-based characteristics of a high-performance building enclosure system.
- » Analyze various preferred natatorium roof and wall assembly details and applications in a case study.

SPEAKERS



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Jonnie Hasan has more than 25 years of experience in commercial construction, design-build, and cladding. He holds a structural engineering PE, Six Sigma green belt, and Building Envelope Commissioning and Project Management certification. In his position with IMETCO, he has held various roles, including building enclosure designer, WUFI analyst, manufacturing engineer, and director of building envelope products. He strives to guide clients to the most cost-effective and efficient product selection and application. He is a registered professional engineer with numerous patents related to building cladding systems and design. Hasan is an active member of ASTM, BEC (local chapter), PCI, ACI, ABAA, and ASCE.

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INTRODUCTION

Natoriums (indoor swimming pool facilities) combine high interior humidity, elevated air temperatures, and chemically aggressive atmospheres. These conditions create strong vapor pressure differentials that drive moisture into roof and wall assemblies. This paper summarizes enclosure risks and control strategies for natatoriums and illustrates their application through a case study—from concept and design through construction, inspection, and handover.

ENVIRONMENTAL CHALLENGES AND FAILURE MECHANISMS

Characteristics of the Natatorium Environment

Indoor pools maintain high relative humidity levels (50%–60%) year-round. This moisture-saturated air is rich in chloramines and other disinfectant byproducts that significantly increase its corrosivity. Combined with high interior air temperatures and lower exterior temperatures, natatoriums generate a persistent vapor pressure differential that pushes moist air into the enclosure assembly.

Common Causes of Enclosure Failures

Most enclosure failures in natatoriums stem from a combination of the following:^{2,3}

- » **Uncontrolled air leakage:** Even small air leaks can cause warm, moist interior air to condense on cold surfaces within the building enclosure.
- » **Thermal bridging:** Metal components such as fasteners and framing members provide a direct

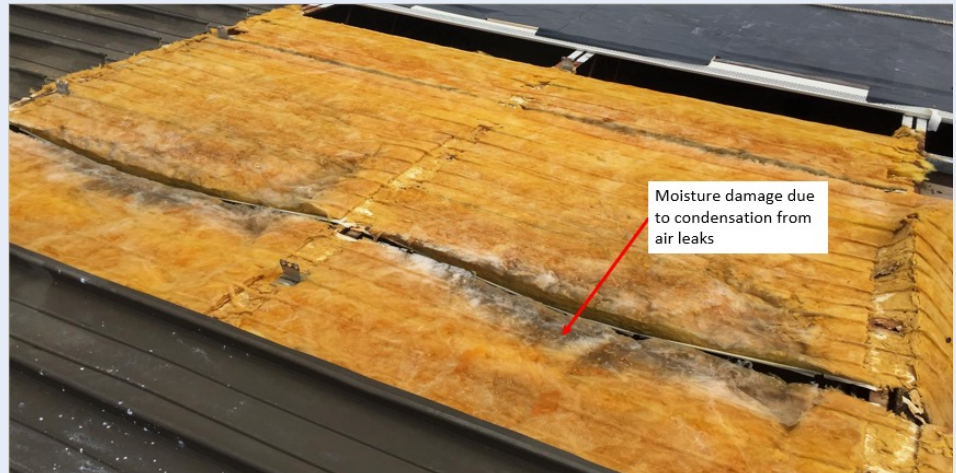


FIGURE 1. Natatorium roof enclosure failure.



FIGURE 2. Natatorium wall failure.

- » **Inadequate vapor control:** Improper placement or specification of vapor retarders can result in moisture accumulation in wall and roof cavities.
- » **Incompatible materials:** Some materials deteriorate rapidly in

high-chlorine environments if not adequately protected.

Figures 1 and 2 illustrate these issues, which may remain hidden for years, with the first signs being corrosion, mold, or water staining on interior surfaces.

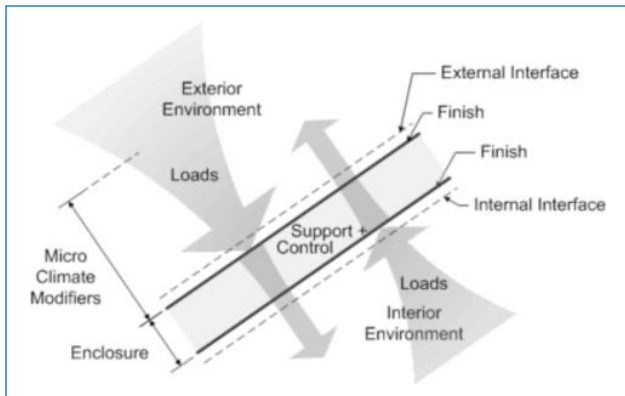


FIGURE 3. Building Science Corporation – Building Science Digests 018: The Building Enclosure by John Straube (2006).

PRINCIPLES OF BUILDING ENCLOSURE DESIGN

A successful natatorium enclosure begins with a clear understanding of the functional roles that each layer of the building enclosure must fulfill (Fig. 3).¹ These functions fall into three primary categories:

- » **Support functions:** Structural integrity, including resistance to live, dead, wind, and snow loads
- » **Control functions:** Management of air, water, vapor, and thermal energy transfer
- » **Finish functions:** Durability, appearance, and performance of interior and exterior surfaces

Control of Moisture and Air

Well-designed wall assemblies in natatoriums are governed by fundamental building science principles rooted in hygrothermal performance.^{2,3} The key control layers must be continuous, compatible, and correctly sequenced.

- » **Air barriers** must be continuous to prevent convective loops that transport moisture. Hygrothermal modeling is useful to determine how to keep humid air from contacting cold surfaces within the wall or roof.
- » **Vapor retarders** should be strategically positioned based on the specific climate conditions and interior environmental factors. In natatoriums, where high humidity levels originate from within the space, it is generally recommended to place vapor

retarders close to the interior side of the building enclosure—both in wall and roof assemblies—to control inward vapor diffusion. However, while roof assemblies typically benefit from vapor-closed systems to limit moisture migration, wall assemblies often require vapor-open configurations to facilitate drying and reduce the risk of trapped moisture

within the wall cavity. Optimal moisture management will be tailored to the function and orientation of each building component.

- » **Thermal insulation** is designed to maintain wall and roof cavity temperatures above the dew point. Continuous insulation (CI) outboard of structural elements reduces thermal bridging, helping to avoid condensation points.
- » **Water-resistive barriers (WRBs)** stop liquid water from penetrating the wall assembly while remaining vapor permeable to allow for drying. Depending on climate condition of the project, two layers of WRB may be necessary.

For all these layers to work as intended, transitions and penetrations must

be meticulously detailed. A single discontinuity in the air or vapor control layer can undermine the entire assembly's effectiveness.

Maintaining proper pressure relationships is essential to prevent moisture-laden natatorium air from infiltrating colder exterior assemblies. Industry guidelines recommend sustaining a slight negative pressure (0.05–0.15 in. WC) relative to adjacent spaces, achieved through active HVAC strategies such as exhaust fans, variable-air-volume controls, and pressure sensors. This approach minimizes the risk of condensation and corrosion within the building envelope and ensures consistent hygrothermal performance under variable operating conditions.⁶

ROOF DESIGN STRATEGIES

Interior Exposed Steel Roof Deck Standing Seam Assemblies

Steel roof decks offer structural efficiency and can be easily integrated with insulation and air barrier systems. However, Traditional hot-dip galvanized steel roof decks often lack sufficient corrosion resistance in highly humid, chemically aggressive natatorium environments. Consequently, duplex coating systems—comprising a polymeric or paint topcoat over galvanized steel—are recommended to substantially enhance durability and corrosion protection.⁷ Figure 4 shows a three-coat system interior



FIGURE 4. Three-coat metal deck system.

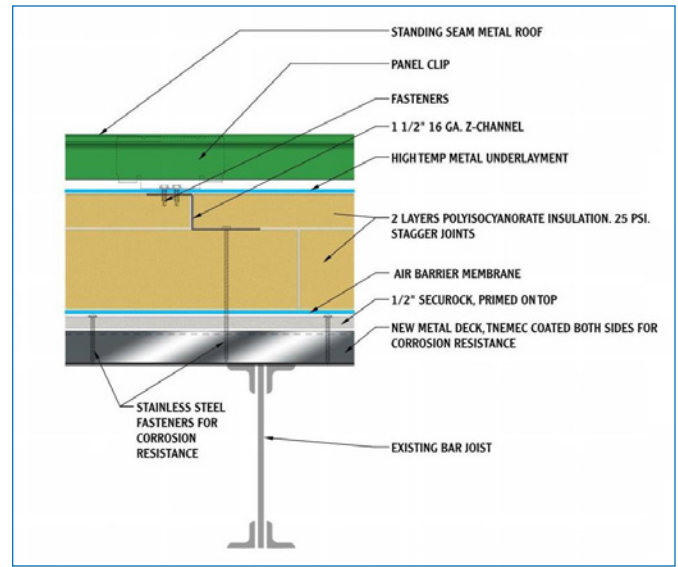
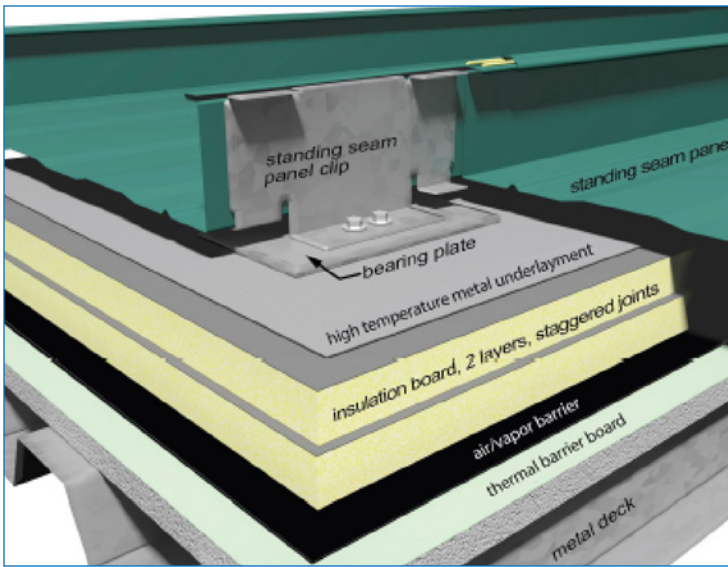


FIGURE 5. Multilayered standing seam roof assembly.



FIGURE 6. Examples of inappropriate sealing and attachment systems.

finish in which the galvanized base layer provides foundational corrosion protection, baked-on epoxy primer enhances adhesion and provides an additional barrier, and a field-applied high-performance coating boosts durability by covering fasteners and “risky” elements.

Standing Seam Assemblies With Steel Deck

The thermally broken and isolated layered roof system (Fig. 5) is designed to enhance durability, energy performance, and moisture control under demanding environmental conditions. The assembly begins with a G90 galvanized steel deck that is factory coated with a polyvinylidene fluoride (PVDF) primer to enhance corrosion resistance and allow for the application of subsequent high-performance protective coatings. A minimum 50-mil

membrane or a multiply membrane application is installed above the deck, serving as a vapor-closed layer to limit moisture ingress into the system. Thermal insulation is applied in staggered layers to reduce thermal bridging and improve continuity across the assembly. Above the topmost insulation board, a vapor-open air- and water-barrier (AWB) membrane is installed, facilitating outward drying while maintaining air and moisture control. This configuration balances the need for vapor control with the capacity for drying, minimizing the risk of condensation and ensuring thermal and hygrothermal performance across the roof enclosure.

Detailing and Terminations

To ensure that the roof correctly connects to adjacent components, key practices include the following:

- » Use ceramic-coated fasteners that resist corrosion even in direct exposure.
- » Seal terminations with ethylene propylene diene terpolymer (EPDM) or styrene butadiene rubber (SBR) blocks that match deck profiles.
- » Avoid foam sprays and generic sealants that degrade over time (Fig. 6). Spray foam insulation often cannot fully seal off corners and edges creating air leakage at critical junctions.
- » Avoid puddle welding of deck to purlins (Fig. 6). Welds remove the all protective coatings applied to the metal deck. This can lead to serious rusting.

Transitions within the building enclosure should be treated as integral elements of a unified air- and vapor-barrier system, rather than isolated

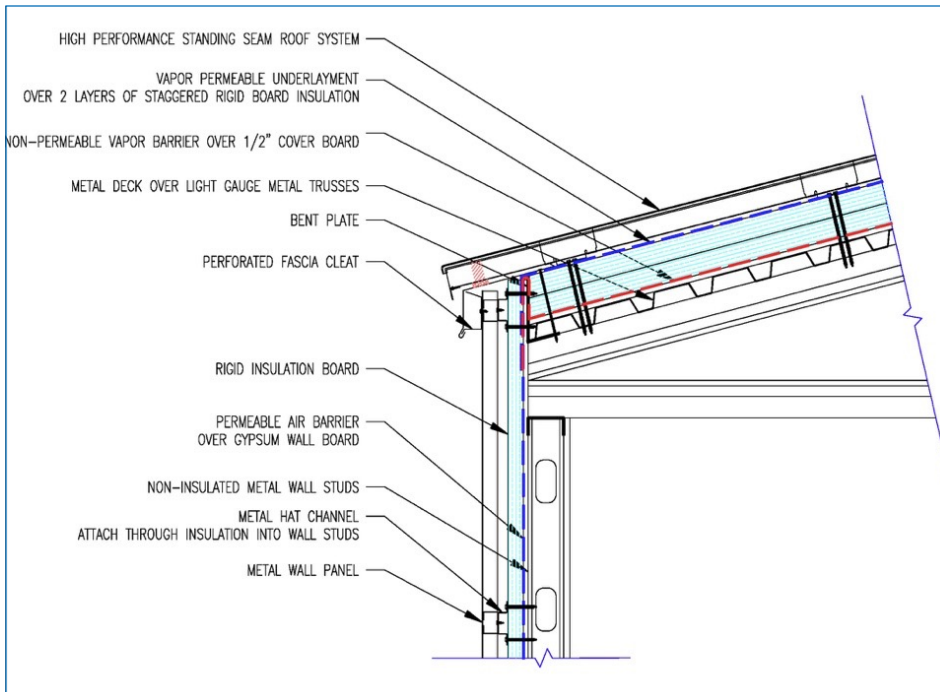


FIGURE 7. Roof-to-wall transition detail.

components, to preserve continuity and prevent envelope breaches.⁸ Proper coordination between trades and clear sequencing during installation are essential to maintain integrity (Fig. 7). The AWB from roof assembly to wall assembly is a critical component of the overall design. Separation of Vapor Closed vs Vapor open AWB's need to be clearly called out and the transitions noted.⁸ In addition, the specifications for the AWB's should clearly note the performance requirements with Basis of design called out.

WALL ASSEMBLY COMPARISONS

Wall assemblies in natatoriums must balance thermal performance with moisture management. This study evaluates four common wall systems.

Hygrothermal modeling is a critical tool in the design of natatorium enclosures, where elevated interior humidity, strong vapor pressure differentials, and chemically aggressive conditions create a high risk of condensation and material degradation. Simulation tools such as WUFI enable designers to predict heat

and moisture transport through roof and wall assemblies, assess long-term moisture accumulation, and optimize placement of air, vapor, and thermal control layers to minimize failure risk.^{4,10}

Using WUFI, hygrothermal simulation models for the wall assemblies below, were ran from January 2025 through December 2030 to assess moisture behavior, thermal performance, and associated risks under expected climate conditions.

All materials and input parameters were modeled in accordance with ASHRAE 160 guidelines.⁹ Springfield, MO climate data was used to simulate boundary conditions, and the southeast-facing wall was selected for modeling based on its exposure to prevailing weather patterns.

Assembly 1: Face Sealed ACM Panel (R-24.16)

R-Value: 24.16 h-ft²·°F/Btu

U-Value: 0.04 Btu/h-ft²·°F

Layer Composition (Exterior to Interior):

- » Metal Panel (4mm ACM-Face Sealed)
- » Vertical Metal Framing (No ventilation provided at base or head of the wall)
- » Semi-Rigid Mineral Wool
- » Vapor Open Air and Water Barrier
- » Exterior Gypsum Board
- » Mineral wool Batt Insulation
- » Interior Board

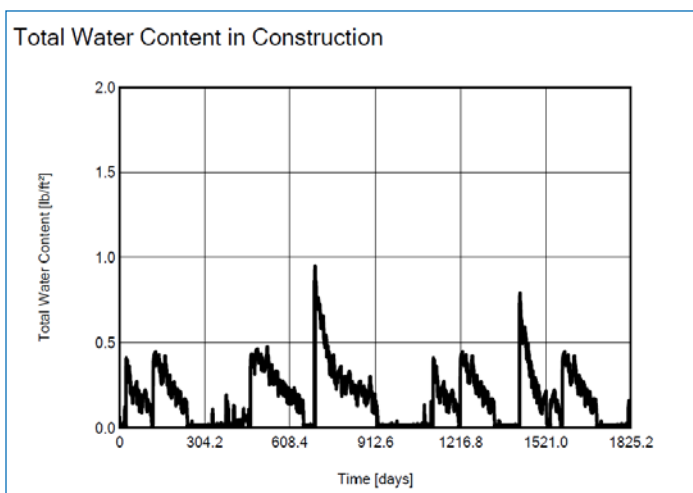


FIGURE 8. Assembly 1 and 2 model output: typical accumulated moisture in outer gypsum board.

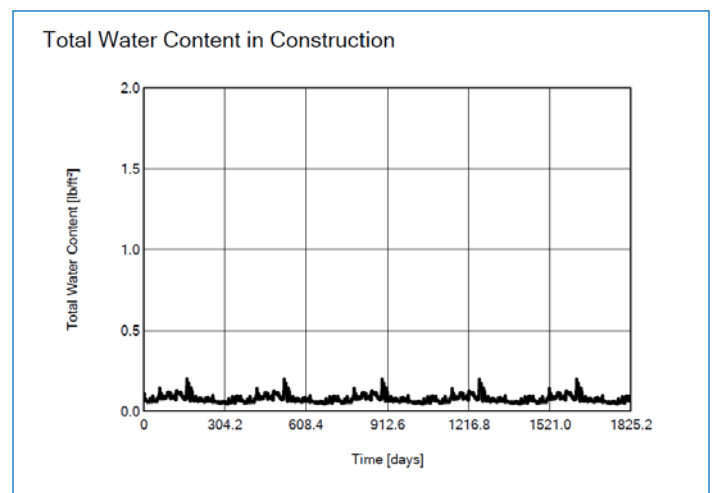


FIGURE 9. Assembly 4 model output: typical accumulated moisture in outer gypsum board.

Assembly 2: Flush Metal Wall (R-24.15)

Total Thickness: 6.87 in

R-Value: 24.15 h·ft²·°F/Btu

U-Value: 0.04 Btu/h·ft²·°F

Layer Composition:

- » Metal Panel (22 ga face sealed)
- » Semi-Rigid Mineral Wool
- » Vapor Open Air/Water Barrier
- » Exterior Gypsum Board
- » Mineral Wool Batt Insulation
- » Interior Gypsum Board

Assembly 3: Brick and Stone Veneer (R-26.0)

Total Thickness: 12.81 in

R-Value: 26.0 h·ft²·°F/Btu

U-Value: 0.037 Btu/h·ft²·°F

Layer Composition:

- » Limestone (4.0 in)
- » Air Cavity (50 mm / 1.97 in)
- » Semi Rigid Mineral Wool Insulation
- » Vapor Open Air/Water Barrier
- » Exterior Gypsum Board
- » Mineral Wool Batt Insulation
- » Interior Gypsum Board

Assembly 4: Rainscreen with Exterior CI (R-24.86)

Total Thickness: 7.81 in

R-Value: 24.86 h·ft²·°F/Btu

U-Value: 0.039 Btu/h·ft²·°F

Layer Composition:

- » Metal Panel (22 ga) Open Jointed
- » Air Cavity (25 mm / 0.984 in) with base and head perforated trims for drainage and ventilation.
- » Rigid Mineral Wool Insulation
- » Vapor Open Air/Water Barrier
- » Exterior Gypsum Board
- » Mineral Wool Batt Insulation
- » Interior Gypsum Board

HYGROTHERMAL PERFORMANCE

Moisture Accumulation

- » **Assemblies 1 and 2:** Continuous increase in moisture levels within the gypsum board layers over time. This

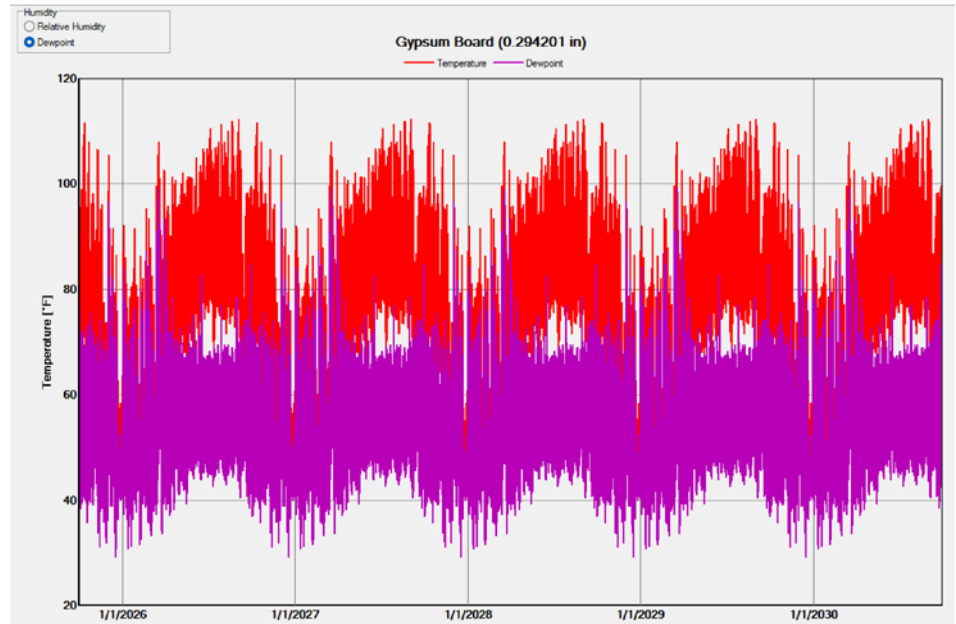


FIGURE 10. Assembly 1 and 2 model output: temperature versus dewpoint.

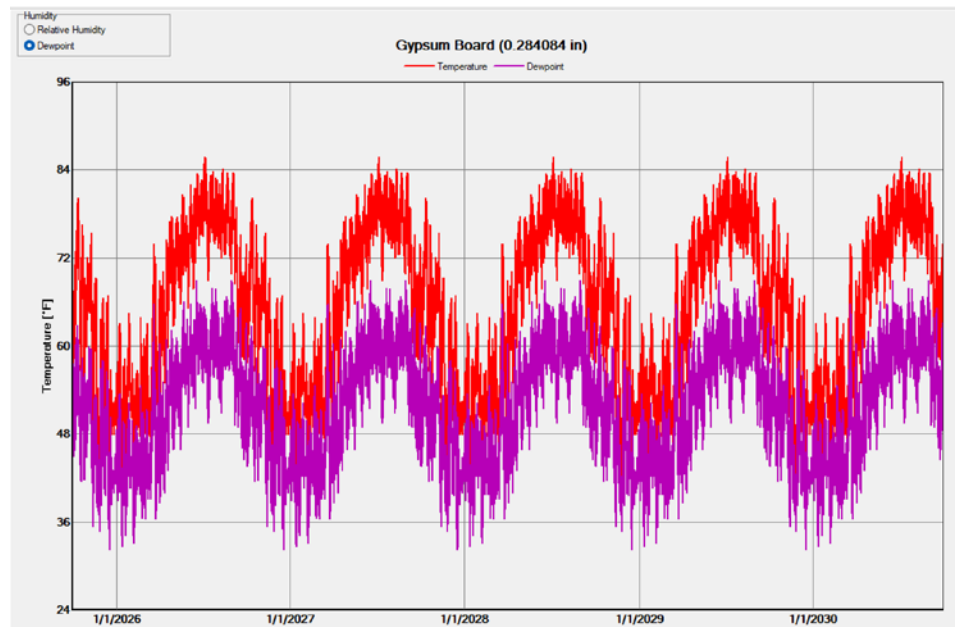


FIGURE 11. Assembly 3 model output: temperature versus dewpoint.

is due to the lack of cavity ventilation, which inhibits drying of accumulated moisture (Fig. 8).

- » **Assembly 3:** The moisture content remained stable throughout the analysis period, indicating satisfactory system performance. The high thermal mass of the stone/brick façade minimized thermal bridging, thereby reducing fluctuations in temperature differentials.
- » **Assembly 4:** Incorporates ventilated cavity to promote outward drying,

reducing long-term moisture accumulation risk (Fig. 9).

Relative Humidity and Dew Point Risk

- » **Assemblies 1 and 2:** Repeated dew point occurrences within the gypsum board during winter months suggest high potential for condensation-related failures. Lack of air movement exacerbates the issue, especially in the flush wall configuration (Fig. 10).
- » **Assembly 3:** This assembly fares better than assemblies 1 and 2 due to its ability to buffer short-term

humidity spikes. However, without ventilation behind the veneer, any trapped moisture inboard of the sheathing can persist (Fig. 11).

- » **Assembly 4:** Ventilated design significantly reduces dew point risk by enabling consistent vapor drive. The wall assembly model predicts high performance for natatorium applications. The rainscreen cavity facilitates air exchange and continuous drying, while continuous insulation (CI) maintains thermal continuity. The vapor-permeable weather-resistant barrier (WRB) permits outward vapor diffusion, and inward drying is achievable through controlled HVAC operation.

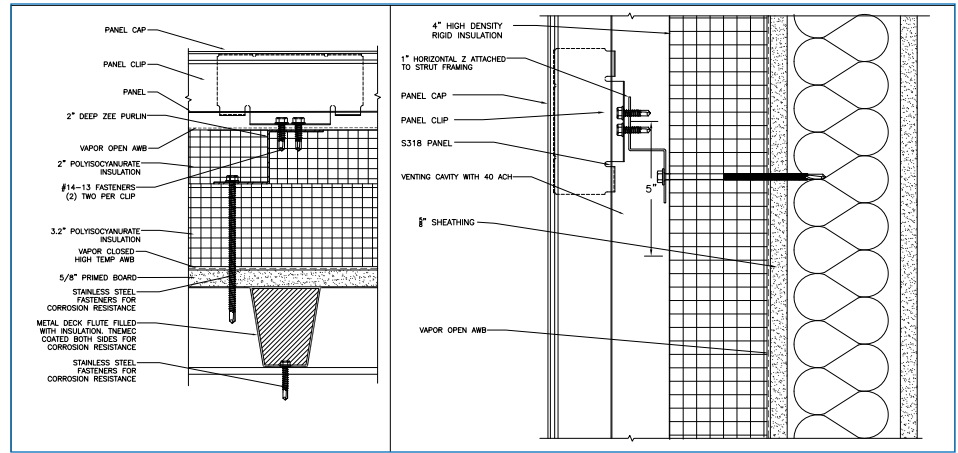


FIGURE 12. The manufacturer proposed roof and wall assemblies engineered to satisfy specified performance criteria, including hygrothermal, structural, and durability requirements.

SECTION CONCLUSION

Natatorium enclosures present demanding hygrothermal conditions driven by elevated humidity, chemical exposure, and persistent vapor pressure gradients. Assemblies lacking ventilation or continuous control layers are highly susceptible to moisture accumulation and condensation-related failures, while systems that incorporate ventilated cavities, continuous insulation, and carefully sequenced air- and vapor-control layers demonstrate far greater resilience. The manufacturer’s role in detailing these assemblies and ensuring continuity across transitions is essential, with single-source hygrothermal warranties providing added assurance of long-term durability and reliable performance under such extreme environmental conditions.

CASE STUDY: LONGBRIDGE AQUATIC CENTER

Location: Arlington, VA

ASHRAE Climate Zone: 4 (Mixed Humid Class A)

Characteristics: Cold winters, hot/humid summers, with significant heating and cooling loads.

Roof Construction (Fig 12): Metal Deck, 5/8" Roofboard, Vapor Closed High Temp Underlayment, 5.2" Polyiso Insulation (2 layers 3.2" base+2" top), Embedded 2" 20ga Zee on top insulation layer, High Temp Vapor Open Underlayment, Standing Seam Roof.

Wall Construction (Fig 12): Interior gyp board, Steel Stud Framing 6", Exterior Wall Sheathing, Vapor open AWB, 4" Insulation (Mineral Wool), 1" Vented Z girt air cavity (fastened thru insulation), Standing Seam Wall.

Scope

The Designer of Record engaged multiple building envelope material manufacturers to evaluate comprehensive roof and wall assembly solutions capable of addressing the project’s specific climate zone conditions and elevated interior humidity levels. Following the selection of a manufacturer, an extensive series of design and consultation meetings was undertaken to evaluate strategies for managing heat, air, moisture, and vapor transport across the envelope. The objective was to develop an integrated system approach, culminating in a single-source hygrothermal warranty covering all components from the sheathing outward, thereby ensuring continuity of performance across the entire building envelope.

Design Process

- » A hygrothermal model was developed by the manufacturer using WUFI software to evaluate vapor migration and potential condensation risks, and the results were submitted for review by the Designer of Record. Following approval, transition details were refined in close collaboration with the manufacturer to ensure material compatibility,

continuity between control layers, adequate structural support, and robust protection against air and water leakage. These coordinated details are further discussed in the Collaboration section.

- » Complete air/vapor barrier systems, not individual components, were selected.
- » Termination blocks and corrosion-resistant fasteners were specified.
- » Mock-ups were created to verify detail performance before full-scale construction.
- » Mockups were field tested using ASTM E73, ASTM E1186, ASTM E1105 standards.^{11,12,13} No issues were found with the roof assembly, however, at the wall assembly water leaks were observed and sources identified. Based on the outcome, additional flashings were recommended at the framing screw penetrations for the walls.

Collaboration for Constructability

Ridge to Wall Transition (Fig. 13): Although wood blocking is generally avoided in high-moisture environments due to its susceptibility to degradation, its use may be necessary to address constructability requirements. In this project, wood blocking was incorporated to facilitate the transition of the air- and water-barrier (AWB) from roof to wall, while maintaining continuity of the thermal envelope. Where employed, the blocking must be protected with a high-temperature-

RECOMMENDATIONS AND BEST PRACTICES

To achieve successful natatorium performance:

- » Design for full-system performance, not component compliance.
- » Conduct hygrothermal modeling in high-risk environments.
- » Engage with manufacturers early to access proven details and products.
- » Field mock-ups should be required, supported by quality assurance/quality control protocols. For this project, designers specified that testing be performed both on the mock-up and on the completed

building. Establishing acceptance criteria during the mock-up phase allowed subsequent field testing to serve as verification, ensuring that the constructed assemblies met the agreed-upon performance requirements.

- » Prioritize materials that offer long-term chemical resistance.

CONCLUSION

Designing for natatorium environments demands more than simply adding vapor barriers and insulation. It requires a systemic understanding of moisture physics, material science, and architectural detailing. This paper

highlights the essential strategies to prevent premature failure, including the adoption of rainscreen assemblies, duplex-coated steel components, and integrated control layers.

A thorough case study demonstrated how advanced planning, manufacturer collaboration, and mockup testing deliver a resilient enclosure system capable of withstanding the harsh natatorium environment. By sweating the details, designers can protect investments, preserve building integrity, and reduce long-term liability.

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