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Schedule times and presenters are accurate as of press time in January 2024.

FRIDAY, MARCH 8, 2024

AUXILIARY SEMINAR

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SATURDAY, MARCH 9, 2024

GENERAL SESSION

8:00 a.m.–9:30a.m.

CONCURRENT SESSIONS

9:45 a.m.–10:45 a.m.

11:00 a.m.–12:00 p.m.

SUNDAY, MARCH 10, 2024

CONCURRENT SESSIONS

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2:45 p.m.–3:45 p.m.

Soar in 24

IIBEC International Convention & Trade Show

A Deep Dive into Hail-Caused Dents:
A Study of Corrosion Resistance within Dents in Galvalume-Coated Steel Roof Panels

ABSTRACT

This presentation is based upon the results of impact testing, salt-spray testing, metallurgical analysis, and field analysis of 26-gauge Galvalume metal R-panels. The panels were tested in accordance with UL 2218 Impact Resistance of Prepared Roof Covering Materials and then subjected to 336 hours of salt-spray testing. A metallurgical analysis of the simulated hail-caused dents in the panels was performed after the salt-spray testing. In addition to the simulated hail impacts, the panel was subjected to a foot-caused buckle in the rib and an induced scratch in panel. The results of this testing were compared to a case study of a 26-gauge Galvalume metal R-panel that was impacted by very large hail. The presentation also includes a discussion of micro-fracturing and water retention in dents included in previous studies by MBMA and others.

LEARNING OBJECTIVES

- Differentiate between and describe differences of various simulated hail-impact tests of metal roofs (including UL 2218 and ANSI FM 4473).
- Explain the effects of salt spray (fog) testing of 26-gauge aluminum-zinc alloy coated steel R-panels after simulated hail-caused impact testing and scribing.
- Describe the extent of corrosion (if any) typically detectable at real-world examples of large hail-caused dents in aluminum-zinc alloy coated steel panels.
- Compare the results from the laboratory testing to our real-world investigations and previous published studies to evaluate whether the conditions observed in the laboratory are analogous to real-world weathering effects.
- Explain the long-term effects of hailstone impact to the corrosion-resistance of aluminum-zinc alloy coating and whether those effects are expected to shorten the service life of steel roof panels.

SPEAKERS

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Mr. Beckner, PE, RRC, is the Director of Engineering Services at Roof Technical Services Inc. and a Registered Roof Consultant. He earned a Bachelor of Science in Mechanical Engineering from Baylor University and is a licensed professional engineer in eleven states. He has been working in the engineering field for more than 20 years, with more than 10 of those years specifically focused on roofs. He has investigated more than a thousand engineering projects related to storm damage, moisture intrusion, construction defects, structural failures, and building enclosure issues.

Stephen Patterson, PE, RRC
Roof Technical Services Inc., Fort Worth, Texas

Stephen L. Patterson, PE, RRC, has been in the roofing industry for 50 years. He founded Roof Technical Services Inc. (ROOFTECH) in 1983 and has been an active consulting engineer and roof consultant ever since. ROOFTECH has provided laboratory testing, including testing for hail damage and hail resistance of prepared roof coverings, since the late 1980s. Prior to becoming a consultant in 1983, he was a technical director/director of engineering for two roofing manufacturers and managed a roof contracting company.

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For metal roofs in hail-prone regions, such as the area stretching generally from Wyoming, through the Front Range, to Texas—commonly referred to as "Hail Alley"—the occurrence of hail-caused dents is more a question of "when" than "if." Consequently, in recent years the insurance industry has been writing exclusions or endorsements that limit coverage to the effects of hail deemed "functional," as opposed to "cosmetic" or "aesthetic." While various definitions abound, and it is not the intent of this paper to haggle over legalese, functional damage is generally considered to be damage (typically, dents or deformations) that results in diminished water-shedding ability of the roof assembly (in other words, that causes leaks) and/or damage that will reduce the roof assembly's expected service life. Conversely, cosmetic damage is generally understood to be dents that only affect the appearance of the panel, but not its performance or service life. An oft-cited industry definition is that used by United States Steel:[1]

> In general, hailstone damage can be categorized into two types: aesthetic damage and functional damage. Aesthetic damage is simply damage that has an adverse effect on appearance but does not affect the performance of the roof. Functional damage results in diminished water-shedding ability and a reduction in the expected service life of the roof.

The intent of the cosmetic damage endorsements and exclusions is fairly clear: to eliminate or reduce the insurance carrier's liability for hail-caused dents that do nothing but affect the appearance of otherwise functional roof panels.

Recently, however, various engineers, metallurgists, forensic experts, and other property-claim stakeholders have challenged the idea that hail-caused dents can ever be merely a cosmetic issue, even in cases that do not result in moisture intrusion. In the case of hail-caused dents that have not split, fractured, or punctured the metal, or otherwise compromised the panel's ability to resist moisture intrusion (such as by disengaging a seam), the argument that the dents still constitute functional damage generally comes in the form of a concern for the long-term performance, or service life, of the roof panels. The arguments against cosmetic-only dents typically take on one of two forms (or both). The first challenge usually goes something like this: "The hail-caused dents created microfractures (or microfissures, coating craze cracks, and the like), which will lead to premature failure of the corrosion-resistant coating and, in turn, premature corrosion of the underlying base metal." A related, but separate, challenge usually states something along the lines of "The hail-cased dents (or divots) will accumulate water, which will evaporate slower than the panel would otherwise (increasing the time of wetness) and accelerate coating deterioration, thereby causing premature corrosion of the underlying base metal." The intent of this paper is to evaluate these two assertions as they pertain to Galvalume-coated steel panels.

While there are a number of different metal panels currently available in the market, the most common types of panel are Galvalume-coated steel panels. As such, the focus of this paper specifically relates to effects of hail-caused dents in Galvalume-coated steel panels.

Previously, two recent research projects on the effects of hail to Galvalume-coated steel panels were commissioned by the Metal Building Manufacturers Association (MBMA).[2,3,4] A summary of these findings was also presented at the 2023 IIBEC International Convention and Trade Show in the proceeding "Oh Hail! Metal Roofs, Hail Impact, and Long-Term Performance."[5] In response to the arguments based on coating damage, the researchers concluded the following, as summarized by Dutton:

> The coating damage study is based upon a metallographic assessment of rollformed profile rib specimens from a 43-year-old roof in Denver. The profile of the Denver roof is representative of trapezoidal standing seam metal roofing that is common industry wide. The results show that a minor degree of metallic coating crazing may occur immediately upon manufacture and may even occasionally penetrate through the coating to expose the base steel, but that no detrimental corrosion has occurred on this roof for over 40 years. This observation is consistent with the unique and well-documented corrosion resistance mechanism characteristics of 55% Al-Zn alloy-coated steel globally.
>
> This study also demonstrated that the occasional minor degree

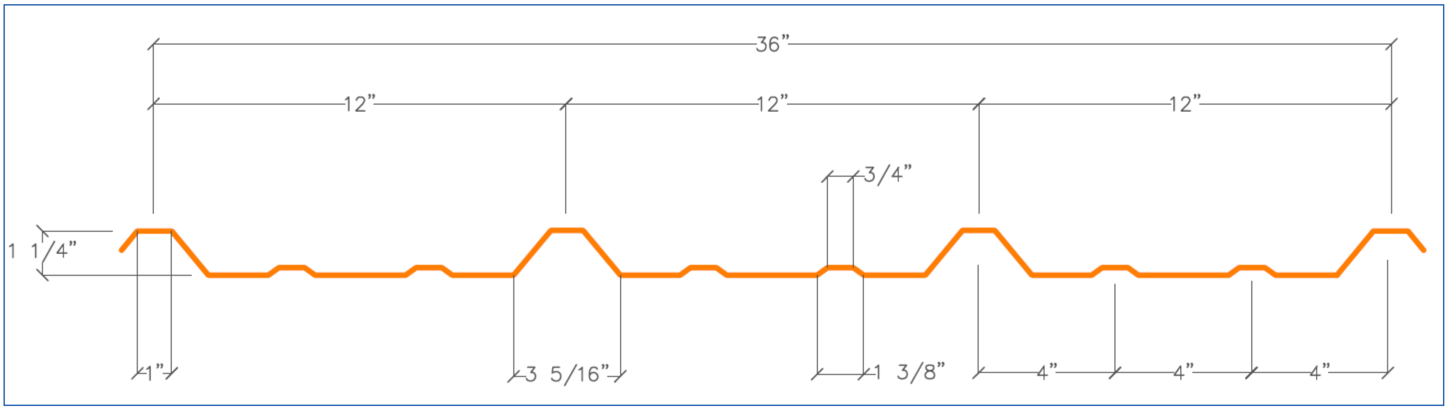

FIGURE 1. Diagram of a typical R-panel. .

of rollformed coating damage is much smaller in size than the size of 55% Al-Zn alloy-coated steel uncoated spots of up to 0.079 inches in diameter which, upon exposure to marine, industrial and rural atmospheres, showed no adverse effects on corrosion resistance after 9 years. In addition, the degree of coating damage associated with a recent hailstorm "functional" damage insurance claim was about 50 times smaller than the coating damage associated with rollforming on the 43-year-old Denver roof. Thus, it is concluded that such minute coating cracks or base steel exposures from hail impacts do not rise to the level of "functional" damage when compared to the degree of coating crazing which may occur on newly produced 55% Al-Zn alloy-coated steel roof panels.

In response to the arguments based on the accumulation of water ("ponding"), the researchers concluded the following, as summarized by Dutton:

The water ponding study is based upon a controlled laboratory assessment of the time required for water to evaporate from simulated hail divots in a commercially produced GALVALUME standing seam panel. A standard laboratory impact testing apparatus was used to produce simulated hail divots by delivering energy impacts of 1, 4, 8 and 13.3 ft-lbs, energies which correlate with hail stone diameters of about 1 to 1-3/4 inches striking a surface at terminal velocity. The resulting divots ranged in depth from 0.035 to 0.159 inches. To put this in perspective, hail stones measuring up to about 1-3/4 inches in diameter have been documented as representing about 75 to 95% of the hail stone diameters associated with hailstorms in the U.S. and Canada.

The study shows that the time for water to evaporate from 0.150-inch divots is faster than the times for evaporation to occur at intentionally manufactured mechanical deformations associated with panel flutes employed to strengthen roof panels. For hail divots up to about 0.160-inch depth, water evaporates in a small fraction of the time required for the sheared-edge panel eave to dry.

Based on these results, any argument that divots produced by hail stones up to about 1-3/4-inch diameter will result in accelerated corrosion of the 55% Al-Zn alloy-coated steel panel due to ponding water in the divots is not supported. Such 55% Al-Zn alloy-coated steel [standing seam roof] systems featuring flutes and sheared-edge conditions have performed excellently in service for over 40 years.

Our research builds on the findings of the previous research conducted by Dutton, Wilson, Giansante, Haddock, and others, in order to expand the knowledge base of this often-controversial topic. Our research was twofold:

- We commissioned a metallurgist for laboratory salt spray testing of panels with simulated hail dents.
- We evaluated the condition of in-service panels that were subjected to large hail impact (from hailstones up to approximately 2½ inches in diameter) more than 27 years prior.

SALT SPRAY TESTING

Roof Technical Services Inc. (ROOFTECH) secured a 26-gauge Galvalume-coated steel R-panel meeting ASTM A653 Grade 80 and UL 2218 Class 4 hail rating. **Figure 1** is a drawing by ROOFTECH showing the profile of the R-panel that was tested.

The R-panel was tested in general accordance with UL 2218-2012, *Impact Resistance of Prepared Roof Covering Materials*,[6] which is a test method that "provides impact resistance data for the evaluation of roofing materials." In addition, a rib of the panel was stepped on to simulate a typical foot-step deformation (buckle) in a rib, which commonly occurs on these types of roofs as a result of foot traffic or mishandling during maintenance, construction, or other rooftop activity. UL 2218 provides Class 1 through 4 hail impact resistance classifications. The test was based upon dropping 1.25-, 1.50-, 1.75-, and 2.00-inch steel balls from a distance calculated to simulate the kinetic energy of hail impacts of 1.25-, 1.50-, 1.75-, and 2.00-inch hailstones. The kinetic energy of hailstones has been established by the National

TABLE 1. Drop height and kinetic energy

Class	Steel ball diameter		Distance		Energy	
	in.	mm	ft	m	ft-lbf	J
1	1¼	31.8	12	3.7	3.53	4.78
2	1½	38.1	15	4.6	7.35	9.95
3	1¾	44.5	17	5.2	13.56	18.37
4	2	50.8	20	6.1	23.71	32.12

Note: Data from Underwriters Laboratories (2012).

Bureau of Standards and others. **Table 1** shows UL 2218's four hail classifications and associated kinetic (impact) energy.

Samples from the test panel subjected to the simulated hail impacts and footstep damage were delivered to Hurst Metallurgical Research Laboratory Inc. (HMRL) for metallurgical testing, which included a visual examination, salt spray (fog) testing, and evaluation at low and high magnifications using a variety of metallurgical methods both before and after salt spray (fog) testing was performed.

UL 2218 Impact Testing of Prepared Roof Covering Materials

The panels were stored inside at approximately 73°F, and each panel was subjected to two steel ball impacts: one in the rib and one in the flat portion of the panel. The locations of the impacts were circled and noted on the panel. **Figure 2** shows the tower used to drop the steel balls and a view of a typical panel after the UL 2218 impact testing (in this case, the impacts shown were from 1.25- and 1.50-inch steel balls dropped from a height calibrated to approximate the energy of 1.25- and 1.50-inch hailstones).

The width and depth of the resulting dents were measured. **Figure 3** shows the measurement of the depth of the dents resulting from the 2.00-inch steel ball impacts to the rib and flat portion of the panel.

Research performed by others and ROOFTECH's experience had found the impact dents in metal panels typically exhibit an inside diameter and an outside or overall diameter. Mathey[7] first reported the phenomenon wherein impacts to metal panels form a shallower outside dent and a steeper inside diameter. Mathey[7] included a diagram showing these diameters, which are depicted in a diagram of the typical cross section shown in **fig. 4**.

The depth and width of the indentations were measured. **Table 2** summarizes the recorded measurements of the width and depth of the indentations resulting from the various hail sizes. UL 2218 states, "visual observations are to be facilitated by examining the samples under 5x magnification and the observations recorded for each impact location." The samples were examined under 5x magnification, and there were no visible cracks in the coating or other evident failure of the metal panel. There was some scuffing of the Galvalume surfacing resulting from the steel ball impacts, which would not be expected from actual hailstones. The impact locations were also examined under 80x magnification. **Figures 5** and **6** are photographs taken at the maximum magnification of an 80x microscope with no evidence of a fracture in the Galvalume coating or failure of the panel.

Most metal roof panels, including 26-gauge Galvalume metal R-panel roofs, meet UL 2218 Class 4, which is the highest rating available with the UL 2218 test. Our testing corroborates the Class 4 resistance and provides an example of the approximate sizes of dents that can be expected from the various hail sizes.

FIGURE 2. Test apparatus.

FIGURE 3. A field dent depth measurement.

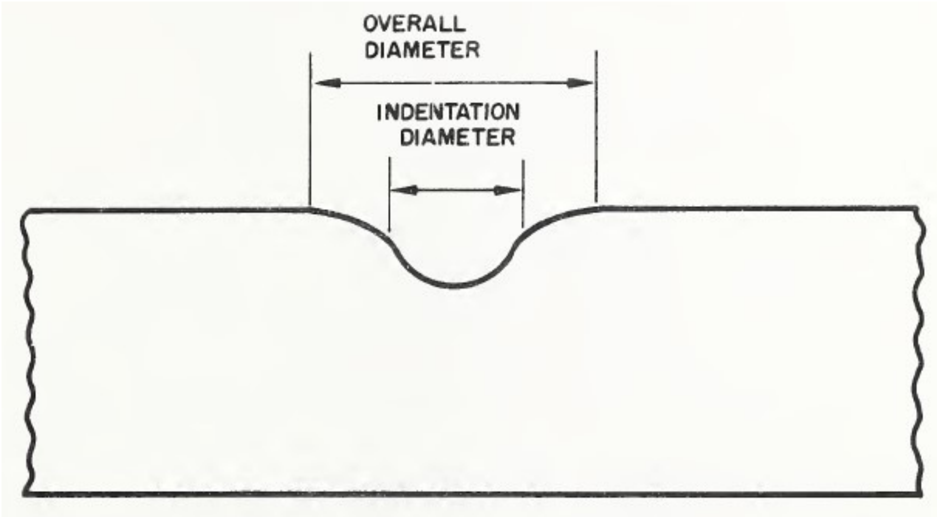

FIGURE 4. Diagram showing inside and outside or overall diameter of impact dents in metal panels. .

TABLE 2. Depth and width measurements of the panel dents by various-sized steel balls

Hail size, in.		Field dent, mm	Rib dent, mm	Field dent, in.	Rib dent, in.
1.25	Depth	0.14	1.01	0.01	0.04
	Width	5.08	24.13	0.20	0.95
1.5	Depth	0.32	2.14	0.01	0.08
	Width	10.16	27.94	0.40	1.10
1.75	Depth	0.96	3.13	0.04	0.12
	Width	12.7	30.48	0.50	1.20
2.0	Depth	1.17	3.56	0.05	0.14
	Width	13.97	27.94	0.55	10.10

Hurst Metallurgical Research Laboratory

A total of 11 samples were extracted from the test panel and delivered to HMRL in Euless, Texas, for metallurgical testing. The salt spray testing was performed in accordance with ASTM G85-11, Annex 5 Dilute Electrolytic Cyclic Fog/Dry test method. The HMRL examination included a visual examination; salt spray (fog) testing; and evaluation under various levels of magnification, using a variety of metallurgical methods both before and after salt spray (fog). The 11 test samples included the eight samples that had been impacted by the 1.25-, 1.50-, 1.75-, and 2.00-inch steel balls and two samples that HMRL scribed (scratched) to simulate a large crack in the Galvalume coating. Finally, the sample with the rib buckle caused by foot pressure was also tested. The HMRL findings are contained in Madhani.[8] **Table 3** shows Madhani's summary of the findings of the salt spray testing; note that the rust observed within the 1¾-inch dent on the rib surface and 2-inch dent on the rib surface was found to be corrosion of the superficial residue from the steel ball and was not corrosion of the steel panel itself.

No visual evidence of corrosion (specifically, iron oxide or rust) was observed on the scribed roof surface after 336 hours. Isolated rust was

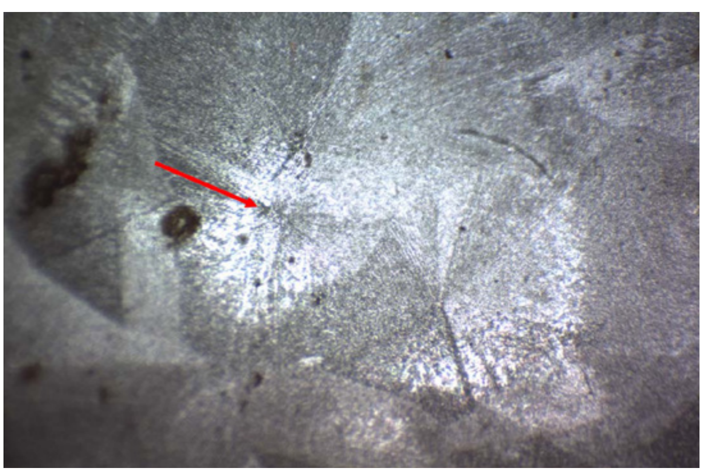

FIGURE 5. A view of a 1.75-inch steel ball impact point center under 80x magnification. The red point indicates a coating scuff.

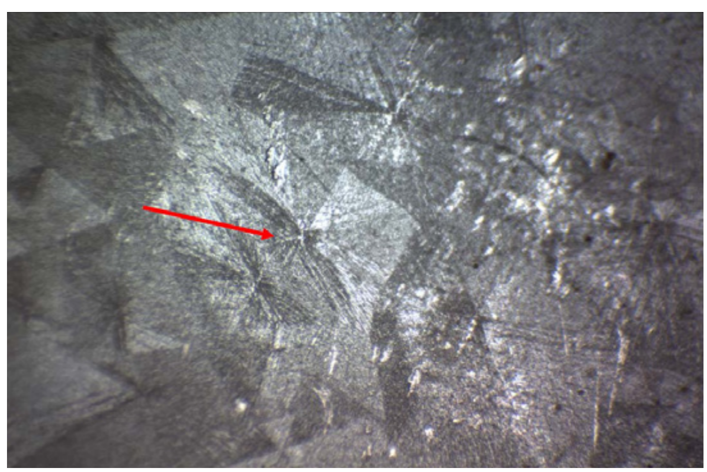

FIGURE 6. A view of a 2-inch steel ball impact point center under 80x magnification. The red point indicates a coating scuff.

TABLE 3. Summary of Salt Spray Testing

Specimen	Results								Comments
	After 72 hours		After 162 hours		After 252 hours		After 336 hours		
	Within dent.	Outside of dent	Within dent.	Outside of dent	Within dent.	Outside of dent	Within dent.	Outside of dent	
1¼ in. dent on rib surface	10	10	10	10	10	10	10	10	
1¼ in. dent on flat surface between ribs	10	10	10	10	10	10	10	10	
1½ in. dent on rib surface	10	10	10	10	10	10	10	10	
1½ in. dent on flat surface between ribs	10	10	10	10	10	10	10	10	
1¾ in. dent on rib surface	10	10	9-S	10	9-S	10	9-S	10	Isolated rust-colored spots observed after 162 hours
1¾ in. dent on flat surface between ribs	10	10	10	10	10	10	10	10	
2 in. dent on rib surface	10	10	10	10	10	10	9-S	10	Very slight rust-colored spots observed after 336 hours
2 in. dent on flat surface between ribs	10	10	10	10	10	10	10	10	
Scribed on rib surface	10	10	10	10	10	10	10	10	
Scribed on flat surface between ribs	10	10	10	10	10	10	10	10	
Footstep on rib	9-S	10	9-S	10	9-S	10	8-S	10	Isolated rust at scuffed area first observed after 72 hours

Note: Data from Madhani (2017). For dents, 10 = <0.01% surface rust; 9 = >0.01% and <0.03% rust; S = spot per ASTM D610-08 (2012). For scribes, 10 = 0 in. creepage per ASTM D1654-08 (2016).).

observed within the footstep buckle after 72 hours. Slight rust-colored spots were observed on the dented ribs from the 1.75- and 2.00-inch simulated hail impacts after 252 hours on the 1.75-inch test sample and after 336 hours on the 2-inch test sample.

However, the examination of these rust-colored spots "revealed that the rust-colored spots were extremely superficial" and, upon further investigation, were found to be caused by residuals from the steel ball—an effect that would not occur with real hailstone impact. Madhani[8] noted that there was "no evidence of cracking or pitting of the coating" at the impact locations. The spots were cleaned and examined and "no cracking or corrosion of the coating or the substrate" was observed.

The scribed sample, which was tested to simulate a crack in the coating, revealed no evidence of rust

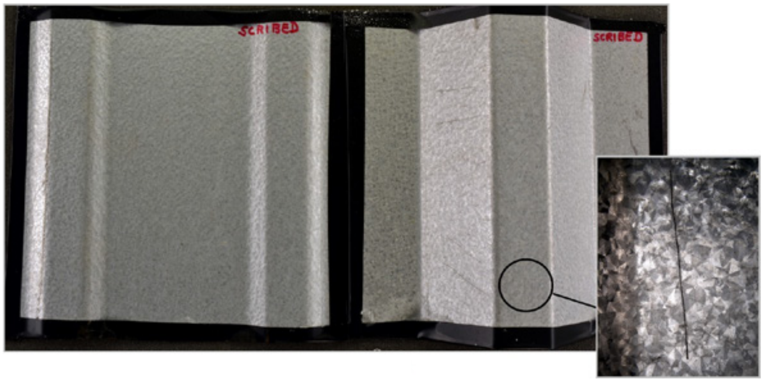

FIGURE 7. Photograph of the scribed samples of Galvalume roof panel sample showing the lack of visible evidence of corrosion following 336 hours of test cycle. Reproduced with permission from Madhani (2017).

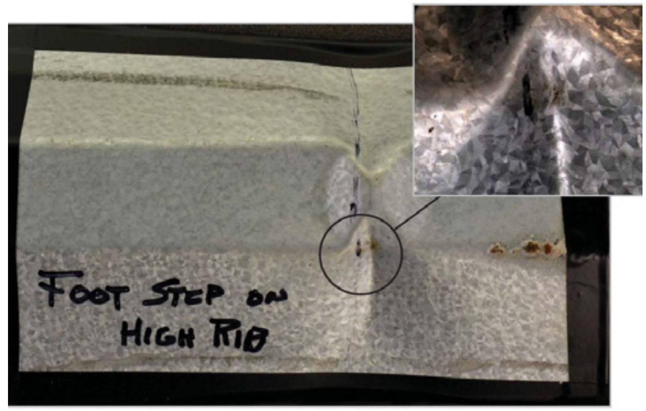

FIGURE 8. Photograph of footstep buckle showing corrosion after 162 hours of salt spray testing. Reproduced with permission from Madhani (2017).

after 336 hours of salt spray (fog). The cracks extended through the coating and into the carbon steel and were visible without magnification. Madhani[8] concluded, "the absence of corrosion of the carbon steel demonstrates the galvanic protection provided by the coating on exposed areas of the substrate." **Figure 7** is an excerpt from Madhani[8] showing the scribed area after 336 hours of salt spray (fog) testing with no evidence of corrosion. However, at the crimped area of the foot-pressure-created rib buckle, corrosion was evident after 162 hours in the salt spray at the crimped area of the footstep buckle. **Figure 8** shows the corrosion at the footstep buckle after 162 hours.

Madhani[8] concluded, "The various metallurgical tests and evaluations of the simulated cracks and hail impact dents in the GALVALUME® carbon steel panels … performed satisfactorily and disclosed no evidence of any corrosion to the substrate carbon steel material" even after exposure to 336 hours of salt spray (fog). The metallurgical testing did reveal corrosion occurring in the sample damaged by the footstep and within a mechanically scuffed portion. This indicates that the salt spray testing was sufficient to cause corrosion to portions of the panel at which the Galvalume coating sustained significant damage.

REAL-WORLD CASE STUDY

Background

One of the most damaging hailstorms in history occurred in Fort Worth, Texas, on May 5, 1995. The storm caught 10,000 people outside without shelter at a spring Mayfest event. More than 400 of those attending Mayfest were injured, including 60 who required hospitalization. There was widespread softball-sized hail across Fort Worth that caused an estimated $2 billion in damages, and the hailstorm became known as the "Mayfest Storm."[9] According to the National Centers for Environmental Information's Storm Events Database, there were several

FIGURE 9. Photograph of the case study roof taken in 2013, approximately 18 years after the hail event, when the roof was 27 years old.

FIGURE 10. Photograph of the dents in the case study roof caused by the Mayfest Storm.

FIGURE 11. Photograph of typical hail-caused indentations with stains in the dents.

FIGURE 12. Photograph of a cleaned hail-caused dent—note the absence of evident corrosion.

FIGURE 13. Photograph of a cleaned hail-caused dent under 10x magnification—note the absence of evident corrosion.

reports of hail within Fort Worth (the location of the subject case-study building), including reports of 2.75-, 3.5-, and 4-inch hailstones.[10]

The building that is the subject of this case study is a one-story strip shopping center built in 1986 and located on the east side of Fort Worth. The general construction consists of a slab-on-grade foundation with pre-engineered metal building framing and a 26-gauge Galvalume steel R-panel roof. The roof panels were attached to Z-purlins approximately 5 feet apart using screws with rubber washers. There were stitch screws at the side laps approximately 24 inches on center.

Inspection and Analysis

The roof on the building was subjected to impact from hailstones up to at least 2½ inches in diameter, with some hailstones possibly reaching 4 inches. The roof was not replaced after the Mayfest Storm. The roof on the building had numerous dents but no hail-related leaks. The building has a history of minor leaks occurring at the end laps of the metal panels and at screws. In 2013, one of the authors reinspected the roof to evaluate its performance. **Figure 9** is a photograph of the roof taken in 2013, approximately 18 years after the hail event, when the roof was 27 years old. The roof leaks were minor and in generally the same locations, related to end laps and screws, as they were in 1995. There were a few repairs to the screws and penetrations.

Numerous hail-caused dents were visually examined, including examination at 10x to determine if there had been any deterioration as a result of the hail-caused dents. **Figure 10** shows typical hail-caused indentations with stains in the dents that were randomly spaced across the roof.

The larger hail-caused dents were stained with sediment in the dents. **Figure 11** shows a close-up of one of the larger hail-caused dents with stains. **Figure 12** shows the hail-caused dent cleaned. There was no evidence of corrosion or other evidence of deterioration. **Figure 13** shows a 10x view of the impact area. There is no visible corrosion or deterioration of the Galvalume coating at 10x.

Stains at the screws and end laps of the panels had stains similar to the stains at the hail-caused dents. This type of staining is normal and commonly occurs on these types of metal roof. There was no evidence of corrosion in the Galvalume panel. There was, however, corrosion on the screw. At the end lap panels, the overlap results in a shallower slope (with slower drainage and evaporation) and, consequently, staining similar to the staining in the hail-caused dents. There also appeared to be some evidence of slight pitting of the Galvalume coating at the end lap.

In 2022, one of the authors again reinspected the roof to evaluate its performance. **Figure 14** shows an overview of the roof on the building taken in 2022 approximately 27 years after the Mayfest Storm. The roof was approximately 40 years old at the time of this inspection. Overall, the appearance of the roof was in a substantially similar condition to its condition at the previous inspection.

Again, numerous hail-caused indentations were visually examined and

FIGURE 14. Photograph of case study roof taken in 2022 approximately 17 years after the Mayfest Storm.

FIGURE 15. Photograph of large dent in the rib of the panel.

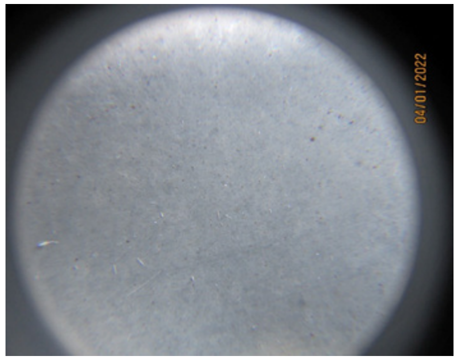

FIGURE 16. Photograph of cleaned dent in the rib under 10x magnification.

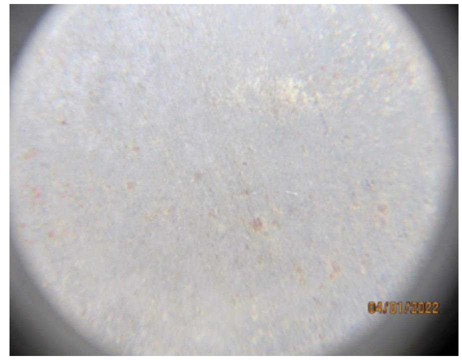

FIGURE 17. Photograph of small spots of corrosion at the eave panels of the 40-year-old roof.

examined under 10x magnification. **Figure 15** shows a large dent in the rib of the panel with sediment accumulation. **Figure 16** shows a 10x view of a rib dent after cleaning with no evidence of corrosion. However, small spots of corrosion were beginning to show at the eaves after 40 years of service, shown in **fig. 17**.

Case Study Conclusions

There was no evidence of corrosion at the various hail-caused impacts after 27 years of weathering, though there were staining and sediment accumulations at the hail-caused dents. The Galvalume panels were performing well, and there was no evidence of corrosion in the metal panels caused by the hailstone impacts. We found that there was no visible evidence of corrosion at the hail-caused indentations. We also found that the sediment in at the depressions in the metal panels at the screws and the sediment at the end laps and eaves were similar in appearance to the stains in the hail-caused dents, which is consistent with the findings reported in Dutton and Wilson.[3] In this case study, it appeared that there were some minor pits from corrosion in the Galvalume coating at end-lap seams that were not present in the hail-caused dents.

CONCLUSION

The salt spray metallurgical testing verified that dents caused by impacts from steel balls up to 2 inches (with the approximate energy of a similarly sized hailstone) would not be expected to corrode at a rate that would exceed the rate of other areas of the panel due to normal weathering, such as at end-lap seams or overtightened fasteners, or at areas with mechanical-type damage, such as at rib buckles. The metallurgical study included subjecting the dented samples from the test panel to salt spray testing for 336 hours, which is a significantly more corrosive environment than normal atmospheric conditions, and evaluating the sample before and after the test. This metallurgical evaluation confirmed that there was no corrosion as a result of the simulated hail-caused dents in the metal panels even when subjected to the salt spray testing. The metallurgical study also showed that there was no corrosion in the scribed areas. Moreover, the lack of corrosion in the scribed areas confirmed that the coating performed as designed to prevent corrosion, even if the coating had minor scratches or cracks. The testing was, however, sufficient to cause corrosion in areas of the panel that were buckled by footfall and mechanically scuffed.

The observations of the subject case study found that Galvalume-coated steel panels were not corroded at the hail-caused dent locations, even after 27 years of weathering. The Galvalume-coated panels were performing well, and there was no evidence of any significant deterioration in the metal panels caused by the hailstone impacts. We also found that the sediment in at the depressions in the metal panels at the screws and the sediment at the end laps and eaves were similar in appearance to the stains in the hail-caused dents, which is consistent with the findings reported in Dutton and Wilson.[3] While this study was limited to panels subjected to hailstones up to approximately 2½ inches, larger hail is an extremely rare occurrence and thus, these results are comparable to the large majority of cases of hail-dented Galvalume-coated panels, most of which would have been impacted by smaller hail. This case study was consistent with the authors' experience inspecting thousands of hail-dented Galvalume-coated metal roof panels, none of which have ever exhibited corrosion correlated to the dent locations. Moreover, the authors have never seen photographs of Galvalume-coated panels with corrosion specifically correlated to hail-caused dents (though if such photographs exist, we welcome their production).

Together, the metallurgical testing and case study indicated that metal roof panels will generally corrode at various areas due to normal weathering before they would be expected to corrode at dents caused by impact from hailstones up to 2½ inches. In other words, by the time hail-caused dents corrode, the metal panels will have already corroded elsewhere and, therefore, these hail-caused dents will not result in a reduction of their expected service life. In sum, based on the salt spray testing and the case study, it can be concluded that hail-caused dents from hail 2½ inches or less will not corrode at an accelerated rate such that their expected service life is shortened. With regard to the distinction between cosmetic and functional damage, the authors conclude that unless they cause a vector for moisture intrusion (such as a split panel or seam disengagement), dents caused by hail up to 2½ inches will generally not meet the definition of functional damage and are deemed cosmetic.

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Conundrums in Stucco Codes and Standards

ABSTRACT

Minimum requirements for portland cement-based plaster (stucco) wall cladding design, construction, and products for buildings are specified in the building code and its ASTM stucco reference standards, where harmony is expected. However, certain aspects of these requirements are confusing or not explicitly clear, inducing conflict and division which pervades the stucco industry in the US. Clear, fact-based, and compelling answers to the most significant stucco conundrums facing the stucco industry today are presented as significant new information, resulting from specialized research and a combined 60+ years of stucco industry experience to encourage consistency and quality within the stucco industry going forward.

This presentation contains advanced-level subject matter. Attendees should be familiar with stucco cladding requirements found in the *2021 ICC Building Code* Chapters 1 and 25, and reference standards *ASTM C926-18b*, *C1063-18b*, and *C1861-18*.

LEARNING OBJECTIVES

- Recognize stucco is an assembly of different components, assembled in different ways, to achieve the intended quality and performance specific to each project.
- Explain the building officials process for review and approval of alternative means and methods, including the requirement for approved testing.
- Distinguish between mandatory and non-mandatory language in ASTM standards and differentiate between minimum requirements and nonrequirements.
- Explain why the EOS clauses are neither valid nor enforceable and meet the International Building Code requirements at 102.5 for Partial Invalidity.
- Recognize legitimate, codified regional practices for stucco claddings in the building code and ASTM standards.

SPEAKERS

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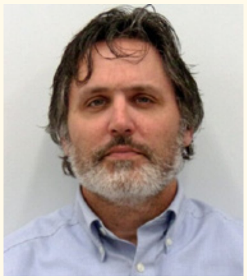

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ESSENTIALS OF THE BUILDING CODE: 2021 IBC

For this paper, references to the building code refer to the *2021 International Building Code*[1] (IBC), the model building code generally adopted and enforced in many states in the US. The building code both broadly and specifically establishes the minimum requirements for providing a reasonable level of safety, health, and general welfare for building construction. It requires a reasonable level of life safety and property protection from hazards such as fire, by providing a reasonable level of safety to fire fighters and emergency responders during emergency operations.[2] Building codes rely on the expertise of industry professionals expressed in code-adopted reference standards which are developed by specialized industry professionals through consensus organizations such as ASTM, ANSI, and NFPA.

Reference standards for stucco are developed following the consensus process, by industry stakeholders consisting mostly of product and material manufacturers, designers, and stucco trade partners. The benefits of building code—adopted reference standards to the construction industry are vast. They include improvements to economic, training and expertise, material and product uniformity, inspection, and craftsmanship. In other words, reference standards benefit construction quality, establish the minimum expectations of building construction stakeholders, and support the purpose of the building code as previously described.

The IBC is the generic model code promulgated by the International Code Council which is largely adopted and enforced by most local building construction regulatory jurisdictions in the US and currently reaches into a few international jurisdictions such as for Abu Dhabi, United Arab Emirates. Where adopted, the IBC is often locally revised to best accommodate local conditions for local enforcement. The building construction community including building code officials, designers, stucco trade partners, and manufacturers are required by various laws and regulations to comply with building code minimum requirements, which are law.

Regarding our topic of conundrums in stucco codes and standards, it needs to be clearly stated and understood that not all stucco is the same. Stucco exterior-wall cladding is an assembly of many different materials and products installed and applied in different ways to achieve the intended quality and performance which varies as specified, from project to project. The IBC in Chapter 25[3] describes several specific stucco cladding requirements such as for approved substrates including gypsum sheathing over framing and cementitious "solid" bases. Over framed substrates a water-resistive barrier is required under lath and cement plaster to function as a drainage plane, whereas cement plaster direct applied to solid bases function as barrier walls due to their mass and ability to accommodate a minimum amount of water penetration. The IBC describes additional specific requirements such as for weep screeds at the drainage plane, and the most recent requirements for drainage layers under cement plaster in wetter climates and for continuous insulation under certain stucco claddings.

As required in the IBC, stucco claddings for building exteriors are required to be 1) portland cement-based plaster (not lime-based or any other type of plaster), and 2) that cement plaster be applied over an approved, mechanically fastened lath or directly bonded to approved cementitious solid bases. Most significantly, the IBC requires that portland cement-based plaster for building exteriors comply with the prescriptive requirements of ASTM reference standards: C926 for Plastering Application, C1063 for Lathing Installation, and C1861 for Lathing Accessories, and additionally the specified lathing and product standards and material standards such as for C150 portland cement. The IBC-adopted ASTM reference standards describe the minimum requirements for stucco cladding as individual components and of the completed, functional assembly.

As with stucco, architectural building designs and construction projects are not always the same, and designers and stucco trade partners occasionally seek more than the prescriptive solutions in the IBC and reference standards to comply with the building code requirements. The local building official is ultimately responsible for local building code enforcement. Approval from building officials for using atypical materials, products, and stucco cladding systems typically follows the routine requirements, a review and approval process similar, if not identical, to that required by the IBC 104.11[4] for *Alternatives*. This process is routine for using certain proprietary materials and systems with a code evaluation report and known by the building official and design professionals, but sometimes stucco trade partners are not aware of the requirements or approval process for Alternatives. Receiving approval for Alternatives requires building official evaluation of the proposed Alternative for quality, strength, effectiveness, fire resistance, durability, and safety. The evaluation is based on the approval of research reports from approved sources and testing by approved agencies.

ESSENTIALS OF THE ASTM STUCCO STANDARDS – C926, C1063, C1861

Where the IBC text states a limited number of actual technical requirements for stucco claddings, it most significantly adopts by reference and requires building official enforcement of the minimum requirements contained in the adopted reference standards for stucco claddings which are much more comprehensive. The primary reference standards for stucco are ASTM 926[5] and C1063,[6] and the IBC building code adoption requirements for reference standards are detailed in *ICC Reference Standards Guide*[7] and ICC Council Policy document *CP #28-05 Code Development (CP28)*[8]. Among the basic and essential requirements for the IBC building code codified reference standards to be enforceable, the requirements of reference standards must be 1) stated in mandatory language (to establish enforceability), and 2) shall not state that its provisions govern whenever the referenced standard is in conflict with the requirements of the referencing code (to establish a hierarchy of authority).

Each of these codified reference standards includes by internal reference, the requirements of second-tier reference standards such as ASTM C847, C933, and C1032 for lathing products, and C1861 for lathing accessories and fasteners.[9] Second-tier reference standards are equally codified minimum building code requirements and are enforceable by building officials.

ASTM coordinates the development of industry reference standards categorized as Classification, Guide, Practice, Specification, Terminology, and Test Method. Note that the primary ASTM stucco standards are Specifications. ASTM Specification standards are developed following ASTM requirements described in the document *Form and Style of ASTM Standards (Form and Style).*[10] *Form and Style* requires that Specifications be "an explicit set of requirements to be satisfied by a material, product, system, or service." Enforceable, codified requirements are stated in explicit, mandatory language, not vague, ambiguous language which is subject to multiple interpretations. Mandatory language requirements use the term 'shall' and not 'should' or 'may.' All terms shall be defined when they deviate from an ordinary accepted meaning or a dictionary definition.

ASTM reference standard Specifications for stucco claddings follow a consistent organization for ease of use: Scope, Referenced Documents, Terminology, Delivery and Storage of Materials, Materials, Substrate Requirements, Installation (or Application) Requirements, Keywords, and optionally an Annex and Appendix.

An interesting aspect of ASTM stucco standards, as Specifications, is a conundrum which is frequently misunderstood in their scope, which is stated in Section 1.1 of each standard. For example, this is from ASTM C1063, but other stucco Specifications are similar:

> 1.1 This specification covers the minimum technical requirements for lathing and furring for the application of exterior and interior portland cement-based plaster, as in Specifications C841 or C926. These requirements do not by default define a unit of work or assign responsibility for contractual purposes, which is the purview of a contract or contracts made between contracting entities.

The scope of the ASTM stucco Specification describes the requirements for stucco cladding as a system. The scope is not solely a scope of work defining the work required of a specific craftsperson unless the general contractor designates and coordinates the work of all of the stucco Specification requirements to a specific trade partner. For example, ASTM stucco Specifications include requirements for gapping wood-based sheathing panel edges as substrates for stucco, which is more appropriately designated to the carpentry trade which installs the panels. Likewise, requirements for framing member deflections are an engineering design responsibility. The sealant application requirements specified in C926 may best be performed by a sealant trade partner. Other conundrums as far as assigning contractual responsibilities include requirements such as wood-based framing installation tolerances, substrate moisture content verification, and trade coordination for utilities and flashings. These requirements specified in ASTM stucco standards are for the general contractor in charge of coordinating and allocating the work amongst various trade partners to define, determine, and coordinate. Even ASTM stucco standards whose titles begin with "Installation of" or "Application of" are much more than merely construction how-to requirements for sole use by craftspeople. ASTM stucco standards state requirements for materials and products by manufacturers, for stucco designers, which are relied upon by inspectors, which collectively determine the requirements and expectations for quality.

Content in the ASTM stucco standards Annex and Appendix sections has proven to be problematic in the industry due to the use of conflicting terminology that causes misinterpretations and misapplications. Fundamentally, ASTM requires that Annex information be stated in mandatory language and contain mandatory, enforceable requirements. *Form and Style* requires Annexes to be subtitled Mandatory

Information and defines Annex information as "any detailed information such as that an apparatus or material that is a mandatory part of the specification; but too lengthy for inclusion in the main text." Further, *CP28* states that "mandatory language is applicable to the standard or the portion of a standard that is intended to be enforced."

To illustrate a few conundrums, please review the ASTM C926 Annex, subtitled Mandatory Information. Conflict and disagreements arise around the use of the sections titled "Information" (not "Requirements") and "A2. Design Considerations" (again, not "Requirements"). Consider that these titles are mere section titles and not technical content. ASTM C926 Annex technical content includes requirements for conditions such as the fire resistance of cement-plastered assemblies; substrate requirements for solid bases to receive cement plaster; slope requirements to prevent water, snow, or ice from accumulating; coordination of flashings; the sealing of cement-plaster panel edges to prevent the entry of water; drainage provisions behind cement plaster; requirements for ornamental features; and much more. Clearly, the technical content stated in mandatory language of the conditions addressed in C926 are enforceable requirements in spite of their unfortunate section titles. Be assured that ASTM committee C11 overseeing ASTM stucco standards is in the process of rectifying these conundrums to state requirements in clear, unambiguous, explicit language, including their titles.

In contrast, ASTM C926 Appendix information is stated in non-mandatory language. Its information is not enforceable. Form and Style requires Appendix information to be subtitled "Nonmandatory Information," to which the ASTM C926 Appendix conforms. *CP28* further clarifies that information in the Appendix are not enforceable requirements as long as they are not stated in mandatory language and "clearly and conspicuously identified as not being a mandatory part of the standard." The ASTM C926 Appendix includes technical content such as optional finish-coat texture descriptions, optional fiber additive information, and guidance for critical lighting evaluation, which are informational but are not enforceable requirements.

Other conflicts and division within the stucco industry are not yet addressed by the building code or its reference standards. Examples of some of these issues are driven by differences in climate, regional practice, installer preference, or to some extent an interest in minimizing costs. Examples include requirements for minimum redundancies such as sealant around windows/doors to "prevent the entry of water." Stucco cladding by itself is not waterproof, as explicitly stated in ASTM C926 Annex A2.1.1, as some amount of bulk water gets through stucco cracks and around stucco panel edges at joints and openings, such as windows, doors, and penetrations.

The reality for stucco claddings is that in all climates, including arid climates, where stucco cladding is used, wind-driven rain occurs if not frequently, then at least sporadically. The minimum requirements for a vapor-permeable water-resistive barrier behind stucco, a dry-lapped membrane with countless lath fastener penetrations remains the minimum requirement for stucco claddings intended to protect water-sensitive substrates and assemblies. Preventing bulk water from penetrating around the exposed ends and edges of cement-plaster panels of stucco cladding with sealant joints as required in ASTM C926 Annex A2.1.3 is a mandatory requirement too often overlooked, as it benefits the water management function of the stucco-clad drainage plane. Arguments to omit sealant "to prevent the entry of water" in dry climates are ill-founded—as proof, consider recent weather extremes throughout the US, including in arid climates. Death, taxes, and wind-driven rain are unavoidable wherever one may reside.

Inexplicitly worded text in ASTM C926 continues to cause industry conflict. Challenges to achieving consensus include a host of reasons such as differences in regional preferences and practices, climatic variations, fear of litigation, and other influences. ASTM Committee C11, responsible for developing ASTM stucco standards, conforms to a rigorous process to achieve consensus in the development of stucco industry standards that are codified in our building code. The following are some example passages that Committee C11 continues to attempt to resolve:

ASTM C926 at 7.3.4: "Separation shall be provided where plaster abuts dissimilar construction materials or openings." The definition of "dissimilar construction materials" is subject to various interpretations. Is a casing bead a dissimilar material to the plaster, or is it part of the plaster assembly?

ASTM C926 at A1.5.2: "Lathing accessories shall be installed prior to the application of plaster; therefore, their type, location, ground dimension, and orientation shall be included in the contract documents." What does "orientation" mean? Some think of orientation in terms of vertical and horizontal, while others consider orientation to be the layering of a construction assembly.

ASTM C926 at A2.1.1: "Sufficient slope on faces of plastered surfaces shall be provided to prevent water, snow, or ice from accumulating or standing." What is sufficient slope? For sheet metal, it could be as little as simple positive slope. For an articulated textured cement-plaster surface, a steeper slope is needed, but how much steeper? For example, proprietary acrylic-finish coatings require a 6:12 minimum pitch.

ASTM C1063 at 7.3.1.5: "Lath shall not be continuous through control joints, but shall be stopped and tied at each side." This oft-quoted requirement is probably the most ignored and unenforced requirement in the stucco industry, and yet control joints with discontinuous lath, where effectively used, are known to reduce stucco cracking by 50%.[11,12] The text is inadequate by not explicitly stating all requirements for installing control-joint lathing accessories where the edges of discontinuous lath must be fastened to framing members to prevent cement-plaster panel-edge curling—the framing and attachment is rarely detailed.

ASTM C1063 at 7.4.6: "*Casing Bead*—Install a casing bead lathing accessory or other suitable means, at locations to separate cement plaster from dissimilar materials, penetrating elements, load bearing members and to avoid transfer of structural loads." Exactly what does "other suitable means" describe? Some opine that separation refers to the cement plaster shrinking away from windows and doors creating the separation, but that narrow gap allows bulk water entry behind the hardened stucco cladding, and the gap is too narrow to be effectively sealed against the "entry of water" as required elsewhere in ASTM C926.

Another point—when the requirements of the building code and ASTM reference standards conflict, which governs? This is an easy one, and it is very clear. The IBC building code states at 102.4.1: "Where conflicts occur between provisions of this code and referenced codes and standards, the provisions of this code shall apply."

ASTM C926 – THE EOS CLAUSES

As previously established, ASTM C926 and C1063 are the specifications prescribed by the code for the installation of cement-based plaster. According to the code, C926 and C1063 establish the **minimum** requirements.

While ASTM C1063 generally addresses specifications for the installation of lathing and furring to receive cement-based plaster, and ASTM C926 generally addresses specifications for the application of cement-based plaster, ASTM C926 does include some specifications regarding the installation of lathing accessories and fasteners, including:

- 6.1 Metal plaster bases, lathing accessories, furring accessories and fasteners used to receive plaster shall be installed in conformance with Specification C1063, ***except as otherwise specified***.
- A1.5.1 Metal plaster bases, backing, attachment, and lathing accessories to receive plaster shall be examined to determine if the applicable requirements of Specification C1063 have been met ***unless otherwise required by the contract specifications***.

Additionally, ASTM C1063 includes the following:

- 7.10.1.3 Lath shall be installed with the long dimension at right angles to the framing members, ***unless otherwise specified***.

It should be noted that the term "specifier" is also used within ASTM C926, but it is not explicitly defined within the standard.

The phrase "except as otherwise specified" and similar wording within ASTM C926 and C1063 have been misinterpreted and misapplied by some who are specifying conditions that do not comply with C1063.

One part of their argument is that the "specifier," in their view, has the right to provide alternative installation materials or methods as they see fit, without the review and approval of the building official or the authority having jurisdiction (AHJ).

Another part of their argument includes the opinion that ASTM C926 and C1063 are "application standards," not "design standards," and thus the "except as otherwise specified" clauses were added to allow the "specifier" to make those substitutions.

This statement is simply not true, as ASTM C926 includes a "Mandatory" section titled "Design Considerations," which includes requirements for the designer.

An additional factor in their argument is the opinion that different regions and climates require different installation methods, which they say are not factored into the "international" codes and standards, and therefore they must be specified on a case-by-case basis.

Some of the "alternative methods" we have seen specified and/or installed include but are not limited to:

- Omission of control joints
- Excessive distance/area between control joints
- Omission of casing beads and/or sealant at windows, doors, and other wall openings
- Installation of window frames with integral stucco keys without perimeter sealant
- Omission of sealant at lathing accessory joint splices/intersections/transitions
- Installation of weep/drip screeds over the water-resistive barrier (not lapping the water-resistive barrier over the weep screed attachment flange)
- Omission of weep/drip screeds where horizontal and vertical surfaces intersect
- Omission of foundation weep screeds when wood-framed construction is over solid-base construction
- Installation of lath continuous through control joints
- Metal lath not installed backing on backing and metal on metal
- Fastening down of lath laps between framing members rather than wire-tying
- Installation of "face barrier" systems where control joints and weep/drip screeds are eliminated altogether

This misinterpretation or misapplication of the "except as otherwise specified" clauses has caused or contributed to property damage, such as water intrusion, structural wood framing member decay, microbial growth, etc., in some cases creating dangerous or unsafe conditions.

FIGURE 1. Example of damage resulting, at least in part, from fasteners installed between framing members.

FIGURE 2. Example of damage resulting, at least in part, from lath not installed backing on backing and metal on metal.

FIGURE 3. Example of damage resulting, at least in part, from the fastening down of the control joint accessory.

FIGURE 4. Example of damage resulting, at least in part, from improper separation between window and stucco.

FIGURE 5. Example of damage resulting, at least in part, from improper separation between window and stucco.

FIGURE 6. Example of damage resulting, at least in part, from a missing weep accessory at the horizontal-to-vertical intersection.

"EXCEPT AS OTHERWISE SPECIFIED" VS. THE CODE

The code makes the following clear:

- Any alternative material, design, or method of construction shall comply with the intent of the provisions of the code.
- The material, method, or work offered shall be not less than the equivalent of that prescribed in the code in quality, strength, effectiveness, fire resistance, durability, and safety.
- Any alternative material, design, or method of construction needs to be approved by the building official or the AHJ.

This has been further affirmed by the Building Officials Association of Florida (BOAF) Informal Interpretation Report No. 8088,[13] in which the following question is posed: "Does the 'unless otherwise specified' in C926 and C1063 allow a designer to specify something in their plans that is less than the equivalent of that prescriptively prescribed in the code or code-referenced standards in quality, strength, effectiveness, fire resistance, durability and safety?"

The BOAF's response: "No, an alternate method or material **must be approved by the building official** and must be **equal to or better** than specified in the code or standard" (emphasis added).

The phrase "except as otherwise specified" in ASTM C926 has been problematic from a code-enforcement perspective, in that it is vague and ambiguous and does not include explicit language.

In fact, this ambiguity is in violation of *CP28*. The ICC Reference Standards Guide, which provides guidance with regard to *CP28*, states:

> "A standard or portions of a standard intended to be enforced shall be written in **mandatory** language... The standard must be presented so that the **application and the intent are clear** to all readers. The use of recommendations, advisory comments, and permissive, non-mandatory terms fails to provide sufficient, specifically enforceable direction to all users. **A potential result is non-uniform interpretation or misapplication of the requirements**" (emphasis added).

Criteria for the "specifier" are not provided in the ASTM C926 and ASTM C1063 standards. Nothing stops any party in the design or construction process from declaring himself or herself a "specifier" and providing specifications or installation which is not in accordance with the ASTM standards. This ambiguity has allowed for those with a potential conflict of interest to design or construct a project in a manner that suits their interests more than those of the eventual building owner.

We have also seen the "except as otherwise specified" clauses employed as an excuse when the designer or builder gets caught not following the ASTM standards.

The code states: "102.5 Partial invalidity. In the event that any part or provision of this code is held to be illegal or void, this shall not have the effect of making void or illegal any of the other parts or provisions."[14]

The building official or AHJ should consider that the "except as otherwise specified" clauses satisfy the requirements of this "partial invalidity" code section, but they shall not have the effect of making void or illegal any of the other parts or provisions of the code or reference standards, including ASTM C926, C1063, or lower-tier standards they reference.

At the very least, the "specifier" does not have the authority to specify anything other than full compliance with the code or to override the building official's or AHJ's authority and duty to enforce the code requirements, including those in ASTM C926 and C1063.

SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

As long as the "except as otherwise specified" clauses exist in ASTM C926 and C1063, there will be misinterpretation and misapplication of the standards.

To combat this, industry professionals and building officials or AHJs need to become informed and make some changes in their approach.

Building officials and AHJs should strive towards thoroughly understanding and enforcing the code for stucco cladding.

Design professionals should strive towards creating complete, consistent, and clear construction documents for the project. They should either become familiar with stucco cladding and its components or they should retain a specialist advisor who can advise them in their design of the stucco cladding and its components. Additionally, design professionals shall obtain approval from the building official or AHJ for any alternative materials or methods they intend to use in their design.

Stucco contractors should strive toward understanding the codes and referenced standards, while recognizing that they are only **minimum** requirements. They should work closely with design professionals and code enforcement to benefit the project.

If construction documents are not clear, stucco installers should require clarity from the designer.

Ultimately, any alternative material, design, or method of construction shall be equal to or better than specified in the code or standards, and it shall specifically be reviewed and approved by the building official or AHJ.

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A Not-So-Perfect Storm:
The Convergence of Large Buildings, Wood Decks, and Mechanically Attached Low-Slope, Single-Ply Roofing Systems

ABSTRACT

Recent indicators suggest the potential need for additional design considerations when installing mechanically attached, low-slope, single-ply roof systems over oriented strand board (OSB) decking in large warehouse applications. Specifically, sustained wind uplift forces, building pressurization, or a combination of the two can sometimes coincide to subject the roof system to excessive stress. This, in turn, may cause the mechanical fasteners securing the roof to loosen or withdraw.

To gain a deeper understanding of the potential concerns associated with employing standard fastening patterns in such systems, we conducted a limited sampling of cyclic and dynamic testing. This limited sampling allowed us to formulate prospective conclusions on the potential effects of wind uplift and building pressurization on mechanical fastener pullout values.

This white paper is dedicated to exploring the potential performance of in-seam mechanical fastening patterns in OSB decking systems within large warehouse building environments when they are exposed to a variety of environmental conditions. Furthermore, we aim to provide suggestions for design professionals to consider when choosing to use a mechanically fastened single-ply roofing system over an OSB deck in large warehouse applications.

LEARNING OBJECTIVES

- Identify wind uplift and building pressurization issues with wood decks on large warehouse and industrial structures and the resulting effects on mechanically attached, single-ply roofing systems.
- Describe wind and pressure-related failures of single-ply roof systems on distribution centers in the western United States.
- Recognize variability in wood decking materials as well as the effect of pressure, cycling, and eccentric uplift forces in the acceleration of roof system failures.
- Explain design and installation best practices along with repair recommendations to reinforce roof system reliability.

SPEAKERS

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INTRODUCTION

Construction materials, techniques, and needs are ever evolving, driven by a multitude of factors. OSB has become a common building material due to its availability and favorable cost. In the western US, wood decking has long been a preferred roofing substrate in commercial construction, with plywood being common for the last 50 years. More recently, OSB decking has started replacing traditional plywood while, simultaneously, mechanically attached single-ply roof systems continue to gain popularity for similar reasons. At the same time, how Americans purchase and receive products has evolved significantly, with exceptionally large distribution warehouses becoming a standard part of the retail supply chain. Significantly larger structures, wood decks, and mechanically attached single-ply systems have all been part of the construction industry for many years; however, the intersection of all three on a common project is a relatively new practice.

Given the growing perception of OSB as a cost-effective alternative to plywood decking, there are recent signs to suggest that in some situations, mechanically attached single-ply systems over OSB decking may encounter issues related to fastener withdrawal. Additional design considerations are necessary for the emerging environmental and dynamic challenges of these structures. This white paper discusses recent research regarding fastener performance in OSB decking for these specific warehouse applications and makes recommendations to effectively design and install a dependable roof system tailored to these buildings' needs.

REGIONAL CONSTRUCTION PRACTICES

Traditional/Typical Methods vs. Western Practices

Traditionally, across much of the US, roof systems have been installed with rigid foam board insulation in multiple layers, sometimes with a cover board over steel or concrete decking. The use of multiple insulation layers distributes stresses more evenly and provides increased thermal performance, which is necessary in much of the country.[1] Over this substrate, rigid bituminous systems or adhered single-ply roof systems have been installed with good results across a variety of different environments. Large temperature swings and cold winters throughout much of the country established the need to control vapor drive. Given that proper vapor-barrier installation requires installation over the roof deck, the vapor barrier often serves dual purposes as a temporary roof and a seal for the interior from the outside environment. Most importantly, for the purposes of this paper, vapor barriers can control airflow and help prevent the interior environment from interacting with the roof assembly.[2]

In the Western US, environmental conditions are much milder, and the access to and tradition of using wood from the Pacific Northwest in lieu of steel or concrete has largely remained common practice. While early construction used solid-wood boards through the 1950s, it was successfully replaced with plywood over time. Acknowledging that plywood is not as strong as steel, it has proven sufficient for the needs of applications in the western region, where built-up roofing (BUR) remained popular well after other parts of the country started migrating to single-ply systems.[3] These BUR systems utilized mechanically fastened base sheets with evenly distributed points of contact at a relative high density. Given the rigidity of multi-ply fiberglass built-up roofs and the low wind speeds generally associated with most of the western region, performance was more than adequate, with long service life being the norm.

Given a milder climate, buildings in this region often used little to no insulation, and vapor barriers were not needed. As energy codes evolved, it became common to use fiberglass batt insulation in the joist space and occasionally a cover board or fanfold on the deck for industrial or warehouse applications.[4] Even as single-ply systems became more common, this building practice remained in place with cover boards installed on the roof deck and thermal efficiency accommodated using fiberglass insulation. While vapor barriers have more recently been employed, it is often to serve a different purpose, such as controlling construction-generated moisture, protecting the structure from high moisture-generating activities, or serving as a temporary roof during construction.[5]

PROBLEM: WIND UPLIFT AND BUILDING PRESSURIZATION ISSUES ON LARGE WAREHOUSES

It's worth noting that the evolution of building construction practices based on regional differences is not uncommon in the construction industry as building requirements, materials, and techniques change. While there is nothing new about large tilt-up construction warehouses, OSB wood decks, mechanically attached single-ply roof systems, or proven traditional Western design and installation techniques, they appear to have come together under evolving environmental factors, resulting in some notable instances of fastener performance issues, even under moderate wind speeds. The following section will examine this further.

Environment

Throughout the US, large warehouses are currently being built outside of urban centers. These peripheral locations are advantageous for businesses because they offer proximity to major cities and infrastructure at a much lower price than real estate within the city.[6]

These locations tend to experience more wind exposure because there aren't other buildings or obstacles nearby to help moderate or obstruct wind exposure. For isolated warehouses with large footprints and little to no buffer, this exposure subjects the roof system to heightened dynamic pressures regularly.

Building codes and designs are tailored to account for regional weather patterns. Significant anomalies in the weather can place buildings in environments that codes haven't accounted for and that building components were not designed to withstand. Consider the Texas power crisis in 2021, when major winter weather caused significant damage to buildings and refineries in the Gulf region because infrastructure was not designed to withstand such extreme weather events.[7] These weather anomalies are occurring with increasing frequency and intensity, challenging codes and standards with weather extremes that are becoming the new normal.[8] Ultimately, material and installation practices that may have been sufficient for historical weather patterns may now be insufficient for the type of extreme weather conditions more recently witnessed.

Structure

In tilt-up construction, structural components supporting the roof deck are bolted to the precast walls. This attachment detail typically leaves a gap between the deck and the wall that can allow air to flow through. Since there is little to no partitioning in a warehouse, bay doors can channel a substantial amount of unobstructed airflow into the warehouse when left open. The path of least resistance for this air to escape is through the gaps between the roof deck and wall and at penetrations in the structural deck.

In this scenario, the warehouse acts as a large common plenum, allowing air pressure within the structure to build up. The air could exploit gaps in the roof deck, resulting in air pressure building against the roof membrane.

Insulation

Rigid polyisocyanurate insulation (ISO), which is typically installed in two offset layers, has a substantially greater ability to moderate airflow and provide resistance to air pressure than fiberglass batt insulation. ISO not only serves as an insulator but also provides airflow restriction. Comparatively, the composition and typical installation method of fiberglass allows for less obstructed internal air pressure to reach the roof membrane.

Materials and Attachment

Typically, BUR roofs installed over wood decking utilize a 3 ft wide base sheet. The base sheet is attached with four to five rows of fasteners evenly spaced across the sheet, creating thousands of points of contact with friction acting as a glue, dispersing forces evenly on the OSB deck; asphalt bleed-through in the base sheet adds a minor adhesive bond. With this type of installation, OSB has demonstrated successful capability as a roofing substrate.

Since OSB had a long history in building construction and performed effectively in BUR systems, one may assume that replacing plywood with

OSB would have similar results with single-ply systems. However, most single-ply systems utilize sheets that are 8 ft wide or more and are fastened with only one row of fasteners per sheet.[9] As a result, each fastener is required to withstand substantially more uplift force. Additionally, over-torquing or over-tightening fasteners, which can occur with all deck types, can reduce fastener pullout resistance.

Design and Construction

Steel deck construction benefits from the availability of thousands of different roof systems that have been tested and approved by independent agencies. Wood decks, often being used for light commercial applications or in the western region where lower wind speeds are common, have not been similarly vetted. As a result, there are few plywood- or OSB-specific assemblies that have been tested, leaving many designers to extrapolate required fastening rates from existing steel deck codes and approvals.[10] The different material properties between steel and wood can lead to fastening rates that may not match project requirements in certain applications. The performance capability of steel, coupled with the availability of tested systems, leads both installers and designers to sometimes use systems that far exceed the actual wind uplift requirements of the building; this, however, may not always be the case with OSB when examining its performance in large warehouse applications.

The warehouses in question utilizing these roof systems have also grown tremendously in size. The guideline of using two or three half sheets as a perimeter/corner enhancement has worked well on traditional projects, generally less than 350 squares. Now, with projects commonly reaching a 5,000- or even exceeding 10,000-square size, enhancements typical for smaller buildings are inadequate. ASCE 7 calculations would dictate perimeter widths out to 16 to 30 ft, with four to six sheets being a typical requirement. Considering pressure resulting from open warehouse dock doors, the required enhancement zone could be greater still.

Large warehouse roofs, like most roof installations, are installed progressively, sometimes leaving wide areas of exposed decking subject to inclement weather during installation. As an “Exposure 1” classified material, OSB can be affected by long-term exposure to moisture during the construction process.[11]

Moisture and subsequent drying can potentially cause OSB to become less resilient after prolonged exposure.[12] Specifically, it has been observed that pullout values can be degraded after extensive exposure of the decking to the outside environment and that fastening patterns based on new material may be suspect.[13]

Coupled together, external wind uplift forces and internal pressure from the large warehouse building structure can cause a combined effect where the wind is pulling the roof membrane away from the structure while the building pressure is simultaneously pushing it away.

Ideally, these combined forces are sufficiently managed by the materials and methods used in the construction process. However, in the western US, the shift to using OSB in conjunction with traditional wide-sheet in-lap mechanically attached single-ply fastening patterns may be more challenging to a roof system’s wind uplift performance. The combined characteristics of the fastener and decking material may be insufficient to withstand the uplift forces on the fasteners at the typical attachment rates. The supplemental safeguards that could offset this in the form of resilient steel decking, overdesign for uplift with tested assemblies, air control through vapor barriers, and multiple layers of insulation are routinely not present. In certain observed instances, roofs exhibited visual signs of being overstressed in the form of varying degrees of failure under what would typically be considered normal conditions.

RECENT OBSERVATIONS OF WIND- AND PRESSURE-RELATED FAILURES OF SINGLE-PLY ROOF SYSTEMS ON DISTRIBUTION CENTERS

In the western US, it has been observed that relatively new commercial warehouses with mechanically attached single-ply roof systems with OSB decking sometimes reveal damage (requiring repair or replacement) that cannot be attributed to any single significant weather event. More concerning is that these specific projects are not 15 to 20 years old with aged materials that have been repeatedly cycled, but rather relatively new projects less than 5 years old that have not seen many, if any, significant weather events. Damage specific to both external wind uplift and internal pressurization has been observed, as well as roof systems exhibiting failures related to both. The observed damage in these instances has varied from facility to facility and included a variety of different failure modes, such as fastener withdrawal, membrane blowoffs, delaminated wall flashings, curbs separated from the deck, and holes in the deck.

The most noteworthy thing about several of these instances of system failure is that they could not be attributed to a major weather event. The observed damage occurred in environments that experienced wind speeds that are less than 75 mph and, in some cases, at wind speeds less than 55 mph. The damage has included four to five significant blow-offs in the southwest region (California, Arizona, Nevada), including a 2,400-square loss in North Central California that occurred at wind speeds under 55 mph. Intermittent fastener withdrawal has also been observed, with one location reporting over 4,000 fasteners partially withdrawn on a single roof.

Observations of fastener withdrawal include multiple groupings of 20 to 50 fasteners per membrane lap and frequently the first 3 to 5 fasteners at the leading edge of the perimeter “finger” enhancements. It is

FIGURE 1. Extensive fastener withdrawal with no corresponding wind event.

possible that wind flutter on the 10 ft wide sheet under moderate winds may, over time, diminish pullout capacity at these enhancements. This issue has not been observed in steel decks with the same finger-style enhancement.

One specific project stood out and was the impetus to begin additional research on how fasteners are driven in the field. A three-building complex in the Southwest with induction-welded TPO exhibited varying levels of damage on each building, from nearly none to extensive loss of cover board and membrane (**Fig. 1**). The damage was not consistent with wind direction or any building features, and no evidence of a wind event was present on the surrounding grounds. The fastening pattern was relatively robust, with perimeter and corner enhancement present. The areas of damage were random, with the field, perimeter, and corners all affected. While maximum wind speeds were recorded as only 45 mph, certain sections lost all their fasteners, and no spalling damage was evident in the OSB decking. The fasteners pulled out cleanly.

Some large warehouses also sustained roof system damage that suggested that building pressure was a contributing factor. In these facilities, the warehouse is generally a large, unconditioned space with numerous dock doors. To improve temperature conditions within the facility, workers frequently leave the dock doors open. Under the right circumstances, this can cause the warehouse to pressurize, even under light to moderate winds.

A 3,900-square facility in North Central California was documented with skylights, HVAC, and various smaller curbs separated from the deck (**Figs. 2** and **3**). The membrane did not appear to cause this damage. Holes were observed in the OSB decking at numerous locations as if internal pressure had pushed through it. Backed-out fasteners were observed not at the perimeter or corners where pressures are highest but rather in the field of the roof.

FIGURE 2. Curb and skylight separation from the deck.

FIGURE 3. Loss of rooftop curb due to possible internal pressurization.

FIGURE 4. Garage door damage, showing distortion from winds at or below 64 mph.

Another 1,670-square facility in the Southwest had wind damage to the interior, including a garage door that was distorted and bent towards the interior of the building (**Fig. 4**). Winds were recorded at 64 mph. No obvious causes were evident at the building or roof level, and the door was rated to withstand wind speeds over 100 mph.

While not a mechanically fastened system over OSB wood decking, a 1,000-square facility in South Central California with an adhered PVC roof over a steel deck experienced approximately 30 squares of damage in the field of the roof (**Fig. 5**). The membrane was bonded to ISO insulation, which fractured, leaving the fasteners intact; the membrane was still adhered to the boards. These observations are not consistent with a typical wind-related failure, which would generally initiate at the building perimeter or edge. In addition, the membrane would typically peel the facer off the board, leaving the boards otherwise intact. Investigation revealed that the facility had recently eliminated one passive gravity vent in the failure area. Additionally, the facility representative admitted that one bay door was often left open. These scenarios illustrate that real-world, daily building operations should be a material consideration when designing a roof system and the potential power of internal pressure in large warehouse structures.

Fastener Efficacy for Mechanically Fastened Single-Ply Roofing on Wood Decks

Wood structural sheathing choices for roof decking in West Coast warehouse building applications consist of either plywood or OSB. Plywood is composed of multiple laminations of softwood veneers (plies) glued together under pressure with adhesive.[14] OSB is composed of thin slices of rectangularly shaped wood strands pressed together in cross-oriented layers using heat-cured resin polymers.[15] In the mid-twentieth century, plywood replaced solid-wood decking as the structural sheathing of choice. Similarly, OSB supplanted plywood in the late twentieth century, largely due to cost efficiency and wide availability.

While plywood and OSB are intended for the same applications and have similar properties, it is fair to conclude that the industry broadly adopted OSB based on the assumption of equivalent performance.[16]

The generally accepted minimum pullout resistance for mechanically attached membrane systems over any structural deck is 400 lbs. This standard applies to qualification for a manufacturer's typical guarantee of up to a 55-mph wind speed and should not be conflated with building code compliance or FM requirements.

Given the apparent lack of publicly available testing, research, or FM assembly approvals for mechanically attached membrane systems over OSB and plywood structural decks, our third-party testing sought to better understand the factors that may be contributing to observed fastener withdrawal failures.

Two types of tests were conducted:

- Fastener withdrawal testing per FM Approvals, Section 4.0: *Pull-Out Tests for Fasteners/Roof Deck and Fasteners/Stress Plate or Batten Bar Combination Using Tensile Loading*.
- Cyclic/dynamic wind testing per CSA A123.21:20: *Standard Test Method for the Dynamic Wind Uplift Resistance of Membrane-Roofing Systems*.

FIGURE 5. Fractured ISO with fasteners and membrane intact.

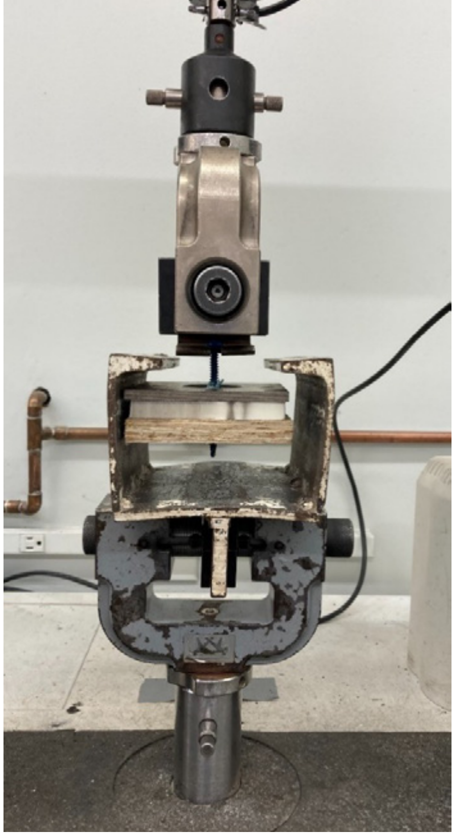

FIGURE 6. Instron tensile testing machine.

Fastener withdrawal was conducted on 4 x 4 in. samples to determine pullout values sorted by decking material, weathering of decking, fastener type, and properly torqued vs. over-torqued fasteners (**Fig. 6**)

The fastener withdrawal testing utilized the following sample types:

1. ½ in. OSB*
2. 15⁄32 in. CDX plywood
3. HD ISO over ½ in. OSB
4. Aged/weathered samples of the same ½ in. OSB, 15⁄32 in. CDX plywood, HD ISO over ½ in. OSB

**Testing involved one OSB material from a major manufacturer.*

The overall goal of the test protocol was to account for several known variables encountered in roof installation.

» 15⁄32 in. CDX plywood samples were tested to provide a comparative reference point for the OSB.

» OSB combined with a cover board was tested because it is a commonly installed assembly in West Coast systems second only to OSB without a cover board.

» Testing of weathered/aged samples was conducted to determine what effect precipitation during construction may have on fastener performance.

» Fastener types. While #15 fasteners are recommended for use in wood decking, #14 fasteners are acceptable and commonly used; each sample type was tested with a #14 and a #15 fastener to gauge if there was any difference in performance based on the fastener type.

» Each sample and fastener type was tested to an overturned or over-driven condition to assess the impact of improperly calibrated screw guns on fastener withdrawal.

RESULTS

Results indicate that decking type and torque during fastener installation could have a significant impact on fastener withdrawal (**Table 1**). In the limited testing, only the 15⁄32 in. plywood exceeded the 400 lb. minimum when paired with the recommended #15 fasteners. In the limited testing, OSB fell well below the minimum in both fastener scenarios. Additionally, the limited testing indicated that fastener choice may matter. Broadly, #15 fasteners outperform #14 fasteners in most cases.

It is important to note that all of the sample types we tested, with the exception of ½ in. OSB yielded pullout values with a maximum of 20% deviation within the three-sample test protocol. In the limited testing, OSB often required four or more samples to meet the required data set. As such, preliminary testing suggested that there may be inconsistencies in the properties of the OSB material tested.

Curiously, the limited testing indicated that aging of the OSB had the opposite effect than expected—it actually improved pullout resistance test results. Additional testing, however, is needed to further understand how OSB properties are affected by weather events.

The increased pullout values observed in the limited testing between HD ISO over ½ in. OSB compared with ½ in. OSB are notable,

TABLE 1. Comparison of withdrawal values for various fastener/torque/deck combinations

Fastener	Fastener Torque	Substrate	Maximum Load (lbf)					
			1	2	3	Avg.	Sd Dev	CoV
JM All-Purpose Fastener	Proper	15/32" CDX Plywood	390	310	393	**364**	47	13
		1/2" OSB	206	179	206	**197**	16	8
		HD ISO over 1/2" OSB	380	297	416	**365**	61	17
		Aged 15/32" CDX Plywood	245	313	235	**264**	43	16
		Aged 1/2" OSB	260	205	281	**249**	39	16
		Aged HD ISO over 1/2" OSB	399	373	283	**351**	61	17
JM High-Load Fastener	Proper	15/32" CDX Plywood	462	447	455	**455**	8	2
		1/2" OSB	221	273	229	**241**	28	12
		HD ISO over O1/2" OSB	326	397	382	**368**	37	10
		Aged 15/32" CDX Plywood	346	347	463	**385**	67	17
		Aged 1/2" OSB	314	403	387	**368**	47	13
		Aged HD ISO over 1/2" OSB	278	315	345	**313**	34	11
JM All-Purpose Fastener	Overturn	15/32" CDX Plywood	162	154	164	**160**	5	3
		1/2" OSB	153	142	99	**131**	29	22
		HD ISO over O1/2" OSB	220	129	167	**172**	46	27
		Aged 15/32" CDX Plywood	226	198	217	**213**	14	7
		Aged 1/2" OSB	157	131	166	**151**	18	12
		Aged HD ISO over 1/2" OSB	181	129	164	**158**	26	17
JM High-Load Fastener	Overturn	15/32" CDX Plywood	415	400	525	**447**	68	15
		1/2" OSB	129	141	107	**126**	17	13
		HD ISO over O1/2" OSB	183	130	142	**152**	28	18
		Aged 15/32" CDX Plywood	169	218	166	**184**	29	16
		Aged 1/2" OSB	51	126	74	**83**	39	46
		Aged HD ISO over 1/2" OSB	256	344	216	**272**	66	24

TABLE 2. Withdrawal resistance of JM TPO membrane fasteners in OSB decking

Gust Loading Interval	Cycle Count	Target Pressure	Maximum Load (lbf)			
			Row A	Row B	Row C	Avg.
1	500	0–25 PSF	290	561	346	399
2	500	0–28 PSF	174[1]	341	35[2]	183
3	500	0–30 PSF	309	383	370	354
4	500	0–32 PSF	328	417	292	346
5	500	0–35 PSF	267	96[2]	330	231
6	3	0–40 PSF	356	222	Fail[3]	289

Notes: 1) Plate deformation observed
2) Fastener visually withdrawn, incompletely from deck
3) Complete detachment of fastener row observed; test terminated prior to completing 500 cycles

TABLE 3. ANSI/FM 4474 wind uplift results

Target Pressure	Duration of Loading	Results
15 PSF	60s	Pass
30 PSF	38s	Fail[1]

Notes: 1) Fastener withdrawal observed during loading

and this observation lends itself to additional investigation to determine whether the HD ISO acts as a cushion or positive stop, preventing even minor overturning of the fastener.

Finally, the limited testing data suggests that over-driving fasteners may be problematic in OSB, and screw guns in the field should be regularly and properly calibrated to avoid over-driving.

Both cyclic and static testing were performed on a 60 mil TPO membrane mechanically fastened over a ½ in. OSB deck.

Cyclic or dynamic wind uplift testing was conducted to simulate wind gusts to investigate the fastener withdrawal-induced failure point for a mechanically attached TPO membrane and to gauge the effect on fastener pullout values over time under cyclic wind loading. The testing was conducted using the CSA A123.21 test apparatus over a 12 x 24 ft specimen of mechanically fastened 60 mil TPO over a ½ in. OSB deck. The attachment rate was set to simulate a 10 ft sheet fastened 6 in. on center, a typical system for the west region. Nine baseline pull values were harvested from sample fasteners driven into the sample OSB deck prior to the start of testing, which averaged 294 lbs.

Five complete gust loading intervals of 500 cycles each were conducted. The target pressure for the first interval was 25 PSF, with pressure increased incrementally to a target of 35 PSF for interval #5. The failure occurred three cycles into Interval #6, with a target pressure of 40 PSF. At the conclusion of each interval, visual observations were recorded, and pull values were harvested from one fastener from each of the three center seams utilizing a different fastener location per seam per interval.

Table 2 below shows the observations and pull values for each cycle.

A static test, ANSI/FM 4474, was also conducted on an identically constructed specimen to establish a reference point. In the limited testing, the failure occurred below the FM testing standard of 60 PSF for mechanically attached single-ply membrane roof systems (**Table 3**).

The results from each of these three tests suggest that cyclic wind loading can be a contributing factor that can compromise fastener pullout resistance. Additionally, OSB material variability in our testing sample is evident from the wide range of pull values throughout testing and the number of cycles specific fasteners could withstand.

DESIGN CONSIDERATIONS, INSTALLATION BEST PRACTICES, AND REPAIR PROTOCOLS TO REINFORCE ROOF SYSTEM RELIABILITY

Our limited testing and observation suggest that mechanically fastened single-ply systems on an OSB deck may require special considerations for roof design and planning.

Design

Building design is central to the success of every roof installation. In light of our limited test results for mechanical fastening in OSB decks, it is our view that design professionals should consider utilizing the following steps during the design process:

- Increasing the perimeter width: Designing in accordance with *ANSI-SPRI RP-4 Wind Design Standard for Ballasted Single-Ply Roofing Systems* increases the perimeter of the roof further into the field in areas with dock doors. Install half-sheet enhancements in accordance with ASCE 7 calculated perimeter width.
- Reducing sources of flutter: Designers should look for areas where they can reduce flutter and stress on the individual fasteners. For example, avoiding finger-style enhancements in favor of traditional picture framing reduces the loads on the individual fasteners caused by sheet flutter.
- Control for unwanted air movement: Finding ways to use the design to preemptively address unwanted air movement in large, open buildings may prove to be an effective approach for reducing the internal pressure on the roof itself. Sealing the perimeter roof-to-deck interface and penetrations throughout the roof area should be considered. Another example of this could be one-way vents at the roof level to relieve over-pressurization.

Materials & Installation

Selecting appropriate materials for the application and using installation methods that work best with those selected materials will have an impact on the long-term success and resiliency of a roof system:

- Sheet width: Consider narrow sheets to reduce membrane flutter; 8 ft sheets put less stress on the fasteners.
- Attachment rates: Use induction-welded systems with equally spaced plates and screws throughout in lieu of in-seam linear fastening. Traditional in-seam fastening with large-width sheets (10 ft) should not be done with OSB.
- Fasteners: Select the best fastener for the materials and ensure that fasteners are not over- or under-tightened. The use of #15 fasteners appears to enhance pullout resistance.
- Fastener design: There is likely an opportunity for a dedicated fastener with thread depth and pitch to reflect the needs of plywood and potentially OSB substrates.
- Cover board: An additional layer can moderate airflow to the membrane and reduce the risk of overdriven fasteners.

Best Practices

- Conservative calculations: Exercise caution when using steel deck–based system assembly information for projects with OSB decking.
- Facility operations: Facilities should be cognizant of the impact that open bay doors can have on the building pressure and the potential damage it can cause to the roof.
- Pullout testing: Every project should have pullout testing once the deck has been installed and again if it has been weathered during the construction process. Perform fastener withdrawal testing at the point of installation and adjust fastening rates based on actual pullout values.
- Testing: The industry needs more wind testing that reflects today's construction methods.

Damage Remediation

If or when damage occurs, it's important to revisit the design standards and best practices outlined above. Each failure is unique and requires rigorous review and input by all stakeholders, such as consultant, owner, manufacturer, and contractor, before embarking on repairs to ensure safety and to reestablish roof system performance.

CONCLUSION

That old saying, assume nothing and question everything, might be the best place to start when considering mechanical fastening in OSB roof decking for large warehouse structures. Weather and building dynamics are evolving. Whereas overdesigned systems installed over steel decking might allow for a less rigorous review before installation, the decision to use mechanical fastening in OSB requires close attention by all parties from planning through installation. Balancing design and value engineering is especially important. In particular:

- Future weather extremes must be considered. Attention to system selection, fastening rate, and layout is imperative.
- Extrapolation based on other tested systems should be especially conservative and always validated with actual withdrawal testing results.
- Controlling airflow within the structure by sealing gaps in the roof deck and ensuring the OSB is not left exposed during construction should be considered standard practice.
- Ensuring that roofing mechanics are trained and attentive to proper fastener torque is critical to successful installation.

Large warehouses with mechanically attached single-ply roofs and OSB decks are here to stay. It is incumbent on the roofing community to apply the skills, experience, and judgment we already possess to ensure delivery of resilient, high-performance results.

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Reviving the Concrete Giants:
The Role of Structures as Building Enclosures

ABSTRACT

The vast inventory of existing buildings with exposed concrete framing will inevitably require repairs. For concrete-frame buildings where the exposed structure also serves as the building enclosure, deterioration can result in structural issues, fall hazards, and unsatisfactory building enclosure performance. This paper presents information regarding concrete deterioration and repair approaches from both structural and building enclosure performance perspectives. Topics include concrete construction techniques, exterior condition assessment best practices, building enclosure performance requirements and energy codes, and considerations for preventative maintenance and repairs.

LEARNING OBJECTIVES

- Discuss the function of reinforced concrete as a structural material and as an integral component of a high-performing building enclosure.
- Identify deterioration mechanisms in concrete-frame buildings and means to address deterioration, considering both building enclosure performance and structural requirements.
- Explain risks associated with deteriorating concrete structures and the potential consequences of deferred maintenance and repairs.
- Delineate best practices for exterior wall condition assessments and appropriate repair strategies to meet project-specific structural and building enclosure requirements.
- Describe the evolution of model energy codes and standards, associated thermal-bridging concerns, and potential thermal-bridging mitigation strategies associated with exterior concrete structural elements.

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The vast inventory of existing buildings with exposed concrete framing will inevitably require repairs. For concrete-frame buildings where the exposed structure also serves as the building enclosure, deterioration can result in structural issues and fall hazards, and also unsatisfactory building enclosure performance, including water leakage. This paper presents examples of deterioration mechanisms and repair approaches from both structural and building performance perspectives. The paper also provides information regarding concrete construction techniques, exterior condition assessment best practices, discussion of building enclosure performance requirements and energy codes, and considerations for preventive maintenance and repairs.

CONCRETE EXTERIOR WALL SYSTEMS

Exterior walls for cast-in-place concrete-frame buildings typically consist of exterior concrete elements (e.g., columns, slab edges, walls, etc.), windows, and exterior sealant joints (**fig. 1**). Collectively, these exterior walls are considered face-sealed barrier walls. Exterior wall insulation is typically located on the interior face of the exterior walls (**fig. 2**). To resist water penetration, the exterior walls rely primarily on the weathertight integrity of the (sometimes coated) concrete surfaces and sealant joints. Face-sealed barrier walls only offer a single line of defense against water penetration and are considered by some as a "zero-tolerance" wall system. Water that penetrates beyond the exterior surfaces of the wall and sealant joints will likely result in water penetration into the building and/or deterioration of water-sensitive materials, including corrosion of embedded steel reinforcement and degradation of drywall and insulation on the interior side of the walls. Water is also able to penetrate cracks at skyward-facing surfaces unless a remedial solution, such as routing and sealing cracks and/or applying a waterproofing coating, is provided and the repairs are maintained over time.

In contrast, exterior wall system designs that include secondary lines of weather protection offer redundancy and are generally more effective at limiting water penetration compared with face-sealed barrier wall systems. Designs with secondary lines of weather protection often include a water management system consisting of a weather-resistive barrier, through-wall flashing, weeps, drips, and accessory components as required to manage and discharge water that enters the exterior wall drainage cavity.[25] Without overcladding the existing walls with an insulated rainscreen system, achieving a redundant exterior wall system for concrete-frame buildings is not practical. As such, preventive maintenance and repairs of the exterior wall systems are imperative to long-term durability and weathertightness of the concrete exterior wall system.

HISTORY OF CONCRETE BUILDING CONSTRUCTION PRACTICES

Concrete is the most-used construction material worldwide. In high-rise

FIGURE 1. Building Exterior Walls Consisting of Concrete Columns, Concrete Slab Edges, Windows, and Sealant Joints.

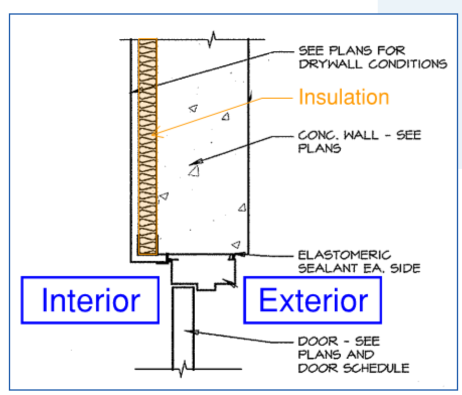

FIGURE 2. Concrete Exterior Wall Design with Insulation on Building Interior.

FIGURE 3. Modern Building (Circa 2018) with Exposed Concrete Beams, Wall Areas, Columns, Slab Edges, and Balconies.

buildings, reinforced concrete construction provides stiffness, mass, and ductility that are ideal for tall and slender structures. Construction practices for concrete-frame high-rise buildings have evolved significantly over time. The first true reinforced concrete high-rise was the Ingalls Building in Cincinnati, Ohio, a 16-story structure completed in 1903 that is still in service today. The building utilized twisted steel bar reinforcement, patented by Ernest L. Ransome in 1884, establishing viability for concrete to be used in future high-rise buildings.[17] By the 1950s, high-strength concrete mixes (f'_c > 5000 psi) began to emerge, allowing for more efficient and cost-effective construction. Ultra-high-strength concrete is now manufactured with compressive strengths over 20,000 psi. Modern concrete buildings are constructed in a wide variety of shapes and sizes, owing to the material's versatility, and often utilize concrete as both the structural frame and architectural finish. Today, construction practices prioritize not only structural integrity but also efficiency and sustainability.

Although modern high-rise residential and commercial buildings provide more natural daylighting than older buildings, many modern structures are constructed with exposed exterior concrete. In these buildings, aluminum-frame curtain wall systems or other high-performing fenestration are typically arranged in a continuous ribbon window configuration at each floor. The concrete slab edges and some columns and shear wall components remain exposed to the building exterior (**fig. 3**).

These buildings continue to be constructed with insulation placed on the interior face of the concrete exterior walls. However, due to thermal bridging of the slabs and balconies where no insulation can be provided, the interior insulation at wall locations may only provide limited thermal benefit with respect to the entire structure.

Although providing fibrous insulation on the interior side of concrete exterior walls theoretically improves thermal resistance and offers increased energy performance, the presence of this insulation increases the risk of condensation in cold climates. The presence of fibrous insulation results in colder surfaces on the interior face of the concrete but does not prevent warm, conditioned interior air from passing through the insulation to the cold concrete surfaces. Additionally, placing insulation on the building interior typically results in discontinuous insulation at window and door locations, thus resulting in localized thermal issues where fenestration is located outboard of the insulation plane.

Some modern buildings are constructed with precast concrete panels with insulation placed between an interior and exterior layer of concrete (i.e., insulated concrete sandwich panels). With proper detailing, these buildings can offer improved thermal performance with respect to cast-in-place concrete structures. However, thermal modeling is typically recommended to allow for the evaluation of conditions at floor slabs, fenestration interface details, and locations of reduced insulation, such as at steel embed plate locations.

FIGURE 4. Concrete-Frame Balconies Cantilever Beyond the Building Exterior Wall.

DISCUSSION REGARDING BUILDING SCIENCE AND CONDENSATION

Continuous exterior insulation is now required by many energy codes for new buildings, especially in cold climates. For existing buildings, achieving a redundant exterior wall system with continuous exterior insulation is not practical unless the concrete walls are overclad with an insulated rainscreen system or as part of a deep retrofit program. As such, improved thermal performance of concrete exterior wall systems is often achieved locally by means of condensation mitigation efforts.

Windows and doors are typically anchored directly to and supported by concrete framing and, thus, are in direct contact with the building's structural concrete frame. Exterior walls for high-rise towers are not anticipated to be high-performing because of the thermal bridging that occurs as a result of the concrete structure being exposed directly to exterior conditions. Cantilever conditions, such as at balconies, exacerbate potential issues associated with thermal bridging (**fig. 4**). Additionally, solid concrete has high thermal mass. In winter months, when the outside air temperature is colder than the indoor air temperature, the surface temperature of the inside face of the concrete wall will typically remain lower than the indoor air temperature. The window and door frames, therefore, are typically supported by and attached to a cold concrete substrate during winter months. Condensation can occur on the cold interior surfaces, including concrete, window and door frames, and glass.

When the surface temperature of the window frames or interior face of the concrete walls falls below the dew point temperature, water vapor in the air condenses on the cool surfaces in the form of liquid water. Similarly, when the surface temperature of the window or concrete surface falls below the frost point temperature, water vapor condenses in the form of frost. Although calculated differently, both the dew point and frost point temperatures are functions of the ambient temperature and relative humidity within the building interior. Assuming the interior air temperature is fairly constant, the interior dew/frost point temperature will rise with increasing values of interior relative humidity. This phenomenon is more likely to occur in "heat-starved" spaces that do not receive direct heat from the interior, such as windows located behind closed curtains, concrete structural components located behind drywall finishes, and other interior surfaces far from heat sources.

Condensate on windows and doors can result in water runoff onto window stools and floor surfaces, resulting in deterioration and/or buckling of moisture-sensitive finishes (**fig. 5**). Condensation within concealed spaces, such as behind drywall finishes, can result in deterioration of the finishes and/or biological growth.

If condensation becomes a nuisance or health issue for building occupants, thermal modeling can be used to analyze the thermal performance of the fenestration in combination with the surrounding construction, including the concrete exterior walls, interior insulation, and interior finishes. Models of existing construction can then be modified to assess options for improving the thermal performance of the fenestration and surrounding construction to limit the possibility of condensation during periods of cold exterior temperatures.

When performing thermal modeling and evaluating options for condensation mitigation, it is advisable to make interior investigative openings at representative areas to verify in-place conditions and monitor interior temperature and relative humidity values to establish a range of interior conditions during winter months. In some cases, condensation potential can be mitigated by means of slight adjustments to interior relative humidity controls during periods of cold temperatures.

FIGURE 5. Condensation at a Concrete-Frame Building in a Cold Climate

CONCRETE EXTERIOR WALL DETERIORATION MECHANISMS

Though concrete high-rise buildings are often designed for long service lives, deterioration will occur due to various environmental factors. Concrete durability is defined by the American Concrete Institute (ACI)[20] as "the ability ... to resist weathering action, chemical attack, abrasions, and other conditions of service." Properly designed and constructed concrete structures are resistant to most natural environments; however, they can be exposed to conditions that initiate chemical and/or physical deterioration mechanisms. Following the onset of initial stages of deterioration, the deterioration tends to accelerate exponentially over time.[22] Due to these factors, even the most durable concrete structures require periodic evaluation and routine maintenance throughout their design life to ensure safety and functionality. If maintenance and repairs are deferred indefinitely, structural failure can occur (**fig. 6**).

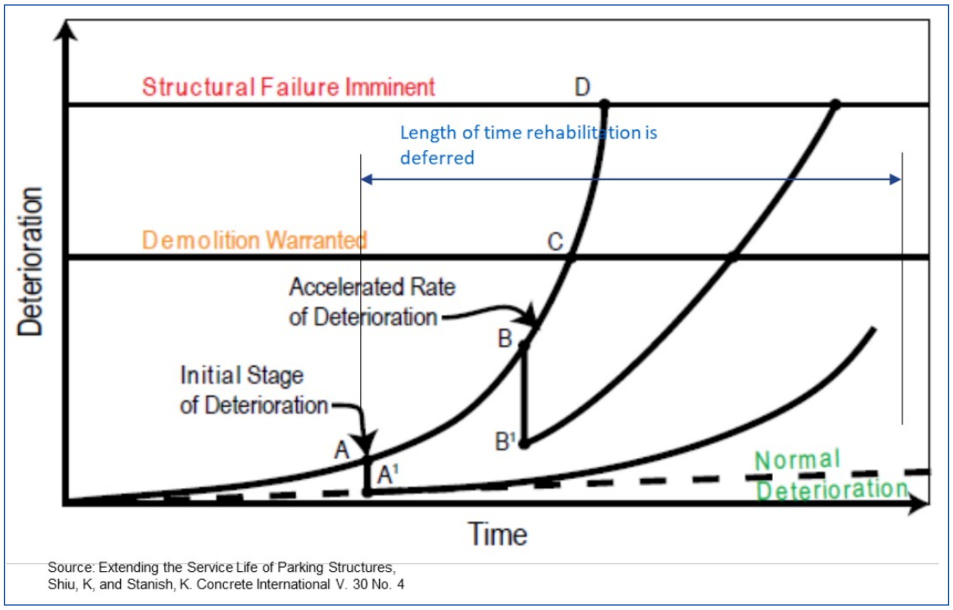

FIGURE 6. Schematic Representation of the Relationship Between Deterioration and Time of a Concrete Structure Exposed to Environmental Factors.

Several variables that increase the risk of deterioration of exterior concrete structures include the following:[23,24]

- **Permeability and diffusivity:** The ease with which fluid/gas can penetrate and migrate through concrete (permeability) and the ease with which dissolved ions (e.g., chlorides) move through concrete (diffusivity) are vital characteristics that are controllable through proper concrete mix design, such as the use of a low water-to-cement ratio and inclusion of supplementary cementitious materials. Higher permeability and diffusivity reduce the ability of concrete structures to resist most forms of deterioration.
- **Deleterious mix constituents:** Some forms of deterioration can be sourced back to the original concrete mixture constituents. Alkali-silica reaction occurs when reactive forms of silica within some aggregates are mixed with a high-pH pore solution and sufficient moisture, resulting in the formation of an expansive gel product, which can manifest as concrete cracking. Concrete mix constituents can also influence the corrosion of embedded steel reinforcement. Admixtures, aggregates, and mix water cumulatively containing chlorides in excess of approximately 0.15% by weight of cement can result in corrosion initiation at the reinforcement without external chloride exposure (see the discussion of chlorides later in this section).
- **Cracking:** Regardless of the concrete quality, extensive cracking in concrete structures, no matter the cause, allows water to enter the concrete, which can initiate deterioration mechanisms.
- **Freezing and thawing:** In colder climates, concrete elements exposed to weathering are susceptible to freeze-thaw deterioration. Pressure within pores of the cement paste and aggregate develops as wet concrete freezes. If this pressure exceeds the concrete tensile strength, these cavities will dilate and rupture. Repetitive cycles of this phenomenon may cumulatively result in the manifestation of visible cracking, delaminations, and spalling. Freeze-thaw exposure is typically considered moderate for concrete exterior wall elements, which are only occasionally exposed to long-term exposure to water accumulation. However, freeze-thaw deterioration can be particularly severe for skyward-facing surfaces, such as at exposed unprotected slab edges, balconies, and railing post pockets, which are more consistently exposed and prone to water ponding.
- **Carbonation:** During the hydration of cement, the pore solution in concrete becomes highly alkaline (pH > 13). In this environment, ordinary, uncoated, steel reinforcement will form a thin protective oxide film, preventing the formation of expansive corrosion products. The natural diffusional ingress of carbon dioxide through concrete over time results in the neutralization of this alkalinity, lowering the pH of the pore solution and destabilizing the protective film. Carbonation leads to the complete dissolution of the protective layer and corrosion of the reinforcing steel.
- **Chlorides:** The presence of chloride ions in the pore solution at steel reinforcement locations can result in the depassivation of the steel's protective layer at certain concentrations, initiating corrosion. Chlorides can be internally sourced as part of the original mix or externally sourced from exposure to seawater, airborne chlorides in coastal regions, or deicing salts. The risk of external chloride exposure is typically considered low to moderate for concrete exterior wall elements but can be severe in localized areas, such as seawater splash zones and lower levels adjacent to roadway traffic in colder climates.
- **Corrosion of reinforcing steel:** Whether due to carbonation, chloride contamination, or other means, corrosion of embedded reinforcing steel forms expansive corrosion products that increase the internal stresses in the concrete, eventually resulting in cracking, delamination, and/or spalling (**fig. 7**).

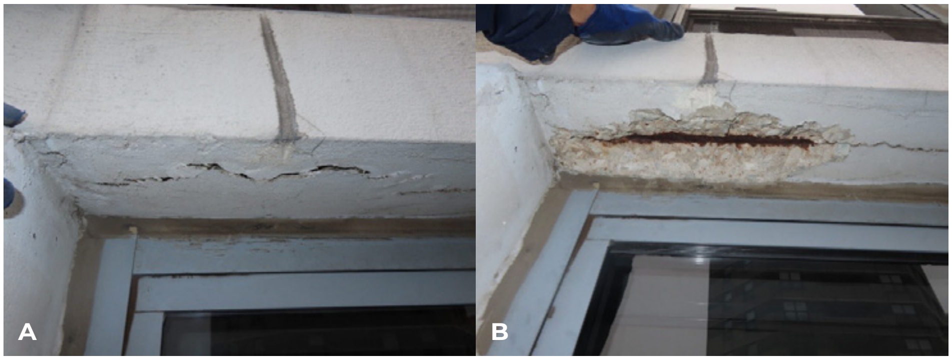

FIGURE 7. (a) Potentially Hazardous Delamination and Cracking at Concrete Slab Edge Soffit (b) Corroded Reinforcing Steel Exposed Following Removal of Spalled Concrete.

CONCRETE SKYWARD-FACING SURFACES

Although not required by most building codes, concrete exterior walls are often coated for aesthetic purposes. A properly designed and applied coating system can also improve exterior wall performance and durability by limiting water penetration, thus delaying the onset of several forms of deterioration. Typical concrete exterior wall coatings are often highly permeable such that moisture within the concrete pore structure can evaporate to the exterior, even following coating application.

While a highly permeable acrylic coating may be appropriate for most concrete exterior wall surfaces, design at skyward-facing surfaces warrants further consideration with respect to waterproofing because water, snow, and ice can accumulate on these surfaces. Concrete cracking may occur on skyward-facing surfaces, and water that penetrates into the cracks will result in concrete deterioration and potential leakage into the building. At balcony locations, where deicing salts may be utilized, the salts may also penetrate into the cracks, accelerating corrosion of the embedded reinforcing steel.

Fenestrations are typically integrated with exterior concrete surfaces using sealant joints. Depending on the material utilized, exterior sealant joints may have a useful service life of five to more than 20 years. Even if these sealant joints are appropriately designed, installed, and maintained, water infiltration through concrete cracks at ledge conditions can bypass the joints, resulting in interior water penetration (**fig. 8**).

CONCRETE EXTERIOR WALL CONDITION ASSESSMENTS

Concrete deterioration can affect structural integrity and durability and potentially also the health and safety of the public. Concrete delaminations can result in spalls and fall hazards, posing safety risks. Unrepaired spalls reduce concrete cover and may expose embedded steel reinforcement, accelerating the deterioration. Addressing concrete degradation requires periodic repairs and maintenance; deferring these issues can lead to more extensive deterioration over time and higher long-term building maintenance costs. To mitigate these issues, regular condition assessments and timely maintenance are essential.

ASTM International standard E2018, *Standard Guide for Property Condition Assessments: Baseline Property Condition Assessment Process*,[1] defines professional practices, establishes reasonable expectations for those requesting the condition assessment, and suggests a baseline level of standard of care and recommended protocols for professionals performing the assessment.

ASTM also provides standards specific to condition assessments of exterior walls. ASTM E2270, *Standard Practice for Periodic Inspection of Building Facades for Unsafe Conditions*,[2] defines "methods and procedures for periodic inspection of building facades for unsafe conditions" in order to establish "minimum requirements." ASTM E2841, *Standard Guide for Conducting Inspection of Building Facades for Unsafe Conditions*,[3] is intended to provide "explicit knowledge gained from experience in conducting periodic façade inspections." ASCE/SEI 30, *Guideline for*

FIGURE 8. Cracks at Concrete Skyward-Facing Surface Extend Below Sealant Joints.

Question	No		Not Sure		Yes	
	Responses	Percent	Responses	Percent	Responses	Percent
Does the traffic coating on your balcony exhibit deterioration?	28	54%	13	25%	11	21%
Have you observed cracked concrete on building exterior walls?	31	60%	5	10%	16	31%
Does drywall on the interior side of exterior walls exhibit cracking?	43	83%	3	6%	6	12%
Does drywall on the interior side of exterior walls exhibit water staining?	49	94%	2	4%	1	2%
Has drywall or flooring been removed in your unit due to exterior wall leaks/repairs?	41	79%	5	10%	6	12%
Does your unit experience issues related to water leakage? (windows, walls, etc.)	38	73%	3	6%	11	21%
Does your unit experience issues related to condensation?	25	48%	4	8%	23	44%
Does your unit experience issues related to air leakage? (including drafty windows)	42	81%	3	6%	7	13%
Does your unit experience issues related to temperature control?	41	79%	5	10%	6	12%
Are your windows or balcony doors difficult to operate?	33	63%	1	2%	18	35%
Have your windows or balcony doors been repaired in the last 5 years?	30	58%	12	23%	10	19%

FIGURE 9. Example of Results from an Occupant Questionnaire for a Concrete Frame Building.

Condition Assessment of the Building Envelope,[4] provides similar guidance.

In many municipalities, including Boston, MA; Chicago, IL; Cincinnati, OH; Cleveland, OH; Columbus, OH; Detroit, MI; Jersey City, NJ; Milwaukee, WI; New York, NY; Philadelphia, PA; Pittsburgh, PA; San Francisco, CA; and St. Louis, MO, periodic exterior wall condition assessments are required by means of local ordanances.[21]

The first steps of a condition assessment should include background review of existing documents and discussions with facility managers, building engineers, building occupants, and/or contractors who have been involved in maintaining the property. Ideally, the background review should include an occupant questionnaire to assist in identifying known issues, such as concrete cracking and areas of water leakage. While results from these surveys should not be considered absolute, completed surveys will assist the investigator in establishing patterns of reported issues (**fig. 9**).

Investigations should be performed by experienced professionals. Many municipal ordinances require the condition assessment to be performed by a licensed architect, professional engineer, or structural engineer. Investigations should be tailored to the specific building and site conditions and may include the following:

» **Visual survey:** Visual surveys can be performed from various vantage points, including the ground, balconies, roof, and adjacent rooftops and parking decks, using binoculars and high-resolution cameras. Such "binocular" surveys are limited in their efficacy by the resolution and magnification capacity of the binoculars and cameras used and the inability of the investigator to closely review all exterior wall surfaces. Unmanned aerial vehicles (UAV) equipped with cameras and video recorders can supplement visual surveys by documenting large areas of the exterior walls. Such photographs and videos can be taken perpendicular to the exterior wall surfaces, thus providing images that otherwise would not be possible. UAV surveys are still limited, however, in that the investigator is unable to review concrete building components up close. As such, data obtained during visual surveys are most useful in allowing the investigator to identify areas for a supplementary up-close examination using traditional access methods.

» **Up-close examination:** In certain municipalities, exterior wall ordinances may only require a visual survey; however, the authors often recommend that up-close examination of representative exterior wall areas be performed in conjunction with a visual survey, especially if areas of potential concern have been identified. In other cases, a more comprehensive up-close examination may be required by the authority having jurisdiction or recommended by the investigator in order to develop scopes for repair. Access to the exterior walls is typically accomplished using swing stages, fixed scaffolding, articulating boom lifts, and/or industrial rope access. Evaluation of concrete exterior walls should utilize hammer sounding techniques described in ASTM D4580, *Standard Practice for Measuring Delamination in Concrete Bridge Decks by Sounding*,[5] and International Concrete Repair Institute (ICRI) 210.4R-2021, *Guide for Nondestructive Evaluation Methods for Condition Assessment, Repair, and Performance Monitoring of Concrete Structures*,[6] to mechanically sound areas of the exposed concrete to identify delaminations.

» **Investigative openings:** If loose or delaminated concrete is identified during an up-close examination, removal of the loose concrete should be performed to address the potentially hazardous condition. The authors recommend that up-close examinations be performed by an experienced professional in conjunction with a concrete restoration contractor so that the contractor can perform "make-safe" repairs if directed to do so by the professional. At a minimum, representative investigative openings should be made to verify the concrete cover at steel reinforcement locations, as the extent of concrete cover will influence repair design considerations.

10.4.1 Viewing horizontal surfaces that can pond water (such as sills, ledges, cornices, water tables, and other such horizontal bands) from above wherever possible,

10.4.2 Checking for out-of-plane displacement of facade elements while scanning the facade horizontally and vertically,

10.4.3 Checking for signs of staining, spalling, water or moisture damage, weathering or distress of facade components,

10.4.4 Sounding of the facade surface with a hammer[3] if material delamination of facade components is possible,

10.4.5 Pushing against or pulling on facade elements, or both,

10.4.6 Pull test on adhesively attached components at building corners and in the field of the wall,

10.4.7 Evaluating sealant adhesion by NDT,

10.4.8 Probing (exterior or interior, or both) and NDT to observe concealed facade components such as anchors, inserts or support of facade components,

10.4.9 Removing loose or fractured components to reveal cause of distress, where safe to do so, and

10.4.10 Sampling of material obtained from probes for visual examination and laboratory testing as required.

FIGURE 10. Excerpt from ASTM E2270.

- **Non-destructive testing:** Nondestructive evaluation techniques require a trained and experienced technician. Findings from such testing should typically be verified via a sufficient number of investigative openings. For some projects, it may be beneficial to extract cores from balconies or other projecting elements in accordance with ASTM C42, *Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete*.[7] The contractor should utilize ground-penetrating radar to select core locations free of steel reinforcement, conduit, etc. In addition to concrete considerations, additional investigation should typically be performed to verify sealant joint adhesion and joint geometry, as well as exterior wall coating adhesion and thickness.
- **Laboratory testing:** Prior to specifying repairs, it is useful to verify the chemical composition of existing exterior wall coatings and sealants. In addition, laboratory analysis can be performed to evaluate the concrete chloride concentration and carbonation depth to better understand the condition and properties of the concrete. Such laboratory testing is typically performed in accordance with ASTM C1152, *Standard Test Method for Acid-Soluble Chloride in Mortar and Concrete*[8] and/or ASTM C1218, *Standard Test Method for Water-Soluble Chloride in Mortar and Concrete* (chloride depth profile)[9] and ASTM C856, *Standard Practice for Petrographic Examination of Hardened Concrete* (carbonation depth).[10] Results from the laboratory testing will help to inform future repair strategies.

Minimum requirements for exterior wall examinations per ASTM E2270[2] are summarized in **fig. 10**.

Following the condition assessment, the investigator may be tasked with preparing a report and licensed professionals may be requested to develop drawings and specifications for repair. In some cases, depending on the scope of the original assignment, the report may include additional recommendations, including investigative openings and/or laboratory testing. If water leakage has been reported at the property, forensic water testing may be recommended. ASTM E2128, *Standard Guide for Evaluating Water Leakage of Building Walls*[11] can be utilized as a guide when developing a project-specific forensic water testing protocol. Thermal analysis may also be recommended if condensation-related issues have been reported or are revealed during the investigation.

STRUCTURAL MAINTENANCE AND REPAIR

ASTM E2018[1] describes deferred maintenance as deficiencies that could have been remedied with normal routine maintenance but are overlooked or otherwise not addressed due to budgetary limitations. As maintenance is deferred, the eventual repair typically becomes more expensive, especially if hazardous conditions develop that require emergency repairs that limit owners' ability to obtain competitive pricing for repairs. The best way to avoid this situation is for building owners to budget for and be proactive regarding preventive maintenance.

Where concrete distress has been identified via a condition assessment, the distressed regions should be evaluated and remediated using industry-standard practices and guidelines. Resources for proper repair and maintenance of concrete distress include ICRI 310.1R, *Guideline for Surface Preparation for*

FIGURE 11. In-Progress Concrete Exterior Wall Repairs.

Product 1

CAUTIONS

For exterior use only.

Protect from freezing

Non-photochemically reactive.

Not for use on horizontal surfaces (floors, roofs, decks, etc.) where water will collect.

Not for use on overhead horizontal surfaces (under sides of balconies, soffits, etc.)

Not for use below grade. Will not withstand hydrostatic pressure.

Before using, carefully read **CAUTIONS** on label.

Product 2

Special Information

- Intermix different batches or multiple cans of custom colors. Always test apply a small area to verify color.
- Do not apply if air or surface temperature is below 20°F or if condensation is present.
- Do not apply late in the day or when rain or dew is expected within 12 hours.
- To assure color uniformity, always paint to a natural "break" in the surface.
- Not recommended for below grade masonry.
- Do not apply to horizontal surfaces.
- Not recommended on exterior insulation finish systems (EIFS) surfaces.
- Sealants should not be applied over [redacted] coatings.
- Read label directions, warnings and cautions before using.

FIGURE 12. Exterior Wall Acrylic Coating Product Data (Excerpts).

the Repair of Deteriorated Concrete Resulting from Reinforcing Steel Corrosion,[12] ICRI 320.1R, *Guideline for Selecting Application Methods for the Repair of Concrete Surfaces*,[13] ACI 546R, *Guide to Concrete Repair*,[14] ACI 562, *Assessment, Repair, and Rehabilitation of Existing Concrete Structures*,[15] and ACI 563, *Specifications for Repair of Concrete in Buildings*.[16]

Every building is unique, and there is no one-size-fits-all concrete repair strategy. Industry-standard details and specifications should be adapted to meet project-specific needs. Repair projects should consider the geographic location of the project, exposure to freeze-thaw cycles, exposure to deicing salts in cold regions or saltwater in coastal regions, and the materials used during original construction (**fig. 11**).

WATERPROOFING AND BUILDING ENCLOSURE CONSIDERATIONS

ASTM E2018[1] describes the building envelope as the enclosure of the building that protects the building interior from outside elements. Because concrete-frame buildings are barrier wall systems, deterioration of the exterior concrete structure compromises building enclosure performance. Building enclosure design considerations during a concrete repair project can limit future water leakage and slow concrete deterioration mechanisms.

Various protective coatings are available to extend the service life of concrete structures. Acrylic coatings are frequently selected due to their permeability, which allows them to be applied over concrete surfaces that include high relative humidity values within the open pore structure. Although concrete is expected to cure and gain strength relatively quickly, concrete structures will never be completely dry, even in warm, dry environments. However, acrylic coatings are typically not appropriate for use on skyward-facing surfaces. Warnings against using acrylic coatings on skyward-facing horizontal surfaces are often included within product data (**fig. 12**).

Horizontal surfaces can be treated using silicone waterproofing membranes or urethane traffic coatings (**fig. 13**). The waterproofing membrane color can often be matched to that of the exterior wall coating to achieve consistency of aesthetics.

Given that many concrete repair projects will include sealant joint repairs at cracks and interface conditions, the choice of sealant is also important to ensure compatibility and sequencing considerations. As an example, silicone sealants should typically not be utilized at route-and-seal repair locations if an acrylic coating is applied over the concrete surfaces. However, a compatible silicone sealant should typically be applied at fenestration perimeter locations, especially in cases where silicone waterproofing coatings are applied at horizontal projections below the windows (**fig. 14**).

Even for a project that includes predesign testing and analysis, a

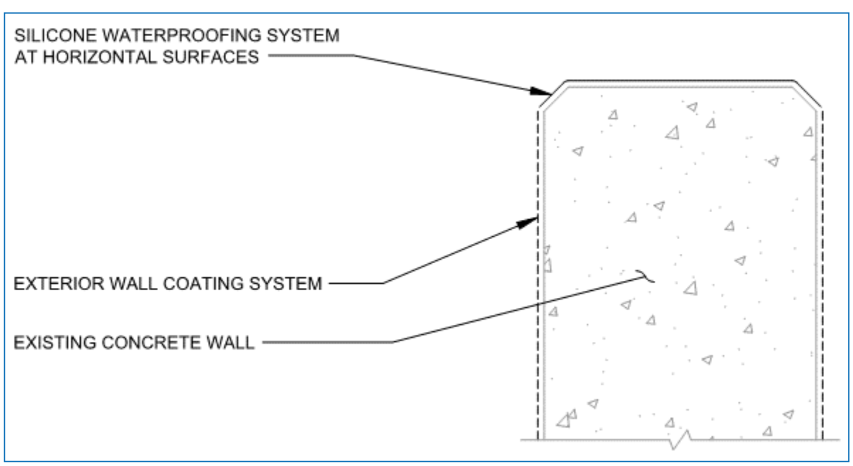

FIGURE 13. Conceptual Repair Detail with Different Coatings for Vertical and Horizontal Surfaces.

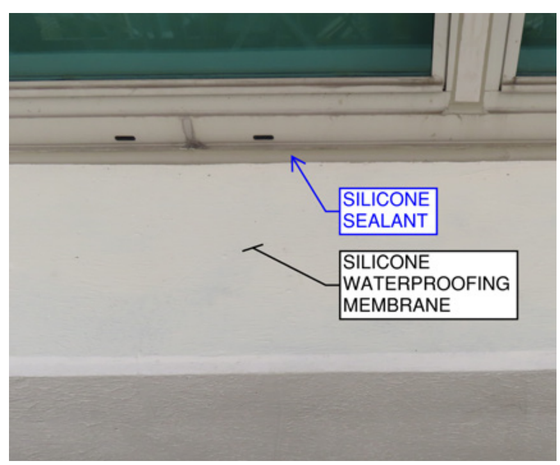

FIGURE 14. Window Sill Interface Condition at Horizontal Projection.

comprehensive design, complete specifications, manufacturer's review of selected products and systems, mock-ups, and an experienced contractor, the authors recommend that field quality control testing be performed to verify adhesion and compatibility of applied sealants and coatings periodically during a repair project. Coating pull-off adhesion strength testing can be performed in accordance with ASTM D4541, *Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers*,[18] and sealant adhesion testing can be performed in accordance with ASTM C1521-13, *Standard Practice for Evaluating Adhesion of Installed Weatherproofing Sealant Joints*.[19] In addition to tests required by the manufacturer for warranty purposes, specifications should also require third-party field quality control testing. The extent of testing should be clearly defined to include information regarding next steps in the case of failed tests. Determining issues early during the project via testing will benefit all parties rather than allowing issues to manifest after demobilization.

CONCLUSION

Maintaining and repairing the inventory of existing concrete-frame buildings is more sustainable than demolishing existing buildings and starting anew. Each concrete repair project is unique, and there is no one-size-fits-all approach to repair design and implementation. The investigation, repair design, and eventual repair of structures with exposed concrete elements require design and construction teams with expertise associated with concrete materials, structural engineering, building science, and waterproofing principles. Reviving the concrete giants will require a concerted team effort now and for many years into the future.

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Unmasking the Layers:
A Journey Through a Masonry Reclad Litigation Case Study

ABSTRACT

A masonry cavity wall cladding system was installed at an office facility in 2012. Seven years later, the owner reported stone dislodging. This case study examines the background, issues, evidence, decision points, and legal analysis resulting in a reclad of the facility. This study highlights the importance of documentation, correspondence between parties, and supporting the claims for a Plaintiff-party, while facilitating continuous use of the facility, without interruption. A concise overview will be provided from the prospectives of the Plaintiff representative Engineer and Attorney offering insight into the complexities and challenges associated with a full building masonry reclad litigation case.

LEARNING OBJECTIVES

- Explore the issues and claims involved in a masonry cavity wall cladding system.
- Discuss legal pitfalls, strategies, and decision points that require consideration and timely action.
- Explain the need for a focused systematic approach in order to minimize cost, and maximize efficiency, safety, and recovery of damages.
- Relate the importance of evidence documentation in supporting claims.
- Describe the roles of the engineer and attorney in a construction defects case in relation to a building that poses life-safety risks and requires massive repair while remaining continuously in use.

SPEAKERS

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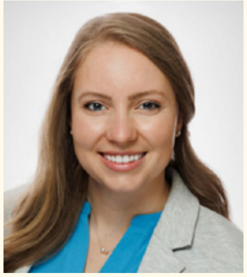

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In late 2016, there were initial owner reports of water infiltration and façade distress at a five-story mixed retail-office facility at a highly visible public plaza area, referred to herein as "the building." The owner initially hired a contractor to perform waterproofing repairs at the manufactured stone façade of the building. While performing these repairs, the contractor raised concerns to the owner regarding several stone units that appeared to be in a loose or unsound condition. Furthermore, the contractor reported one stone that had fully dislodged and landed on a canopy surface prior to the contractor starting repairs.

In January 2017, the owner engaged Walter P Moore & Associates Inc. (Walter P Moore) to perform an immediate initial visual assessment of the building's stone façade. Given the relatively recent construction timeline of the building, the owner also engaged Munsch Hardt law firm for its construction-law expertise, particularly in relation to potential construction and design defect matters. After completion of the initial site review work, Walter P Moore identified 15 stone units that appeared to be laterally displaced, thereby presenting potential falling-debris life-safety hazards. Following further evaluation and tactile push tests, it was confirmed that all 15 stone units were partially to fully dislodged, with four of them posing an immediate fall hazard risk (**Fig. 1**). Emergency stabilization measures were implemented, and it was recommended to the owner to proceed with a comprehensive assessment of the stone façade to determine the extent of distress and causative factors.

In October 2017, Walter P Moore performed a phase 2 assessment focusing on the northwest and southwest corners of the building due to the extent of visible masonry distress observable from the ground at these areas (**Fig. 2**). This comprehensive evaluation included the removal and documentation of dislodged stone units, examination of mortar joint conditions, and assessment of masonry veneer anchor assemblies. The findings emphasized the need for further evaluation of the remaining stone façade areas of the building to identify other potential areas of concern and associated causative factors contributing to these masonry distress conditions.

Following phase 2, phase 3 investigations were conducted, covering additional areas of the façade not previously reviewed. An emergency assessment was initially performed to mitigate potential life-safety risks due to loose stones based on the preliminary ground-level survey. The scope then expanded to include loose-stone removal and exploratory opening assessments of the existing conditions of the masonry cavity and backup conditions at select locations. The phase 3 assessment revealed extensive mortar cracking (**Fig. 3**) as well as multiple

FIGURE 1. Dislodged stone observed as part of the initial investigation reports.

FIGURE 2. Loose stone observed as part of the initial investigation reports. .

FIGURE 3. Extensive mortar cracking as observed in the Phase 3 investigations.

as-built construction deficiencies, such as improperly and excessive spaced masonry anchors; discontinuities in the air-water barrier, including at window transitions; inadequate support of fenestration assemblies; and, most critically, numerous additional dislodged stone elements.

These investigations progressively identified significant distress in the stone façade of the building, leading to safety concerns and a recommendation for comprehensive remediation measures, which required immediate measures to mitigate overhead hazards and led to the recommendation of a full reskin of the stone façade as the appropriate remediation measure.

TIME IS OF THE ESSENCE

Across most jurisdictions in the United States, time is an issue from a legal perspective. This is because there are limits on how long a party has to file suit or arbitration to recover damages; these limitation periods can include periods for claims agreed by contract, statutes of limitations, statutes of repose, and other statutory and contractual limitations on when or if the plaintiff party's construction or design defect claims can be asserted.

This timing comes into play with investigation, inspection, and claim notices, and for getting claims on file (both in court and in arbitration). Accordingly, once defects sufficient to warrant significant repair and expense were encountered, it was important to get notices of defect claims out to the general contractor and architect in order to satisfy notice requirements. It was also essential to file suit within the statute of limitations (usually two years from time of owner knowledge for tort claims and two years from breach for contract claims) and/or the applicable time for a statute of repose (which varies from state to state). For this case, since there was some time left before those periods of time would elapse, it was decided to commence with repairs before filing suit. This was in order to mitigate damages and life-safety hazards, and strategically establish the reasonable cost of repair. Accordingly, it was decided to assemble a team to perform investigation for defects during demolition and repair, document defects and resulting damage, design the recladding/repair work, perform demolition/reconstruction, and perform project management (for the owner).

ASSEMBLING THE TEAM

Because of Walter P Moore's familiarity with the building and the initially discovered defects, and its overall qualifications for forensic evaluation, design, and construction, Walter P Moore was chosen as the engineer and building enclosure consultant (as well as lead design professional). In turn, Walter P Moore retained a qualified subconsultant architect to handle architectural issues. Once a repair design was prepared based on the findings of the initial investigations, the project was let to bid with qualified contractors and one general contractor was carefully chosen on the basis of experience, subcontractor team members, detail orientation evident in the bid, construction schedule, and price (in combination). Lastly, the owner enlisted the services of an adept and experienced construction management company to assume responsibility for the seamless orchestration of the project's execution. This step served as the final layer of assurance that the project would be executed with the precision, efficiency, and professionalism it demanded.

CONTRACTUAL RESPONSIBILITIES OF PARTIES

A legal review of the original construction and design documents, contracts, project files, and insurance declaration sheets helped us in setting up the case by providing the addresses, contact information, and identities of the general contractor, architect insurers, and insurance brokers involved during original construction of the building. The original contract documents for construction, design, and construction administration provided contractual notice requirements, forum requirements (trial or arbitration), choice of law (Texas law), applicable standards of care for the general contractor and architect, and insurance policy coverage amounts.

The design documents provided design details, building code, industry standards, and material requirements. Collectively, this information was used to put all parties, brokers, and insurers on notice; evaluate design and construction defects; determine applicable law and forums for resolution; and carefully draft our pleadings.

Walter P Moore and Munsch Hardt reviewed the subcontractors' contracts to determine their scope of work. It was critical to understand which component belonged to which subcontractor at interfaces in the building enclosure assembly, such as rough opening flashings, and which parties should be put on notice of claims, be given the opportunity to inspect, and be added as defendants. Each of the subcontractors had a responsibility to perform their respective scopes of work in accordance with the contract documents, building code, manufacturer's instructions, and industry consensus standards.

Walter P Moore and Munsch Hardt then reviewed the general contractor's contract, which includes the umbrella responsibility to supervise and coordinate the interfacing scopes of work between the different subcontractor trades as well as between the subcontractors and the design team, and to ensure one trade hands off an acceptable substrate to the next trade. Ultimately, the general contractor is contractually responsible to the owner for construction of a building that is code compliant and in accordance with the requirements of the construction documents.

FIGURE 4. Example of photo documentation of masonry condition pre-masonry demolition .

FIGURE 5. Example of photo documentation of masonry cavity wall post-masonry demolition.

FIGURE 6. Example of photo documentation of backup wall post-sheathing demolition.

INSURANCE OF PARTIES

For plaintiff's work on cases such as this matter, good construction attorneys intentionally craft their pleadings to create insurance coverage purposely and carefully, rather than destroy it. To do this, it is important for the attorney to understand construction insurance and construction insurance coverage law in their state, as well as typical exclusions to coverage. This may sound strange, but it is also important for a good plaintiff's attorney to help general contractor attorneys identify the correct subcontractors to bring into a case and to provide them proper notice of the general contractor's claim; critically, it is paramount for them to craft pleadings properly in order to create insurance coverage among downstream parties.

If possible, this is always preferable over putting parties at risk of going out of business (without insurance coverage). Insurance coverage protects downstream defendant parties, can provide the primary "well" from which to draw your damages, and is an option preferred by most downstream parties over insolvency (and by the owner if insolvency could lead to bankruptcy and getting in line behind banks and other creditors at bankruptcy). In this case, great care was taken to plead "into coverage," and also to make sure nothing was put into expert reports that could erode coverage. Often, for both pleadings and reports, it simply comes down to choosing the right words and avoiding the wrong ones. An experienced construction attorney should know this, and on this case, we employed this know-how to good effect.

DISCOVERY PROCESS AND EVIDENCE GATHERING

As previously discussed, the initial investigation phases included visual observations, a limited arm's-length survey via aerial lift and suspended scaffold access, borescope, and exploratory openings. The initial investigations were essential to understand the underlying cause of observed masonry veneer dislodgement and the extent of associated deficient as-built conditions in the building's enclosure. During the masonry recladding phase, the exterior wall system was reviewed utilizing the following phasing scheme: pre-masonry demolition, post-masonry demolition, and post-sheathing demolition (**Fig. 4** to **6**). This allowed for thorough documentation of each layer of the masonry wall system: masonry façade, air/water barrier over sheathing, and cold-formed metal stud wall. Construction defects were observed in each layer of the masonry wall system; however, the cold-formed metal framing backup wall system will not be discussed in detail within this article for brevity.

During the recladding phase, communication and coordination among the owner, building management representatives, Walter P Moore, and the general contractor ensured that deficiencies were identified and documented accordingly and in a timely manner. The contractor issued detailed two-week look-ahead schedules that categorized the building into areas to be demolished and reclad during a given time frame, which were critical as the building primarily remained occupied during construction. The subcontractor performed demolition work that would then be reviewed and documented by Walter P Moore and other representative defendant and third parties with a reasonable time frame being allocated before ensuing repairs and recladding were started.

The documentation process of the masonry veneer pre-demolition focused on deficiencies in the masonry veneer. The typical deficiencies included cracked mortar joints, loose masonry stone units, and deficient movement joint sizes. The documentation of the air/water barrier over sheathing post-masonry demolition focused on the deficiencies within the cavity wall system. The typical deficiencies included penetrations and discontinuities in the air/water barrier, unadhered through-wall flashing components, and inadequate spacing and improper fastening of masonry veneer anchors. Our documentation process consisted of developing a series of task item notations for expected representative construction deficiencies, field sheets, photographs, and a deficiency tracking log. The task items were developed based on deficient conditions observed during previous initial investigation phases of the project and categorized as pre-masonry demolition and post-masonry demolition. New deficient conditions were added to the task item list throughout the investigation based on engineering judgment and experience, compliance with industry standards, and the frequency in which the deficiencies appeared.

The task item deficiencies were documented on the elevation field sheets, with their corresponding location, photo, and quantity. The deficiency tracking log allowed Walter P Moore to determine the extent of the deficient conditions and whether these conditions were global or isolated. Furthermore, thorough documentation during the recladding phase of the project was essential for the litigation process, as they were used as supporting documents and evidence for the owner's claims.

In summary, the defects identified in the unit masonry veneer cladding throughout the project included the following:

- Inadequately sized horizontal masonry expansion joints that are noncompliant with industry standards and manufacturer's requirements
- Improper installation of masonry veneer anchors per manufacturer's installation instructions and the record construction documents
- Excessive spacing of masonry veneer anchors per building code requirements and the record construction documents
- Inadequate adhesion of mortar to masonry units, which are noncompliant with industry standards.

The defects in the air/water barrier system included the following:

- Unsealed abandoned fastener penetrations at and around masonry veneer anchors
- Holes in the air/water barrier and/or sheathing
- Improperly installed self-adhered flashing membrane, including wrinkles, fish mouthing, inadequate adhesion and backing paper not removed
- Discontinuities in the air/water barrier at locations such as the roof-to-wall interface, fenestration assemblies, unit masonry veneer walls, balcony curbs, and inside canopies. Critically, a view of the lighting-illuminated interior building areas through the improperly installed and discontinuous fenestration flashing transitions was observable at multiple locations, indicating the building was not originally constructed in an airtight manner.
- Inappropriate flashing materials installed at fenestration assemblies
- Discontinuities in the backup substrate at locations such as beneath punched openings, on top of parapet walls, and around canopies.

RECLAD DESIGN AND CONSTRUCTION

The project involved extensive façade repair work, including demolition and reconstruction and, very importantly to the owner, matching the existing original exterior wall aesthetic characteristics of the building. An architect was engaged by Walter P Moore to ensure that the architectural elements, including the masonry veneer, would maintain the same aesthetic appearance as desired by the owner. This involved carefully matching the interior and exterior architectural elements to achieve consistency in appearance.

The selected general contractor commenced work in December

FIGURE 7. Installation of new sheathing, air barrier, and brick ties during masonry re-clad.

FIGURE 8. Installation of new masonry units during the re-clad construction work.

2018, with a scope that included demolition of the existing façade stone, veneer ties, and other architectural elements to allow for repairs and documentation of backup wall conditions. The reclad work involved various aspects such as flashing and sealing window perimeters, adding stone masonry veneer ties, constructing new stone masonry cladding, and installing flashing at key transition areas (**Fig. 7** and **8**).

Walter P Moore initially focused on the unit masonry veneer wall but later expanded the scope to include repairs to the existing air/water barrier, sheathing, and cold-formed metal framing wall due to later-revealed deficient conditions during demolition. Challenges included replacing the air/water barrier while keeping storefront windows in place, which required careful planning and additional flashing components to ensure airtightness.

Throughout the project, there was a proactive approach to addressing unforeseen conditions, and a strong working relationship with the general contractor helped in managing the project effectively. A construction manager was hired by the owner to oversee coordination, host regular town hall meetings with facility tenants, maintain and publish updated construction schedules, and coordinate weekend work as needed to keep the building operational and functional for tenants and patrons.

Testing played a significant role in quality assurance, including mortar testing, air- and water-leakage testing at windows and window perimeters, and field adhesion testing (**Fig. 9**). These measures ensured that the repairs met the required standards and specifications.

ADDITIONAL LEGAL ANALYSIS AND COMMENTS

In some of the sections above, the Munsch Hardt team has, from a proper claim perspective, touched upon the importance of insurance, insurance coverage, and identification of notice requirements (in contracts and in statutes). We have also touched on topics such as artful pleading into coverage and careful word choice in both pleadings and expert reports. For brevity, we will highlight key topics, such as selection of proper experts, the key components of a good expert report, preparation of claims for trial or mediation, and recovery of damages.

Selection of Experts and Expert Reports

Selecting the appropriate contractors for demolition, repair, and remediation endeavors is an imperative undertaking. Of equal significance is the judicious selection of experts. In the field of law, the admission of expert opinions necessitates meticulous consideration. It is not merely a matter of ascertaining qualifications; rather, it demands an evaluation of the expert's experience, training, and educational background, particularly as they pertain to the subject matter at hand. Equally critical is an assessment of the methodologies the expert employs and the reliability and credibility of their opinions. The overarching objective is to ensure that the expert's insights are of such caliber that they can effectively aid a trier of fact, including lay jurors, in comprehending and adjudicating upon matters that lie beyond their inherent understanding.

FIGURE 9. AAMA 501.2 nozzle water testing was performed at a punch window in order to evaluate potential water leakage

Formulating a robust expert report requires the careful integration of a multitude of critical components, each of which plays an indispensable role in the report's ultimate effectiveness and credibility. These essential elements are paramount in ensuring that the expert report not only aligns harmoniously with the case's legal underpinnings but also excels in its comprehensive consideration of salient facts, exhibits discerning thoughtfulness, and garners unwavering credibility.

- **Thorough assessment of relevant facts:** The report should encompass a meticulous examination of all pertinent factual information. Using comprehensive investigation and analysis techniques will ensure that no relevant aspect is overlooked, fortifying the foundation upon which expert opinions are formulated.
- **Thoughtfulness and credibility:** In its entirety, the report must exude thoughtfulness, reflecting a discerning and conscientious approach to the subject matter. This thoughtfulness, when coupled with demonstrable expertise, bolsters the report's credibility and fosters confidence in its assertions.
- **Sufficiency of evidentiary basis:** Every opinion proffered within the report must be anchored firmly in a substantial evidentiary basis. The credibility of these opinions hinges on the strength of the supporting evidence.
- **Accessibility to laypersons:** The report should be crafted with a view toward accessibility and ease of discernment to a lay audience. Avoiding technical jargon and using plain language facilitate comprehension by individuals who lack specialized expertise.
- **Precision in terminology:** The judicious use of precise terminology and the employment of the correct "magic" words are essential to prevent inadvertent repercussions, especially concerning insurance coverage matters. This ensures that the report remains legally sound.
- **Incorporation of visual evidence:** Each opinion articulated within the report should be closely tethered to demonstrable photographs, design specifications, building codes, and industry standards. This visual corroboration lends greater weight and clarity to the expert's assertions, particularly when presenting these findings to lay jurors.
- **Alignment with industry norms:** Expert opinions should seamlessly align with prevailing industry norms, design specifications,

and statutory building codes. This alignment underscores the expert's adherence to recognized best practices.

» **Persuasiveness:** Ultimately, the overarching objective is to craft an expert report that is supremely persuasive. Its contents should inspire unreserved confidence in both the selection of experts and the soundness of their opinions, leaving judges, jurors, and arbitrators nodding in quiet affirmation.

Preparation of Claims for Trial/Mediation

The meticulous preparation of legal claims for trial or mediation should be undertaken with unwavering commitment, irrespective of the ultimate dispute-resolution trajectory. It is essential to approach each case with the intent of thorough preparation, akin to the readiness required for a trial in a court of law. This strategic approach ensures not only the comprehensive presentation of one's case but also sends a signal to opposing counsel, akin to a seasoned equestrian discerning the confidence or trepidation of a rider, that the matter is being handled with the utmost seriousness.

Indeed, defense attorneys possess a discerning acumen that enables them to distinguish cases prepared solely for settlement or mediation from those meticulously prepared for trial. This discernment is parallel to the keen sense of a perceptive horse detecting the apprehension of an inexperienced rider. Conversely, when defense attorneys perceive that the plaintiff's counsel is resolutely prepared and likely to prevail in a trial, they are often more inclined to seek an amicable resolution. The rationale behind this inclination is rooted in the recognition that settling the matter becomes an advantageous course of action. Settling not only curtails the escalating costs associated with protracted legal battles but also provides a pragmatic avenue for dispute resolution.

In essence, the maxim to "prepare for trial to prepare for mediation" encapsulates a prudent approach in the realm of legal advocacy. By diligently laying the groundwork for trial, attorneys effectively fortify their position in mediation. This comprehensive preparation serves as an unequivocal demonstration of resolve and competence, thereby compelling opposing parties to engage earnestly in the mediation process. The net result is a heightened likelihood of reaching an expeditious and mutually agreeable resolution—a course of action that invariably benefits plaintiffs, often referred to as and synonymous with "owners," by curtailing the financial burden associated with prolonged legal proceedings, encompassing attorney and expert fees.

Recovery of Damages

The final phase in the legal process demands a detailed consideration of recovery strategies. A pivotal element in enhancing the prospects of a favorable recovery hinges on the exhaustive preparation for trial. For both attorney and expert, a profound comprehension of the case's minutiae is imperative. This comprehension extends to the intricate details contained within original design documents and investigative findings, ensuring a comprehensive grasp of the case at hand. Moreover, the ability to adeptly illustrate each defect with photographs and articulate explanations is essential. These visual aids serve to expose the defects' inherent deficiencies and lend indisputable clarity to the argument.

In contemporary legal practice, the art of compelling presentations is often underutilized, but it remains an invaluable tool. Whether delivered by a proficient attorney or an expert, a well-constructed presentation possesses the capacity to wield significant influence. During mediation proceedings, it can wield sufficient persuasive power to convince insurers to authorize substantial settlements. In the context of trials, arbitrations, or hearings, it holds the potential to sway the opinions of jurors, judges, or arbitrators in favor of directing the defendant parties to issue substantial compensation.

The overarching goal is to secure comprehensive coverage for the costs associated with repair, remediation, and related expenses. However, it is crucial to bear in mind the fundamental tenets of recovery—that damages are only recoverable if they are deemed both necessary and reasonable. This necessitates the infusion of necessity and reasonability throughout the entire spectrum of design, construction, and expenditure. The synthesis of these principles is the linchpin to achieving a successful recovery.

In summation, the recipe for effective recovery in the legal arena is multifaceted. It necessitates a profound understanding of case details, comprehensive visual representation, and the persuasive power of presentations. The ultimate goal is to secure the requisite coverage for repair and remediation, all while adhering to the vital principles of necessity and reasonability. When executed judiciously, this approach culminates in achieving favorable outcomes that reflect both the rigor of preparation and the merits of the case.

CONCLUSION

This case serves as an illustrative and comprehensive example, encapsulating the intricate interplay of the multifaceted elements we have examined thus far. It stands as a testament to the profound impact that astute decision-making and meticulous preparation can exert within the legal landscape.

In this instance, the owner exercised discerning judgment in assembling a legal team distinguished by experience and expertise. Simultaneously, they enlisted the services of a forensic engineer and lead expert whose qualifications were beyond reproach. With precision, proper notice was extended to defendant parties, insurance brokers, and insurers, setting the stage for an encompassing legal strategy.

The artful crafting of pleadings not only delineated the contours of the case but strategically aimed at invoking insurance coverage. Expert reports, an integral component of the proceedings, were masterfully composed not only to reflect the essence of the pleadings but also to serve as compelling advocates for coverage while proffering dependable opinions in a manner that resonated with clarity and credibility. The abundant inclusion of illustrative visuals—serving as both exposition and elucidation—made these reports all the more persuasive.

The case's meticulous preparation for trial left no stone unturned, delving into the minutiae of details with a precision that compelled witnesses to concur with the assertions of design and construction defects. This unanimous consensus added a formidable layer of strength to the owner's position.

As a result, defense attorneys, acutely aware of the robustness of the case, returned to their insurance clients with a resounding message: "Write substantial checks at mediation." The confluence of factors, including the unequivocal establishment of reasonable and necessary repair costs through the work itself, prompted insurers to issue checks of sufficient magnitude to bring contentment to the owner's doorstep.

In closing, this case represents the embodiment of effective legal strategy and meticulous execution. It is a testament to the art of legal advocacy and a potent reminder that, in the end, even those whose construction or design/administration work might have faltered can find a path to redemption, while simultaneously ensuring their continued presence in the business world. With the right combination of expertise, strategy, and perseverance, "happily ever after" isn't just a fairy-tale ending, but a real-world outcome.

3 Decades of Scientific Advancement to the North American Roofing Community

ABSTRACT

Three decades ago, members of the roofing community met at the National Research Council of Canada and formed a group with a common focus on evaluating roofing systems in a dynamic environment. As A result, the Special Interest Group on Dynamic Evaluation of Roofing Systems (SIGDERS) was created. SIGDERS' operation is one of its kind in the world, with the legacy of a long-lasting research and development consortia. In this session, the impacts of SIGDERS on the industry will be discussed, including advancements in the areas of static vs. dynamic roof evaluations, diagnoses of the weakest link, significance of the roof edge, and field vs. code specification.

LEARNING OBJECTIVES

- Describe wind effects on roofing.
- Delineate wind standards for low slope roofs.
- Recall load calculation as per building code.
- Explain failure mode analysis.
- Discuss climate adaptation.

SPEAKER

Appupillai (Bas) Baskaran, PhD, PEng, F–IIBEC
National Research Council Canada, Ottawa, Ontario

At the National Research Council of Canada, Bas Baskaran, PhD, F-IIBEC, PEng, is researching the wind effects on building enclosures through experiments and computer modeling. As an adjunct professor at the University of Ottawa, he supervises graduate students. As a professional engineer, he is a member of various committees and is a research advisor to various task groups of the *National Building Code of Canada*. He has authored and/or co-authored over 300 research articles and received over 25 awards. Baskaran was recognized by Her Majesty Queen Elizabeth II with the Diamond Jubilee medal for his contribution to fellow Canadians.

AUTHOR:

Appupillai (Bas) Baskaran, PhD, PEng, F-IIBEC

On November 16, 1994, members of the roofing community met at the National Research Council Canada (NRC) and formed a group with a common focus of evaluating roofing systems under dynamic environment. Thus, a Special Interest Group on Dynamic Evaluation of Roofing Systems (SIGDERS) was created. The mandate of SIGDERS joint research program is to carry out generic, pre-competitive research of benefit to all its members. SIGDERS's operation is one of a kind, not only for its legacy as a long-lasting research and development (R&D) consortium, but also for the following industry impacts it created:

» Static versus dynamic evaluations of roofs, and the pros and cons of each
» Diagnosis of a weak link to enable innovation
» Nominal versus design tensile strength of steel deck, and the importance of each
» Investigation of the innovation of membrane seaming
» Differences between air leakage and intrusion
» How much roof edge matters
» Wind science of vegetated roofs
» Climate adaptation of commercial roofs

These advancements were delivered with details consecutively for 20 years at the IIBEC conventions. This presentation is an "extraction" from all those presentations. It will be delivered as a symbolic icon of the SIGDERS's contribution to the North American roofing community. The presentation will also highlights current R&D efforts at the NRC focusing on residential and climate adaptation area.

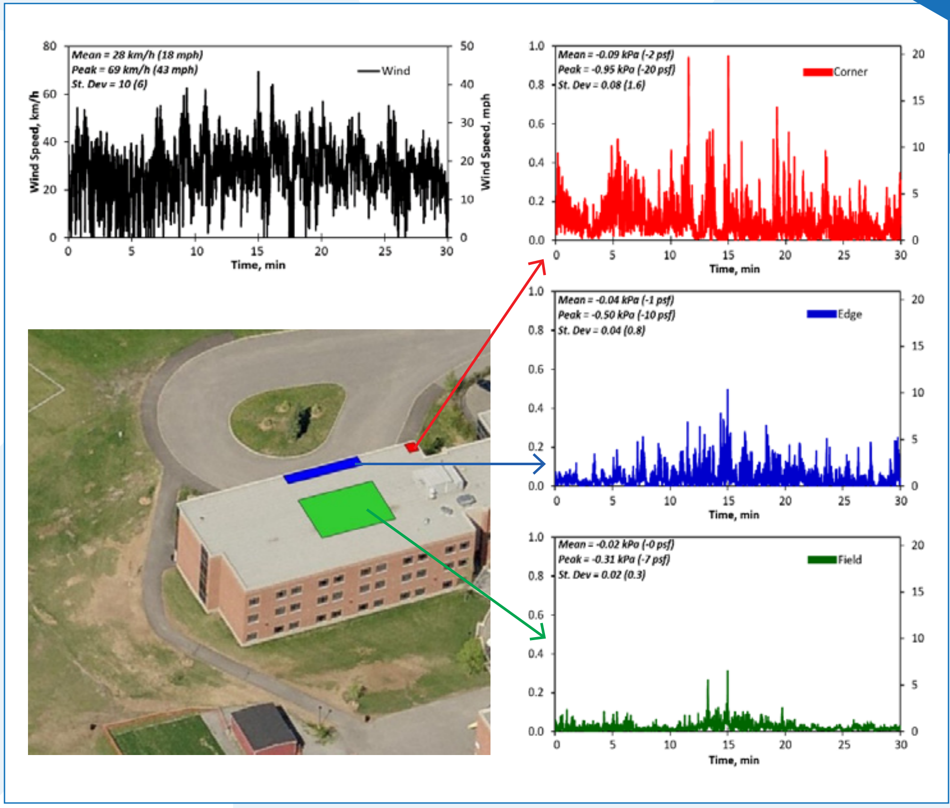

FIGURE 1. Wind and its effects on a school building roof measured in Ottawa.

Q1: WHAT ARE THE ATTRIBUTES OF WIND ON ROOF?

Wind is a random process. When it separates from roof edges, it creates zones of suction (negative) pressure. This suction has two characteristics: (a) it varies from one zone of the roof to the other (spatial variations); (b) it varies from one period of time to another (fluctuation with respect to time). One can simplify the spatial variations from zones of higher to lower suction as corner, edge, and field. A statistical approach is used to simplify the time fluctuations as mean, peak, and standard deviation (**Fig. 1**).

Q2: WHAT ARE THE STEPS IN THE WIND UPLIFT DESIGN OF A ROOF?

The complex process can be simplified into three steps and a case study is presented below.

Step 1: Calculate the design wind uplift

The Canadian model code National Building Code of Canada (NBCC) specifies wind load requirements to design of roof assemblies for the nation. In the US, the American Society of Civil Engineers (ASCE)

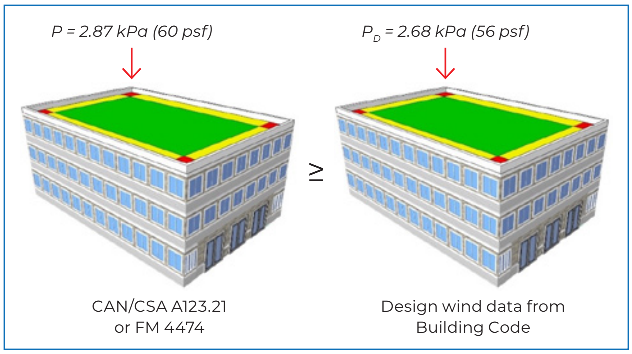

FIGURE 2. Wind uplift resistances should be higher than the design values.

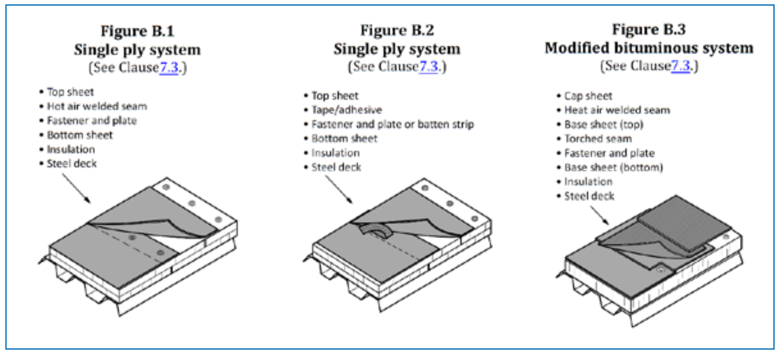

FIGURE 3. Typical component arrangement of a MARS.

standard 7 is widely used. In accordance with the ASCE 7 or NBCC or using Wind-Roof Calculator on the Internet (Wind-RCI https://nrc.canada.ca/en/research-development/products-services/software-applications/wind-roof-calculators-internet-wind-rci), calculate the design wind load (PD) for various zones of the roof cladding (for example: field = 1,341 Pa [28 psf], edge = 1,724 Pa [36 psf], and corner = 2,681 Pa [56 psf]). Wind-RCI is an online calculator which conservatively estimates the wind loads on roofing claddings, and the first version was developed using an RCI Foundation Grant.

Note: Designing the roof system according to ultimate limit state (ULS) requires multiplication of 1.4 (principal wind load effect factor) to the wind loads for various zones.

Step 2: Select the roofing system

Determine the uplift resistance of the roofing system in accordance with the requirements of CAN/CSA A123.21, which is the only compliance standard by the NBCC. The US has several wind uplift test methods, including FM 4474 and UL 1896.

Step 3: Correlation

Select a roofing system and related components with uplift resistance higher than the design load (**Fig. 2**).

Q3: WHAT IS CSA A123.21 AND HOW WAS IT DEVELOPED?

The Canadian model code NBCC specifies wind load requirements for the design of roof assemblies. To comply with the NBCC, the CSA A123.21 standard provides test requirements for resistance evaluation. Tested resistance should be equal to or greater than the design load. First published in 2004, CSA A123.21 was subsequently revised/edited in 2010 and 2014, with the latest edition published in 2020. The R&D for the standard was developed by the National Research Council Canada (NRC) industry-based Consortium, “Special Interest Group for Dynamic Evaluation of Roofing Systems (SIGDERS)”.

Q4: WHAT ARE THE DIFFERENT TYPES OF LOW-SLOPE MEMBRANE ROOFING SYSTEMS?

The roofing assembly consists of a deck and roofing membrane. It may include components such as vapor barrier or retarders, insulation, cover board, etc. The roofing system consists of components above the deck. The standard is applicable to low-slope membrane roofing systems which fall in one of three categories, each of which describes the way the roof system is secured to the deck/structure as indicated below.

Mechanically Attached Roofing System (MARS): a system in which the roofing membrane is intermittently attached to the deck using fasteners, as shown in **Fig. 3**.

Partially Attached (hybrid) membrane Roofing System (PARS): a system in which the roof membrane

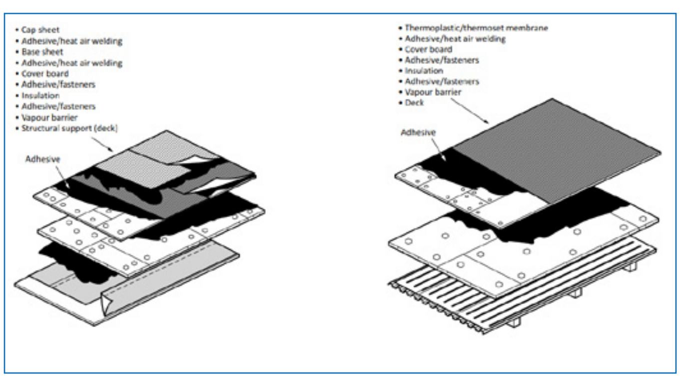

FIGURE 4. Typical component arrangement of a PARS.

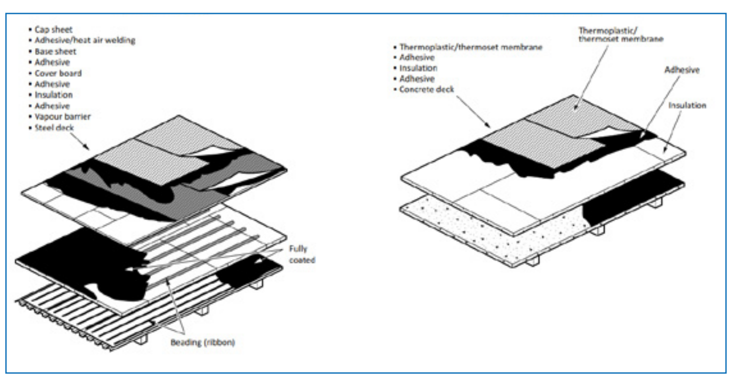

FIGURE 5. Typical component arrangement of an AARS.

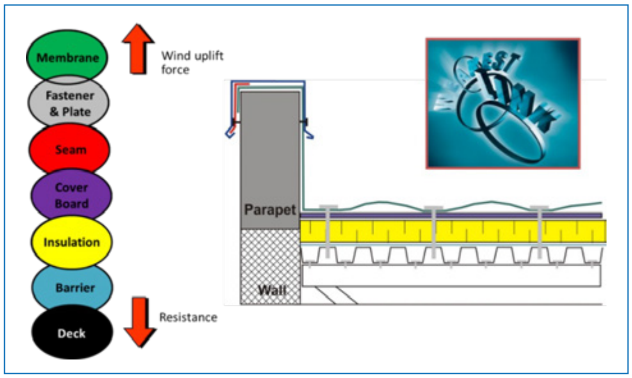

FIGURE 6. Force resistance link diagram: MARS.

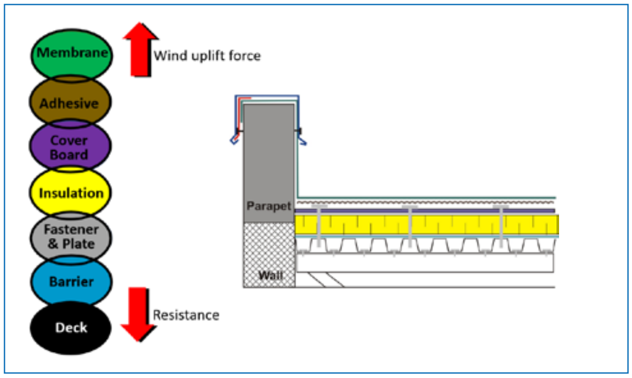

FIGURE 7. Force resistance link diagram: PARS

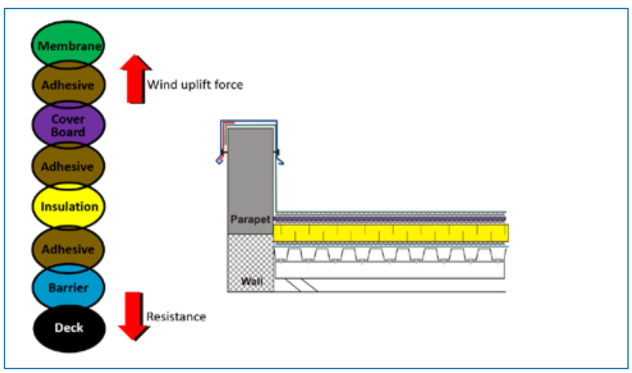

FIGURE 8. Force resistance link diagram: AARS.

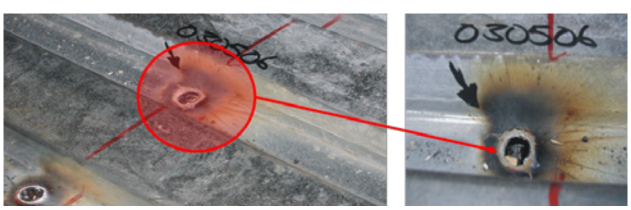

FIGURE 9. Deck weld failure mode.

is bonded to the substrate using adhesives, and a minimum of one component below the membrane is intermittently attached to supporting structure using fasteners, as shown in **Fig. 4**.

Adhesive Applied membrane Roofing System (AARS): a system in which the roof membrane is bonded to the substrate using adhesives, and all the other components below the roofing membrane are integrated using adhesives, as shown in **Fig. 5**.

Q5: WHAT IS THE "WEAKEST LINK" CONCEPT IN THE DETERMINATION OF WIND UPLIFT RESISTANCE?

Wind induces load on the roof. It is resisted by each component by their resistance. This can be illustrated through a force resistance link diagram respectively for MARS in **Fig. 6**, PARS in **Fig. 7**, and AARS in **Fig. 8**. All resistance links shall remain connected to ensure the system will be durable and keep the roof in place. Failure occurs when the wind uplift force is greater than the resistance of any one or more of these links. This understanding helps to choose the appropriate roof components and construction techniques at the early design stage or by replacing/adding components to improve wind uplift resistance during the reroofing.

Q6: WHAT IS THE ROLE OF STRUCTURAL DECK?

Deck provides structural support, and it must have adequate strength and rigidity to support dead and live loads. These loads either induce compressive or tensile forces or a combination of forces. Steel, concrete, and wood are three common deck materials used for the MARS/AARS/PARS. There is a lot of research related to the use of steel decks on commercial roof systems. Therefore, this paper only focuses on the use of steel decks on commercial roofs. However, although SIGDERS has limited research data on concrete deck and wood deck, both deck types are known for having moisture migration issues.

The wind uplift induces tensile forces, which are transmitted to the deck through the structural or pneumatic load path or a combination of both. Therefore, the deck's tensile strength and its attachment to the joists are critical as they can influence the wind uplift resistance of a roof system.

a) Deck attachment methods with joists

Welding or fastening to a structural joist are the two common field attachment practices. Two identical sets (welded versus fastened) of MARSs with modified bitumen (MB) and thermoplastic membrane were constructed and investigated at the Dynamic Roofing Facility (DRF) of the NRC. Specimens that were installed on decks that were fastened to the joists performed better than the welded specimens. The weld was the weakest link, as shown in **Fig. 9**.

b) Deck strengths

Steel deck strengths are determined by the combination of the thickness and yield strength. The most common decks used in North America are 22 ga and 20 ga with 230 MPa (33 ksi) and 550 MPa (80 ksi). Two identical MARSs with thermoplastic membranes were constructed and tested at the DRF of the NRC. The first specimen that was installed on 22 ga, 550 MPa steel deck had a lower sustained pressure of 7.90 kPa (165 psf) than the second system, and the failure mode was determined to be due to the membrane fastener having pulled out from deck,

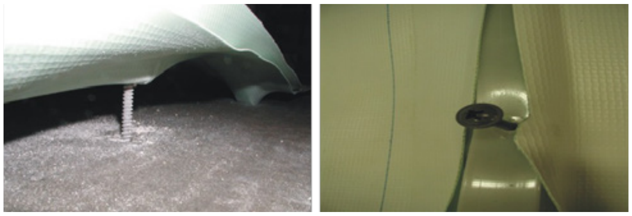

FIGURE 10. Fastener pullout from the steel deck.

FIGURE 11. Membrane pullout from the fastener plate in MARS.

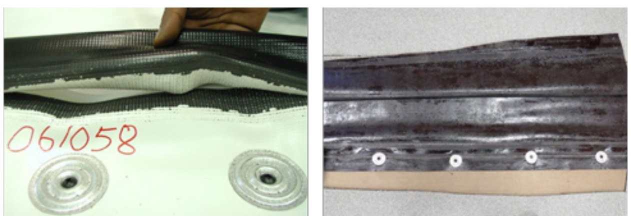

FIGURE 12. Membrane seam failure.

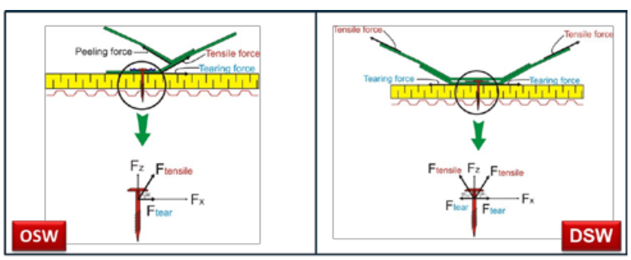

FIGURE 13. OSW versus DSW for MARS.

as shown in **Fig. 10**. The second specimen was installed on 20 ga, 550 MPa steel deck and passed a sustained pressure of 8.62 kPa (180 psf).

Q7: WHAT IS THE ROLE OF MEMBRANE?

Common membranes are thermoset, thermoplastic, and MB. The membrane must have adequate strength to withstand the stress from wind uplift. The physical/mechanical properties of a membrane such as thickness and tensile strength vary from product to product depending on the chemical composition and the reinforcement materials. As shown in **Fig. 11**, the membrane was stretched around the fastener plates, leading it to pull out from the fastener plate; this is known as the "cookie cut" failure. In this case, the membrane was the weakest link for that roofing system. Replacing it with a thicker and/or higher tensile strength membrane will help to increase the wind uplift resistance of the system.

Membrane seam strength is an important parameter that influences wind uplift resistance in MARS. The seam must resist fluttering and pulling forces due to wind uplift force. Some manufacturers supply membranes with factory seams, but most of the manufacturers require seaming during construction. There are three different types of seam application methods for MARS. Thermoplastic membrane seams are hot-air welded by a robotic machine. Thermoset membrane seams have tape and/or adhesive. MB membrane seams are heat air welded. The SIGDERS research showed that using improper speed and temperature for hot/heat air welding results in a very weak seam, as shown in **Fig. 12**. Manufacturers have invented new seam application technologies such as self-adhered seam or torch-free seam in recent years, with claims that the new seam application technologies are better than the traditional methods. Further research is needed to investigate the welding window (temperature and speed), the influence of ambient temperature to self-adhered seam and torch-free seams on wind uplift resistance.

For the MARS with thermoplastic membrane, there are two seaming techniques, one-side weld (OSW) and double-side weld (DSW), as shown in **Fig. 13**. The SIGDERS research showed the roofing system with DSW performed better than OSW. DSW system sustained a minimum of 15% higher wind uplift resistance than OSW system. The OSW system develops an asymmetrical force by pulling the bottom membrane. The fasteners are experiencing a single-direction wind load, which will rock the fasteners sideways and cause fatigue deformation at the steel deck/fastener engagement locations. This fatigue ultimately results in the fastener pullout from the steel deck. The DSW system develops symmetrical forces along the horizontal direction; this minimizes the rocking action on fastener.

The membrane width ranges from 1.83 m to 3.66 m (6 ft to 12 ft). The spacing between two fasteners on the seam is called fastener spacing, and the spacing between two rows of fasteners on the seam is called fastener row spacing. The recommended practice is to orient the fastener rows perpendicular to the steel deck flange, as shown in **Fig. 14**.

Q8: WHAT IS THE ROLE OF INSULATION/COVER BOARD?

In addition to the deck and membrane, insulation is also important substrate/roofing component in a

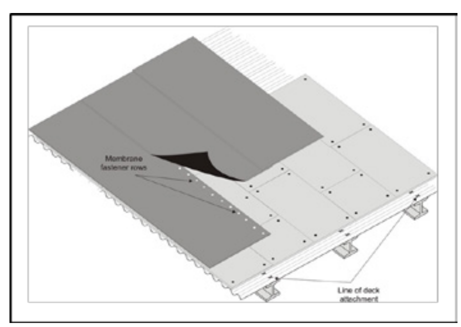

FIGURE 14. Membrane fastener rows are perpendicular to the deck flanges.

FIGURE 15. Substrate pullout from the fastener and plate for a PARS.

FIGURE 16. Facer delamination failures for an AARS.

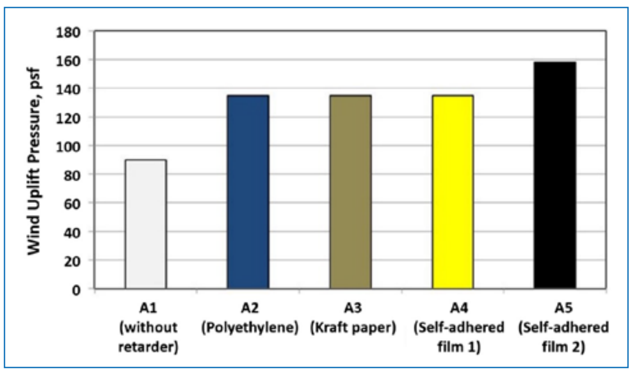

FIGURE 17. Wind uplift resistance with different types of VBs.

FIGURE 18. Physical characteristics of the fasteners.

roofing system. The primary function of insulation is to act as a thermal barrier for the roofing system. The cover board enhances the resiliency and durability of the system. It is installed below the membrane and above the insulation to minimize the deterioration of other components during the service life of the roof. Substrate should have sufficient compressive strength and pull-through strength. A weaker pull-through strength can cause a "cone cut" on the substrate board, as shown in **Fig. 15**. In the AARS and PARS, the membrane is adhered to the top surface of the insulation/cover board. The interface peel strength between the membrane and the substrate should be able to resist the shear forces created from the wind uplift force to avoid the types of failures shown in **Fig. 16**.

Q9: WHAT IS THE ROLE OF A VAPOR BARRIER (VB)?

A VB offers a certain resistance to airflow in addition to its primary function of limiting vapor diffusion into the roofing system from indoors. Based on SIGDERS research, systems' wind uplift resistance increased by 25% to 50% for systems with a VB than the systems without a VB, as shown in **Fig. 17**. The wind uplift resistance was varied depending on the air permeability of the VB and type of roofing system. Also, in the field, poly and kraft paper are more delicate materials that may not stand up to foot traffic, materials being dragged over them (puncture) and the effects of heat or solvents when the roof membrane is applied (assuming that there is a continuous connection between the VB and the membrane at the perimeter and openings). Self-adhered membranes with a tri-laminate facer, for example, will stand up to the rigors of the site activity better.

Q10: WHAT IS THE ROLE OF FASTENERS AND PLATES?

Accessories, fasteners, and plates are used to secure either the membrane or insulation or both to the structural deck.

Fastener/Deck Engagement: The fastener tip and thread design will determine the fastener pullout resistance (FPR) with respective deck engagement. **Fig. 18** shows three different fastener sizes along with the physical characteristics of the head, tip, and thread. **Fig. 19** shows plotted FPR data for five fasteners with four different types of decks. The data shows that the FPR is higher with a greater shank diameter, irrespective of the deck types. The data also shows that the FPR for two different sources with the same fastener type (#15 or #21) measured different values, respectively.

Fastener Plate/Membrane Engagement in a MARS: This engagement keeps the membrane in place. The barbed plates provide a better clamping force compared to smooth ones. The flat, smooth plate allows membrane slippage and tearing along the fastener shank, as shown in **Fig. 20** (left), even at low wind uplift pressures. At high wind uplift pressures, the barbed plate bends due to the membrane billowing and loses its clamping force; the membrane is stretched along the deformed plate portion, which results in the membrane being torn as shown in **Figure 20** (right). If the membrane tensile strength was lower than the wind uplift load, the membrane would stretch and tear around the fastener plates.

Fastener Plate/Membrane Engagement in a PARS: The

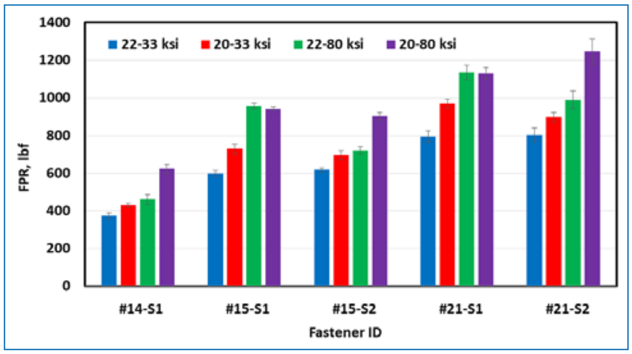

FIGURE 19. FPR for different deck types.

FIGURE 20. Fastener plate/membrane engagement against wind uplift in MARS.

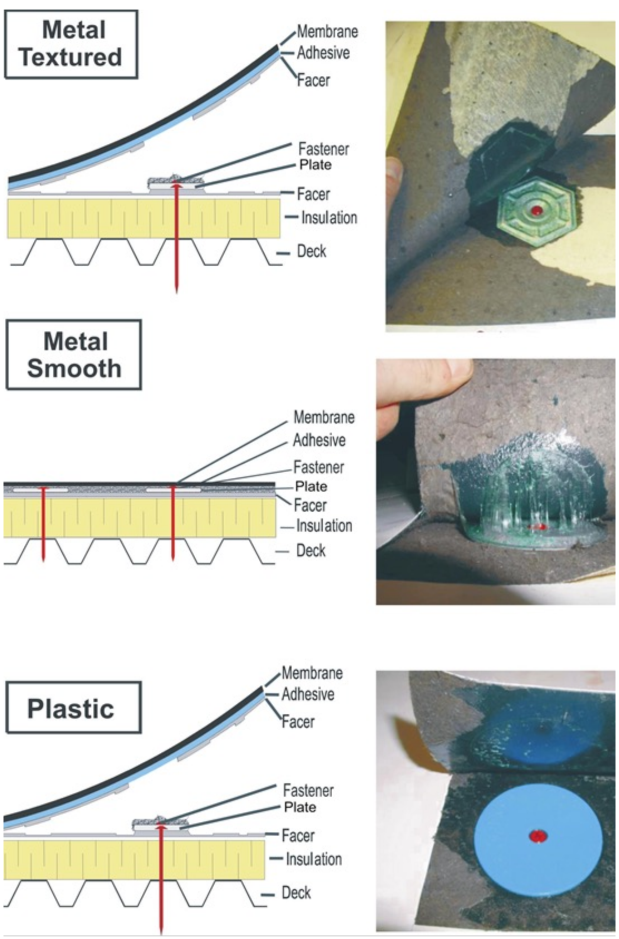

FIGURE 21. Failure modes observed with different insulation plate configurations in PARS.

membrane is adhered to the top surface of the insulation. The insulation is secured to the deck with fasteners and plates. Based on SIGDERS research, systems with smooth-surface insulation plates increased the wind uplift resistance by 50% more than systems with textured insulation plates. **Fig. 21** illustrates the failure modes for different insulation plate configurations. Textured hexagonal plates offer the required contact area with the membrane only through the outer and middle rims of the plates. Smooth circular metal and plastic plates have a larger contact surface area to increase the bonding strength with the membrane.

Q11: WHAT IS THE ROLE OF ADHESIVE, ADHESIVE AMOUNT, AND CURING TIME?

Adhesive curing time is the key factor to determine the adhesive bond strength. The higher the adhesive bond strength, the better the wind uplift resistance. For a scenario tested by SIGDERS, a system failed below 2.87 kPa (60 psf) with 14 days of curing time. The system had a wind uplift resistance of 3.59 kPa (75 psf) with 21 days of curing time and a wind uplift resistance of 4.31 kPa (90 psf) with 28 days of curing time. The failure modes for 14, 21, and 28 days are adhesive failure between the cap and base sheet interface, a cohesive failure between the cap and base sheet interface, and the VB detached from the deck interface, respectively, as shown in **Fig. 22**.

Q12: IS THERE AN IMPACT OF AIR INTRUSION ON A LOW-SLOPE ROOF?

Air intrusion is when the conditioned indoor air enters into the building envelope assembly and cannot escape to the exterior environment with the roof membrane acting as an air barrier. Air intrusion can be a major driving force for movement of moisture in the form of water vapor into a MARS. **Fig. 23** showed the condensation happening below the roof membrane on one of the commercial roofs during field investigation. Limiting air intrusion is critical for good roof design practice, it helps increase wind uplift and thermal resistance, minimize moisture accumulation and condensation issues.

Based on SIGDERS's research, ASTM D7586, *Standard Test Method for Quantification of Air Intrusion in Low-Sloped Mechanically Attached Roof Assemblies*, was developed in 2011. A series of tests were carried out by the SIGDERS consortium to quantify air intrusion rate for a MARS. The result showed the system with a VB decreased the air intrusion volume by 50% to 80% depending on the bubble pressure (the pressure on the top of the insulation/cover board), membrane deflection, and volume change, as shown in **Fig. 24**.

Q13: WHAT ARE THE ATTRIBUTES OF A VEGETATED ROOF ASSEMBLY (VRA)?

In a VRA, a roofing system and a vegetated system are assembled together, as shown in Fig. 25. A roofing assembly consists of a deck and roofing or waterproofing membrane. It includes components such as vapor barriers or retarders, insulation, cover board, etc. A modular vegetated system consists of pre-grown or pre-cultivated vegetation (modules, blankets, or mats), growth media, a root barrier, pavers, and a drainage system. In industry practice, a VRA is sometimes referred to as a green roof. However, the term “green roof” can be misleading because it can be interpreted differently, as follows:

- “Green roof” could be a reference to the color of the roof (e.g., a copper roof).
- “Green roof” is used loosely to denote roofs with environmentally friendly products such as those made from recycled materials (e.g., bio-based insulations).
- Roofs with energy-efficient components such as highly reflective roofing membranes (e.g., white single plies or MB roof with reflective coating).

Based on this, a VRA is defined as intentional placement of an engineered vegetated system over the roof system (**Fig. 25**).

Q14: HOW DOES A VRA RESPOND TO WIND?

Wind aerodynamics on a VRA can be viewed as action, whereas the response of the VRA is the reaction. Not all VRAs react to wind in a similar manner. The response of a vegetated system depends on several factors, such as the membrane attachment method, vegetation type, weight, design, and installation method (e.g., edge restraint conditions). The complex wind dynamics on VRAs can be simplified as effects due to pressure and flow. Responses of the vegetated system to flow include sliding, overturning, and scouring (**Fig. 26**). Responses of the vegetated system to wind-induced pressure include fatigue and uplift.

Q15: IS THERE A TOOL OR STANDARD AVAILABLE TO VALIDATE MY VRA DESIGN?

The wind uplift resistance of the VRA can be evaluated in accordance with CAN/CSA A123.24, *Standard Test Method for Wind Resistance of Vegetated Roof Assembly*. The test results can be compared to the calculated design parameters in Q4 above for pass/fail scenarios.

Q16: WHY ARE VRAS SUBJECTED TO UPLIFT AND FLOW RESISTANCE TESTS?

An uplift test only evaluates the pressure resistance of the VRA, since the membrane acts as an air barrier in a conventional roofing system. Wind flow aerodynamics can simulate the vegetated system’s overturning, scouring, and sliding failure mechanisms. To mimic the wind effects on the VRA (refer to Q14), both uplift and flow testing are needed.

Q17: CAN I USE THE WIND UPLIFT DATA FROM A ROOF SYSTEM TEST?

Yes, in a scenario where the VRA has the same roofing system as the one tested under CAN/CSA A123.21, *Standard Test Method for the Dynamic Wind Uplift Resistance of Mechanically Attached Membrane-Roofing Systems*, the manufacturer or client may choose to use the uplift resistance data obtained from CAN/CSA A123.21. Then the manufacturer or client has to perform only the flow test as per Section 7 of CAN/CSA A123.24 to obtain the flow resistance.

Q18: WHAT ARE THE TYPICAL COMPONENTS OF AN ASPHALT SHINGLE ROOFING (ASR)?

Residential roofs utilize different material coverings such as

FIGURE 22. Failure modes varied with curing time for an AARS.

FIGURE 23. Condensation below the roof membrane.

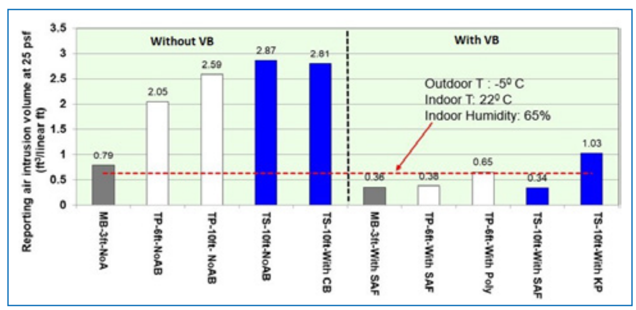

FIGURE 24. Air intrusion volume with and without the VB.

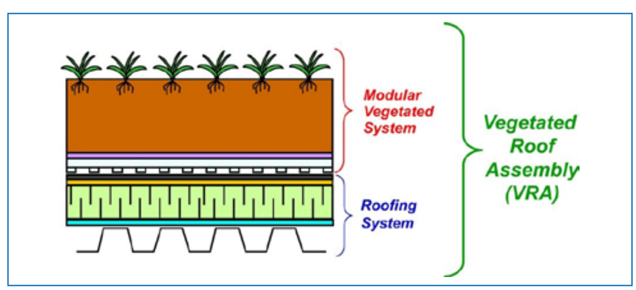

FIGURE 25. Roofing system and vegetated system assembled together to form the VRA.

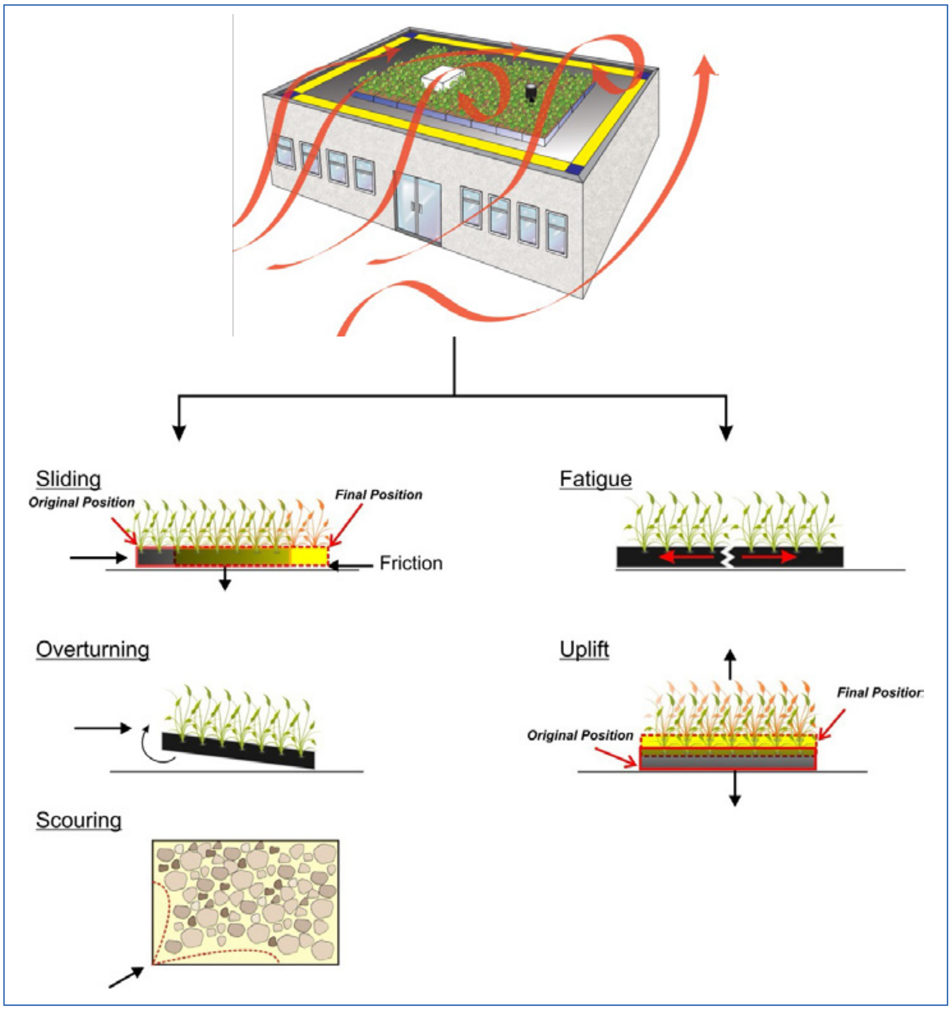

FIGURE 26. Wind aerodynamics and failure mechanisms of a VRA.

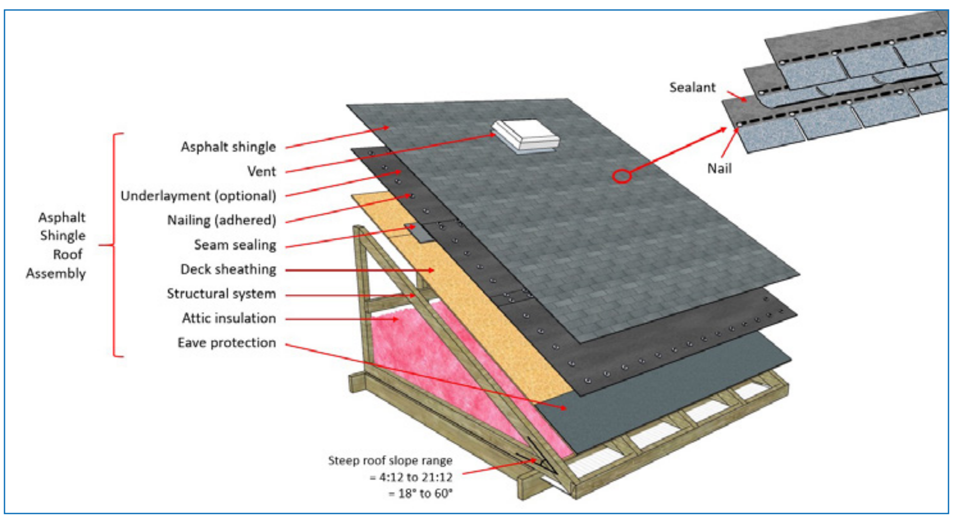

FIGURE 27. Typical components of Asphalt Shingle Roofing (ASR).

metal, tile, and shingles. Asphalt shingles are used on almost 90% of Canadian residential roofs because of their affordability, ease of installation, and adaptability. Residential roof is composed of four major components: asphalt shingle, underlayment, wood sheathing and insulated attic (**Fig. 27**). In addition, accessories such as vents, sealant, nails, and eave protection also form part of the ASR.

Q19: ARE THERE ANY MISSING LINKS IN THE CURRENT CODE?

The current code does not address the following:

» There is no guide for specifiers to have their design meet or exceed the specified wind loads.

» There are no specific climate requirements for materials. The code only provides generic loads that materials are expected to perform against.

» There is no climate adaptation of future loads.

» The code does not provide material installation requirements

Q20: HOW TO CLASSIFY THE FUTURE CLIMATIC CONDITIONS BE QUANTIFIED?

As mentioned in Q1, there is a tool available named Climate-RCI that calculates the design load by accounting for future climatic conditions. It can be accessed at https://nrc.canada.ca/en/research-development/products-services/software-applications/climate-rci.

Climate-RCI has been developed by NRC. It takes into account projected changes in weather elements (wind, rain, and temperature) and provides the design loads for 696 cities across Canada. The climatic loads are classified into three climate zone severity classes: normal, severe, and extreme. This tool also forms part of CSA A123.26, *Performance Requirements for Climate Resilience of Low Slope Membrane Roofing Systems*.

Q21: CAN FUTURE WEATHER SHOCKS BE MODELLED FOR ROOFING AND OTHER BUILDING ENVELOPE MATERIALS?

Based on discussions with the industry, a framework was developed using future climatic loads and how to incorporate them into the experimental methodology. Initially, hourly temperature time series available for 564 locations across Canada were

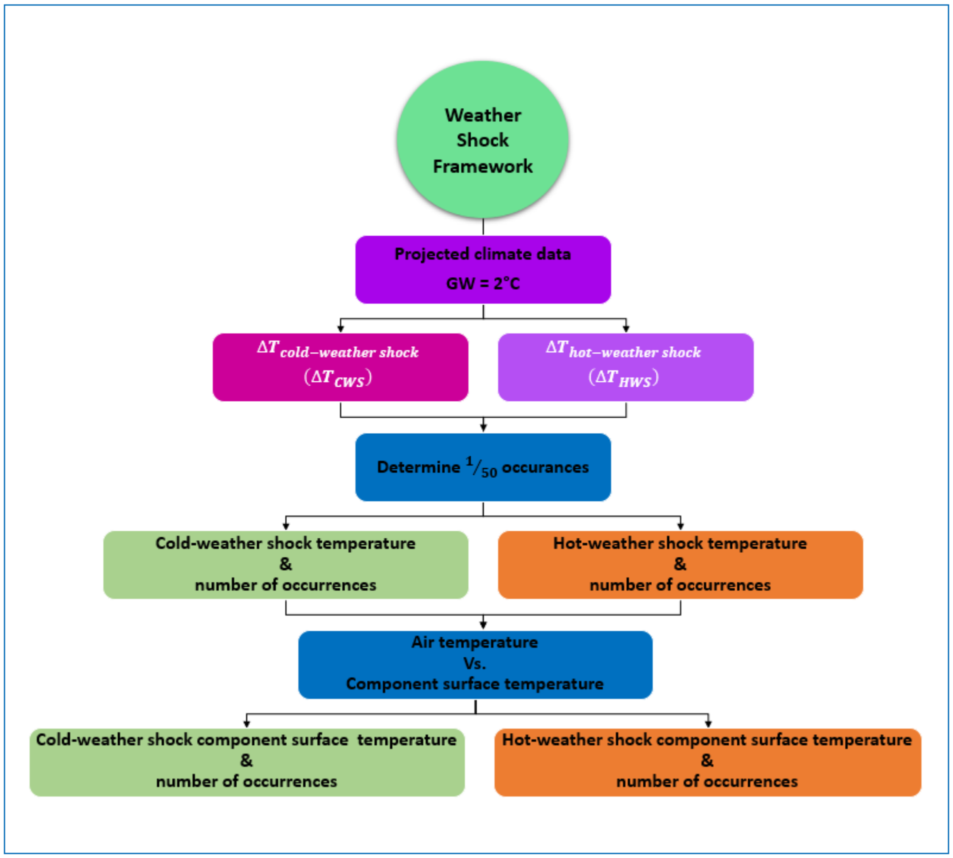

FIGURE 28. Weather shock framework.

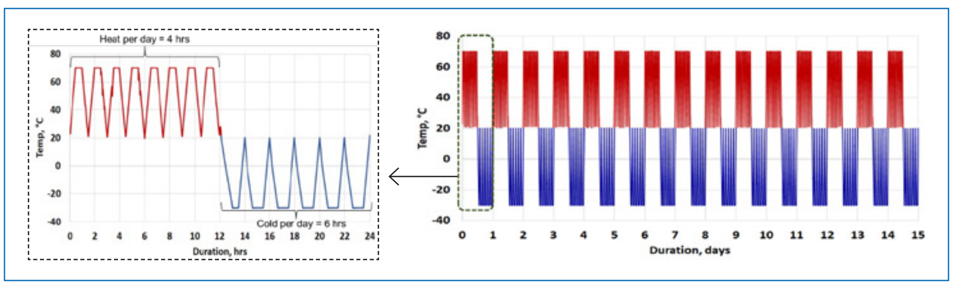

FIGURE 29. Example of the application of the hot- and cold-weather shock for a dark-colored roof covering.

analyzed for hourly fluctuations. The data available for these locations spanned 10 to 20 years, with the majority of the locations having 15 years of data available. A threshold value of 5°C was chosen to identify the instances of hourly fluctuations above the threshold. The number of these cycles per year obtained from the time series were fit to a Poisson distribution (probability of exceedance is 2%), and the number of cycles for 50-year return periods was determined. For the analyses, the period from May to August was considered summer, during which a hot-weather shock would occur, and the period from December to March was winter, during which a cold-weather shock would occur. The above is summarized in **Fig. 28**.

The hot- and cold-weather shock values are initially obtained based on air temperature. The surface temperature that a roof component will reflect under a specific air temperature will differ based on the component and its position within the system. That is why there is a need to establish the relationship between the component temperature and the air temperature.

Thereafter, the hot- and cold-weather shocks the component will be experiencing in a scenario of 2°C global warming magnitude can be determined. This framework can be followed for all building envelope components and is not limited to roof components. As well, the parameters can be established for other global warming magnitude ranges from 0.5°C to 3.5°C.

Q22: CAN I APPLY WEATHER SHOCK PARAMETERS FOR DURABILITY EVALUATION OF ROOFING COMPONENTS?

Materials are currently evaluated at lab temperatures. Materials age and deteriorate differently when they experience weather shock cycles. Using the information from the framework in Fig. 28 the hot- and cold-weather shock component temperatures and their respective number of occurrences are determined. Also, to replicate the cycling that already naturally occurs with the change in seasons, the hot- and cold-weather shocks were alternated. An important step for incorporating the weather shock framework into testing is the duration of the hot and cold cycles to ensure practicality of the experiments. An example of how this can be achieved is by setting a practical duration of the entire weather shock cycle and adjusting the duration of each cycle. This must be achieved while ensuring that the total number of fluctuations for hot and cold weather shocks is maintained. An example of a dark-colored roof covering (asphalt shingle) is shown in **Fig. 29**. The hot- and cold-weather shock cycle has a total duration of 15 days. Within each day there are 8 hot- and 6 cold-weather shock cycles. The duration of 15 days, along with the breakdown of 8 hot and 6 cold cycles a day and the duration of each cold and hot cycle, can be changed to better reflect the building envelope material being evaluated. An asphalt shingle will not absorb and retain heat in a similar manner to a beige wall siding. Therefore, the factors that must be

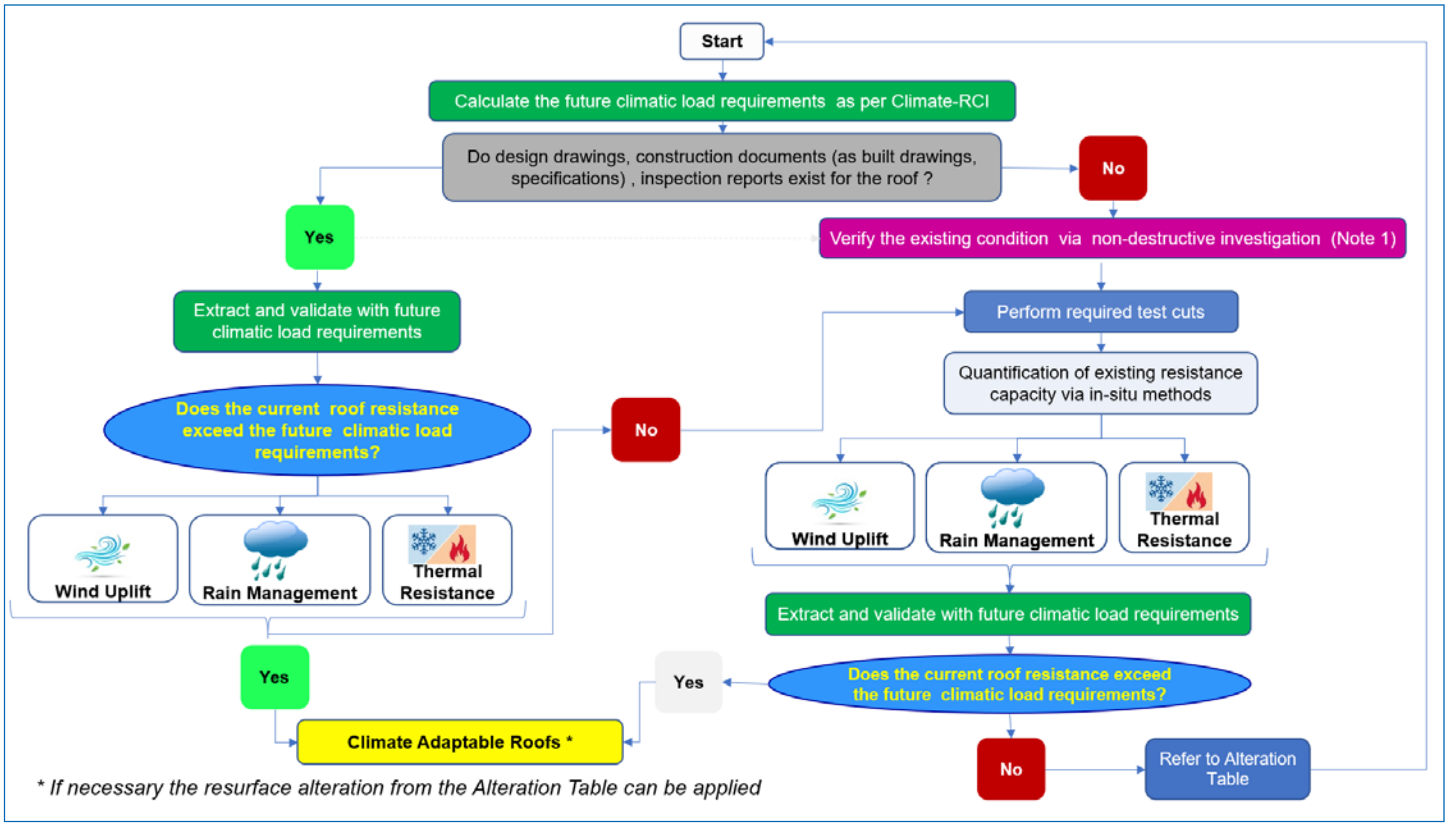

FIGURE 30. Framework for climate-adaptable roofs.

respected when determining the composition of the cycles are:

» The cold and hot component weather shock temperatures
» The number of weather shock occurrences

Q23: CAN A CLIMATE-DEPENDENT DURABILITY INDEX (CDDI) BE DEVELOPED FOR ROOFING COMPONENTS?

By taking asphalt shingles, for example, the CDDI can be explained as follows. Shingle composition and behavior are complex, and attributing performance once installed as part of a system to an individual property is difficult and inadequate. Developing a science-based indicator that would combine key properties with the exposed climate severity of the material may provide a more comprehensive indicator of the material's long-term performance. The CDDI was developed to accomplish this. The CDDI combines five critical properties: tear strength, overlap strength, fastener pull-through, tensile strength, and granule loss.

For each of these properties, the durability factor and importance factor are calculated. The durability factor depends on the property's reduction in strength after exposure to the climate zone –dependent weather shock protocol. If a property is greatly reduced, that is an indication that the durability of the shingle is low. The durability factor ranges from 0 to 3. A durability factor of 0 is corresponds to reduction in strength greater than 45%, and durability factor of 3 is corresponds to reduction in strength less than 5%. A higher durability value indicates a more durable shingle. The importance factor is assigned to each of the five critical properties based on the mode of field failures and industry consensus. The importance factor for each property is greater than zero but less than 1, as follows: tear = 0.2; overlap strength = 0.3; fastener pull-through = 0.2; tensile = 0.1; and granule loss = 0.2. By combining the durability factor and the importance factor for each of the critical properties, one can determine the classification level of CDDI, which can be either silver (CDDI greater than 2 and less than 3) or gold (CDDI = 3).

Q24: WHAT IS THE IMMEDIATE NEED FOR COMMERCIAL ROOFING?

Alterations to existing roofs (AER) have a major market share compared to new construction. In some regions of North America, AER market share is over 70%. AER includes, but is not limited to, reroofing, resurfacing, recovering, and upgrading for energy efficiency and high wind events.

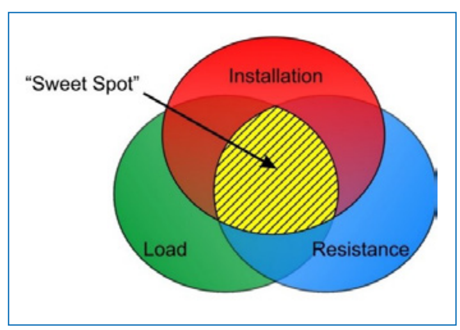

FIGURE 31. Holistic approach for climate adaptation requirements of roofs.

Unfortunately, as a roofing community, there is no consensus exist in the terminology. Moreover, existing limited code specifications are misunderstood due to variations in the terminology at various levels. The NRC is undertaking a nationwide consultation process to gather the state of the current design practice. One of the main objectives of this consultation is to develop building code requirements. Both current climatic and future climatic conditions will be considered. A framework is presented in **Fig. 30**.

Q25: AS A ROOFING COMMUNITY, HOW CAN WE PLACE THE BUILDING OWNER IN THE "SWEET SPOT"?

A holistic approach is proposed so that the building owners enjoy the "sweet spot." Basically, there are three requirements that need to be collectively integrated, including:

- **Load** specification accounting for future climatic conditions
- **Resistance** evaluation through testing incorporating the climatic load
- **Installation** with quality assurance metrics

Fig. 31 illustrates that when the three requirements are combined, then the sweet spot is achieved. The sweet spot indicates the shared segment of load, resistance, and installation. The bigger the sweet-spot segment, the longer the service life of roofing assemblies.

CLOSING REMARKS

This paper presented selected accomplishments of the ongoing roofing consortia at the NRC. The Q&A format has been used to address the wide range of topics. Over the last 20 years, most of these developments have been presented at the annual IIBEC conventions, for which the author is grateful for. This long-lasting industry consortium has published over 100 peer-reviewed publications. Readers who would like to get additional details or data for any of the questions or topics are requested to email the author.

DEDICATION:

The author would like to dedicate this paper to James "J.P." Sheahan, who introduced the author to present for the first time at the IIBEC convention, and Katharine Spavins for her continued welcome to IIBEC.

ACKNOWLEDGEMENT:

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Their valuable insights, collaborative spirit and unwavering support throughout the project have played a significant role in the successful completion of this publication.

Simplifying Whole-Building Airtightness

ABSTRACT

Not only does the 2022 *International Building Code* require whole-building airtightness testing, but an airtight building is also key to moisture management in the building enclosure, proper operation of mechanical equipment, and reduction in dust; odors, such as secondhand cigarette smoke; and poor air quality. This paper discusses the details of the code change and the testing, including test methods ASTM E779 and ASTM E3158. Key items to include in construction documents are covered, including the top details responsible for unsuccessful tests and poor building performance. These include the wall, roof, foundation, and critical transitions between them.

LEARNING OBJECTIVES

- Review the updated air barrier requirements in IECC 2024 and 2022 ASHRAE 90.1.
- Define whole building airtightness testing and identify ways to ensure it is done correctly.
- Describe the necessary components that should be included in construction documents to ensure an airtight enclosure.
- Analyze five of the most frequently missed interface details that impact airtightness.

SPEAKERS

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Adam Ugliuzza brings 16 years of engineering experience focusing on building science and building enclosure construction. Experience includes enclosure consulting/commissioning services for new and existing construction, in addition to forensic investigations to determine root cause of building performance issues. He brings industry leading expertise in whole building airtightness testing, which is at the forefront of high-performance building construction. His project work spans across the United States and abroad providing professional building enclosure consultation in both the residential and commercial space for all types of construction, ranging from multi-family wood/timber framed buildings to high performance institutional/healthcare facilities to high-rise construction.

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Andrea Wagner Watts is the Building Science Education Manager for GAF, engaging with industry professionals to provide guidance, technical support and education for roof and wall assemblies. With more than 15 years of experience in the industry, Andrea strives to improve the overall performance of the building enclosures through application innovation, product development and building science research. Andrea has published on building science, assembly interfaces, durability and resilience and holds multiple patents. She serves as an executive board member of ABAA, is the co-chair of their Technical Committee and chairs the ASTM E06 Task Group on air barriers.

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Andrea Wagner Watts, LEED Green Associate

Soar in 24
IIBEC International Convention & Trade Show

Air barriers, air infiltration, airtightness—these words may seem to have been around the industry forever, but in the timeline of buildings, they are relatively new concepts. The Air Barrier Association of America (ABAA) was founded in 2001 and air barriers were first called out as a requirement in the *International Energy Conservation Code* (IECC)[1] in 2012. As an industry, we are still learning best practices for how to install and test for air leakage in our buildings. And it is for good reason. Air leakage was first identified as a major source of heat and energy loss in buildings. Hence, the code requirements for air barriers are found in the energy code and not with the water-resistance requirements in the *International Building Code* (IBC).[2] Air leakage is also a major source of moisture in our buildings, which comes by way of moisture-laden air. If that moisture is allowed to condense in the wrong place, it can lead to a whole host of problems, such as mold and material degradation. Furthermore, the additional moisture load on the structure increases the operating energy costs for a building. It takes a lot of energy for an HVAC system to remove enough moisture from the air, and it may not be able to remove enough moisture to the levels needed to prevent issues without the addition of a dehumidification system. As such, ensuring a continuous air control layer around the entire building enclosure is critical to long-term success of a building's performance.

Moisture is not the only contaminant that joins unintentional airflow into and out of a building enclosure. Indoor air quality is also improved through an airtight building system. If air enters through the exterior wall and roof assemblies, it brings with it contaminants such as wildfire particles, secondhand smoke, dust, and odors. When air movement into a building comes only through the mechanical system, it is able to be filtered before it enters the occupied space instead of by way of circulating the air through the entire system before filtering. This will also save on the energy load of the mechanical system.

Air control is important for the entire building enclosure (including the roof and foundation), not just the walls. Even more importantly, success relies on the continuity of the air control layer at the interface between different building systems. Because the different systems and transitions are installed by different trades and get hidden during construction, the best way to determine if a truly airtight building has been constructed is to conduct a whole-building airtightness test (WBAT).

AIR BARRIER REQUIREMENTS IN IECC AND ASHRAE 90.1

Buildings are constructed of thousands of products produced by hundreds of manufacturers installed by numerous trades, all with the expectation that they perform together to keep the inside in and the outside out. Manufacturers can test materials and systems of materials in a controlled lab setting, but that cannot guarantee perfection during actual construction. As the importance of minimizing air leakage has become more well known, so has the building code recognized the importance of ensuring that the constructed building is airtight.

The IECC first started requiring air barriers in certain climate zones in 2012 after ASHRAE Standard 90.1[3] first required them in 2009. Over the last 11 years, the requirements for the use of an air barrier, air barrier assembly, and WBAT have continued to become more strict. The current 2021 IECC requires air barriers everywhere but in Climate Zone 2B, which primarily covers southwestern Arizona. The air barrier requirement includes that it is the design professional's responsibility to make sure that the "air barrier and air sealing details, including the location of the air barrier" are included in the construction documents.[1] Air barrier materials and system requirements have expanded to include WBAT for many buildings. It has continued to expand to specific jurisdictions, such as Washington State, and specific building owners, such as the United States Army Corps of Engineers (USACE), requiring WBAT.

The air barrier requirements adopted by the IECC originate in ASHRAE 90.1, which has an ultimate goal of designing buildings to be able to achieve zero energy by 2031. Each version of the model code uses the most recently published version of ASHRAE 90.1 with the associated gradual energy use reduction. This means that the current 2021 IECC references the 2019 ASHRAE 90.1 and has set limits on the air leakage through the building thermal envelope. The 2021 IECC states that a continuous air barrier must be constructed and verified *or* a WBAT must be performed. The intricacies of these requirements are not simple, as diagrammed by Meyer and Weston[4] (**fig. 1**).

The complicated nature of determining what exactly has to be done to meet the code can be simplified by performing WBAT on the building. Both the 2018 and 2021 IECC require a maximum whole-building airtightness less than or equal to 0.40 cfm/sq. ft at 75 Pa. When the 2021 IECC mandated more whole-building testing, an "oops" clause with a limit of 0.60 cfm/sq. ft at 75 Pa was introduced. There are air leakage limits for dwelling units as well.

It is anticipated that the air leakage limit will be reduced further to 0.30 cfm/sq. ft in the next version of the IECC now that it has gone through a code cycle of being required. All of these changes are based around the ASHRAE 90.1 updates going from 2019 to 2022 with the same changes to air leakage limits. Meyer and Weston have published a more detailed overview of all things ASHRAE 90.1 and IECC over the last five years.[4]

The airtightness testing to meet the code requirement must be completed according to ASTM E779,[5] ASTM E3158,[6] ANSI/RESNET/ICC 380,[7] or ASTM E1827.[8] While these tests are all listed together, it does not mean that they are equivalent. The test methods were developed over multiple years as the industry continued to learn how to test for this performance attribute. ASTM E1827, *Standard Test Methods for Determining Airtightness of Buildings Using an Orifice Blower Door*, is rarely used, as its accuracy is limited compared with the other methods. This test method is unable to detect changes in the test specimen while testing. For this reason, ASTM E779 became the default test method until the development of ASTM E3158.

WHOLE-BUILDING AIRTIGHTNESS TESTING

History

Originally approved in 1981, ASTM E779, *Standard Test Method for Determining Air Leakage Rate by Fan Pressurization*, was developed to provide a standardized method for measuring building enclosure airtightness.[5] The standard provided the construction industry with the ability to verify building performance at the completion of a construction project. Initially, ASTM E779 was predominantly a test method for residential construction. Its procedures align with characteristics of smaller buildings, like single-family homes or unit testing in larger residential buildings. However, ASTM E779 did not preclude the use of the test method for commercial construction.

As its use in the commercial space became more widespread, the shortcomings of the test method became apparent. The required test pressure range, lack of restriction

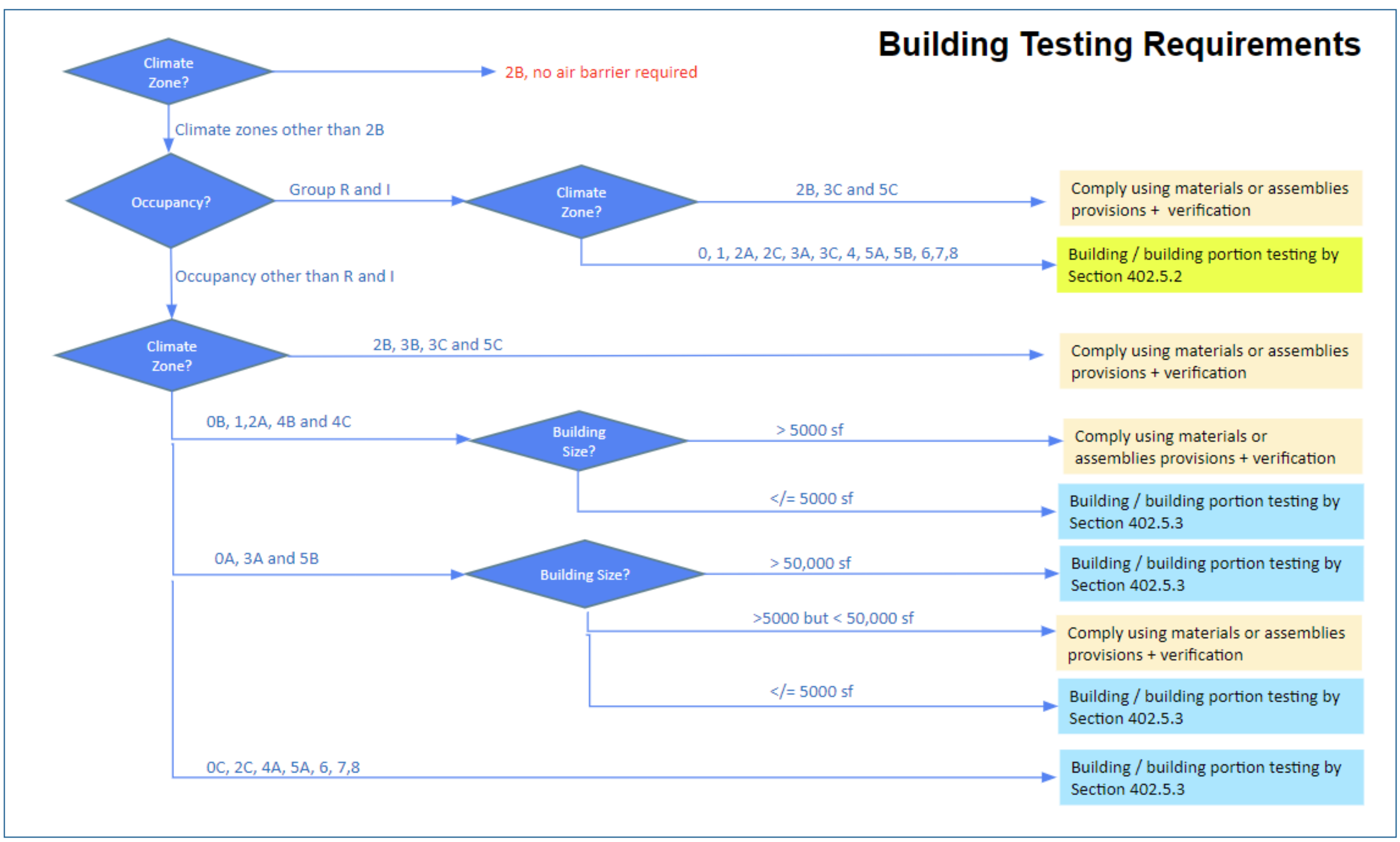

FIGURE 1. Building testing requirements decision tree for compliance IECC-2021 *(Figure courtesy of Siplast).*

of data extrapolation, and limited statistical analysis parameters made the test vulnerable to accuracy and repeatability issues with more complicated, larger, and taller commercial buildings. To a large extent, this was due to the increased impact that environmental conditions have on commercial buildings, mainly wind pressures and temperature difference (stack pressure).

The United States Army Corps of Engineers' (USACE's) *Air Leakage Test Protocol for Building Envelopes*, version 3, in 2012 adopted additional requirements for the ASTM E779 test method to ensure accurate and repeatable testing procedures more suitable for commercial construction.[9] USACE partnered with the ABAA on this project. Significant modifications to ASTM E779 included baseline pressure limits, a higher multipoint test pressure range with minimum and maximum test pressure limits, an acceptable range for the pressure exponent (*n*), and correlation coefficient squared (r^2) pass/fail criteria.

Based on the work with USACE and input from industry professionals, ABAA recognized that the building code adoption of WBAT for commercial construction needed a new test method to address concerns with ASTM E779. This new standard would reflect many of the changes adopted in the USACE test protocol[3] described above. The ABAA WBAT Task Group worked for several years to develop the ABAA Standard Method for Building Enclosure Airtightness Testing, which was published August 25, 2016. This document became the basis for the development of ASTM E3158-18, *Standard Test Method for Measuring the Air Leakage Rate of a Large or Multizone Building*.[6]

In addition to the multipoint test procedure carried over from ASTM E779/USACE, ASTM E3158 also includes updated versions of the single-point and two-point test procedures included in ASTM E1827. These test procedures are not commonly specified or performed, but the industry recognizes that these procedures still provide value in limited use cases. The intent is for ASTM E3158 to become the main standard for blower-door testing to eventually supersede ASTM E779 and ASTM E1827 in commercial construction for WBAT.

Overview of Testing Preparations and Procedure

Typical Building Preparations

A significant amount of time is required for building preparation and this often represents the majority of work involved to execute a commercial WBAT. Typically, this scope of work is performed by the contractor to limit cost and to mitigate liability of the testing agency resulting from damaged equipment or materials that may occur when preparing the building for testing.

- Power down HVAC equipment.
- Mask, seal, and close HVAC dampers/louvers.
- Close and lock all test boundary exterior windows and doors.
- Fill all plumbing traps with water.
- For suspended drop ceiling tiles and underfloor air distribution computer floors, remove one tile for every 500 sq. ft of area (minimum of one tile per room).
- Prop open all interior doors within the official test boundary. Doors connecting the main corridors to any portion of the enclosure, including walls, roofs, and slab-on-grade conditions, must be open to achieve uniform pressurization.
- With taller buildings, elevator doors on each floor may need to remain in the open position with the elevator car parked at the optimum location to promote airflow throughout floors.

Procedure

Blower door fans are set up in exterior doors and can be distributed on each side of the building and/or at immediate and main roof levels. The size and complexity of the building will dictate the number of fans and fan locations. With multiple-fan testing, communication cables are typically run from micromanometers located near each fan and sometimes at specific locations for pressure monitoring, back to a centrally located laptop computer to monitor and control all test equipment and collect pressure and flow data.

Pressure monitoring consists of exterior and interior pressure tubes that are run across the building enclosure and throughout the building to monitor exterior pressure differentials and interior pressure uniformity, respectively, with micromanometers. Fan pressures are also measured with micromanometers to determine airflow (cfm). Interior differential pressure measurement taps are located at representative locations to compare building extremities and verify pressure uniformity throughout the building.

WBAT can include in testing both directions (pressurization and depressurization) or single-sided testing (pressurization or depressurization). Baseline pressure readings are recorded before and after the test flow measurements, with the fans sealed. Test flow measurements are recorded at predetermined test pressure(s), averaged over a period of time (typically a minimum of 10 seconds) for each data point. Single-point testing includes only one data point, typically at the required test pressure. Two-point testing includes two data points, at the lower and upper limits required for the test. Multipoint testing consists of a minimum of 10 equally spaced data points (required by USACE and ASTM E3158), ranging between minimum and maximum test pressures.

Importance of Hiring a Certified Technician

WBAT testing requires a significant amount of organization and test preparation. Project management is key to performing a successful test. It is also critical that the technician have a thorough understanding of the test methods and operation of test equipment. These tests typically require a significant amount of effort to mobilize and limited time onsite to execute, leaving little room for

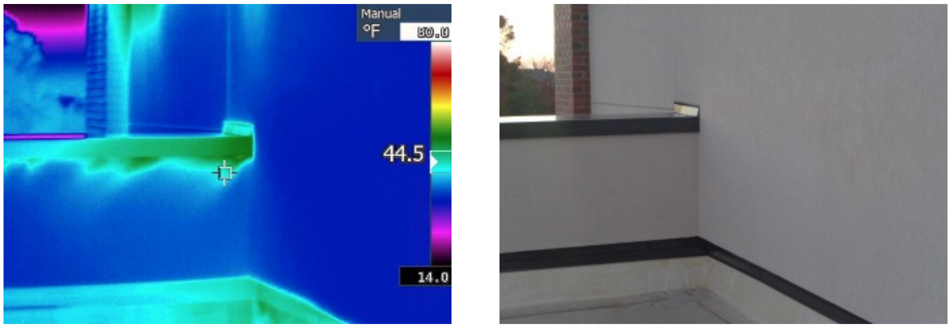

FIGURE 2. (a) FLIR image and (b) photograph of the same rising wall parapet condition showing air leakage at the interface.

error. Because the test specimen is the entire building, there are many ways to have complications, and it is up to the technician to diagnose and determine how to solve issues on the fly that commonly occur when testing. False positive or false negative results can also occur if the test technician is not competent or lacks the required experience needed to perform the test.

ABAA recognized there is a lack of experienced testing agencies in the construction industry that can perform WBAT and determined it was absolutely essential to develop a training program to elevate testing agencies to meet the testing needs of today and the future, when the testing becomes mandatory for all commercial construction. The ABAA now offers the training programs and a blower door technician certification.

COMMON PROBLEMATIC DETAILS THAT IMPACT BUILDING AIRTIGHTNESS

Six common building assembly details are frequent sources of air leakage found during WBAT. Each one needs special attention during the design and construction process, focusing on the materials used for the transition, order of installation, and sequencing of trades during the construction process. Often, simply highlighting the interface's importance for the building performance will cause the installers to give the extra attention these details deserve.

Roof-to-Wall and Rising Wall Conditions

Roof-to-wall and rising wall conditions are frequently a challenge due to the number of materials from different suppliers and trades that must be sequenced in order to perform as required. **Figure 2** shows how a leaky interface can be seen by way of a forward-looking infrared (FLIR) camera. The lighter colors show where cold air is coming through the transition, causing the substrates around the leak to be cooler than the bulk of the opaque wall. Wagner Watts and others have written multiple articles focused on how best to design and install these tricky transitions.[10]

Canopies

The continuity of the air barrier through a canopy condition must be determined during the design phase of a project. The determination of if the air barrier is going to wrap around the entire canopy or be continuous behind it (**fig. 3**), cutting off the canopy from the rest of the building enclosure will determine how it is detailed. Clear communication in the drawings of where the continuous air barrier is at these details will prevent issues during the construction process. It is also important to note that even though the air barrier may cut the canopy off from the building enclosure, that does not negate the need for a water-resistant barrier and/or roof membrane on these structures to prevent water damage.

Podiums/Parking Levels

Podiums and parking structures are often overlooked as part of the building enclosure. This is true when the structure is underneath the building (where it would be the bottom of the whole-building air barrier) or directly adjacent and acts as one of the walls of the continuous air barrier assembly. The entire side of the parking or podium structure that is

FIGURE 3. Canopy transition condition that is frequently a source of air leaks during a whole building airtightness test.

FIGURE 4. Penetrations through the wall of a parking structure that must be sealed airtight to complete the building's continuous air barrier.

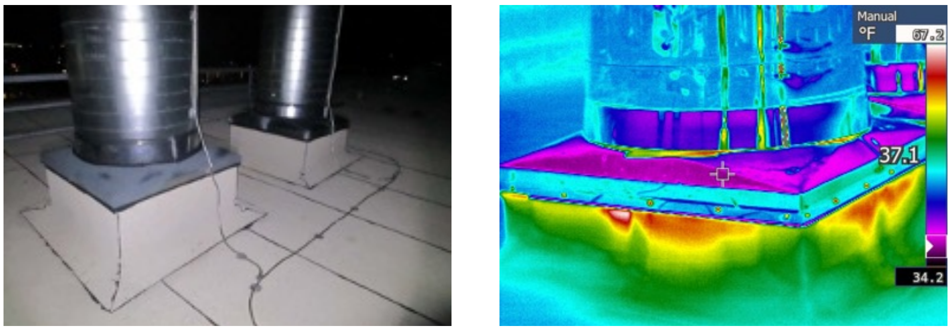

FIGURE 5. Mechanical system ductwork (a) and an FLIR image (b) of the same condition showing the high level of air leakage where the ductwork meets the roof assembly.

part of the thermal envelope must have an air barrier that is tied into the air barrier of the rest of the enclosure. Additionally, these structures often have multiple penetrations that must be sealed for airtightness (**fig. 4**). These details should be reviewed similarly to how they are reviewed for continuity in other parts of the building.

Mechanical Areas/Interfaces

To put it simply, ductwork must be sealed at the interface with the building roof. It is no different than a wall condition where similar penetrations exist. The HVAC contractor is typically responsible for this transition, but does not traditionally have a focus on airtightness with the rest of the enclosure. Because the HVAC team is not responsible for the air barrier assembly, or is not always knowledgeable about the importance of the transition to the performance of the enclosure, sealing of these interfaces is often overlooked, as shown in **figure 5**. Making sure these transitions are clearly called out in project drawings, submittals, and specifications will help ensure they are sealed prior to WBAT.

Traditional mechanical systems are not the only culprits. **Figure 6** shows two images from inside open-air plenums. These are the gray areas between the enclosure and the mechanical systems, as they are both ductwork and exterior wall at the same time. It is often the assumption that the louver is the air barrier plane, but the plenum enclosure is not sealed, so there is a giant hole in the whole-building air barrier assembly. A review of systems during the design process will provide clarity at these extensions of the enclosure.

Loading Docks/Work Bays

Loading docks and work bays are notoriously leaky and are often the culprit in poor WBAT (**fig. 7**). There are ways to enhance the seal of these doors if they are not used frequently. Even adding brush seals to the perimeter will improve performance. Another option is to compartmentalize the loading dock completely and separate it from the rest of the building enclosure. This option can be more reliable but the decision must be made earlier during the design process. It is not a repair option if a leaky door is realized after a test occurs.

CONSTRUCTION DOCUMENT REQUIREMENTS

Air Barrier Boundary Sheets

Air barrier boundary sheets are plans that identify the continuous air barrier boundary and the specific

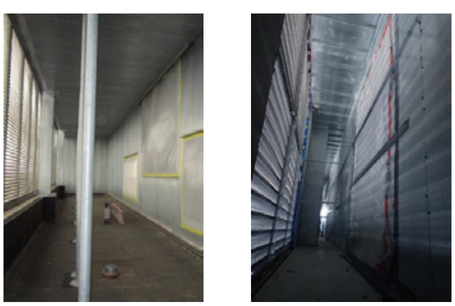

FIGURE 6. Two different plenum shafts where the interior wall must be sealed as part of the air control layer.

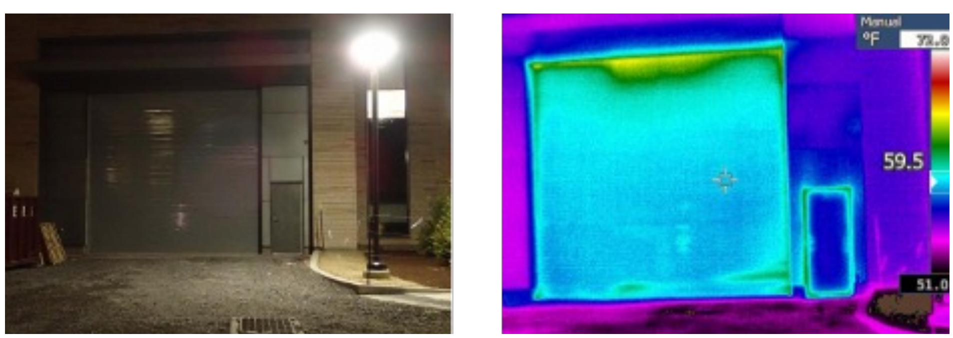

FIGURE 7. Photograph (a) and FLIR image (b) of a loading dock bay and man door displaying large amounts of air leakage.

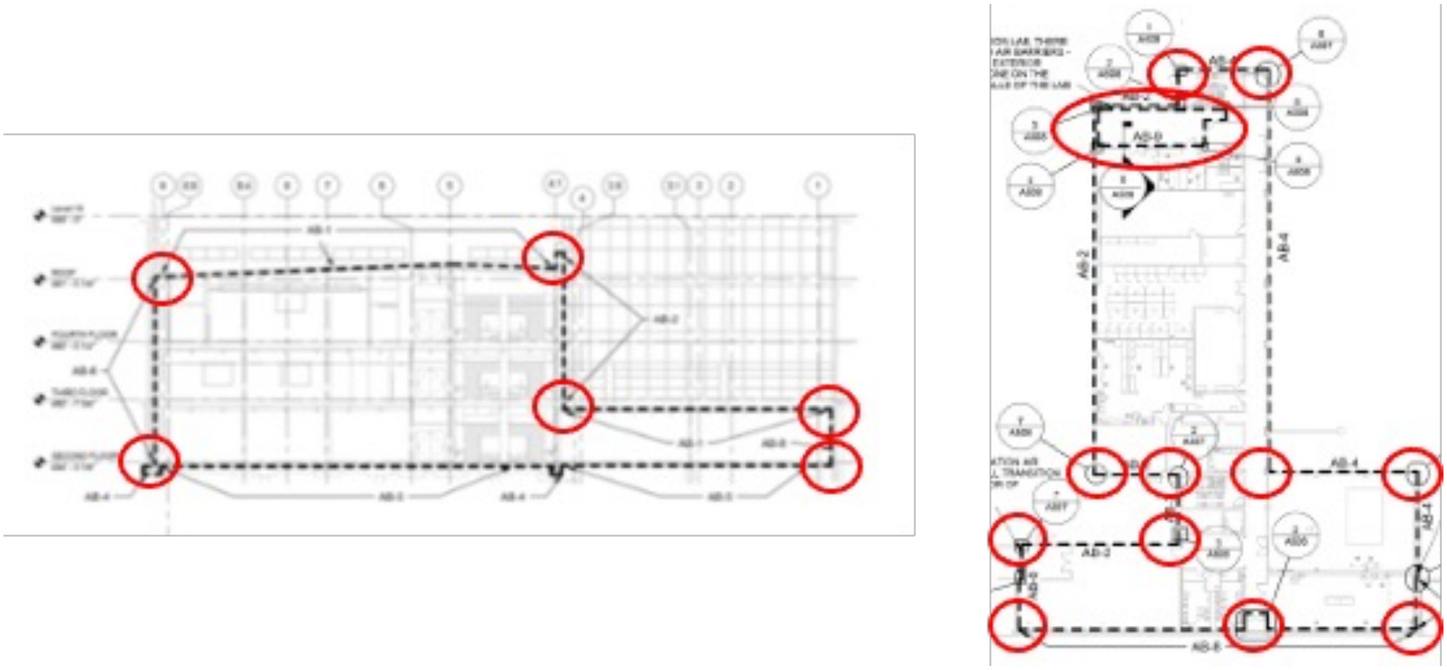

FIGURE 8. Plan and elevation using circles to call out details critical to the air tightness of the building enclosure.

material for each enclosure assembly responsible for the air control. These sheets should be both plan and section drawings. Clearly identify or note the continuous air barrier plane in all plans and the enlarged section details. Continuity is not always apparent in architectural details. If possible, isolate or exclude spaces such as loading decks, vented spaces, etc., inside the building that are frequently/continuously exposed to exterior ambient air conditions. One way to do this is shown in **figure 8**, where circles call out critical details for the performance of the building enclosure. The isolated loading area is circled, as it is clearly excluded with its own air barrier system.

Written Specifications

In addition to clear drawing sets, the written specification should include requirements for WBAT, which should reside in Division 01. This includes requirements for the testing itself and the team performing the testing. The most critical components of the specification are as follows:

- Pretest meeting and inspection
- Submittal requirements, including the qualifications for the technicians and agency performing the test
- Equipment requirements
- Testing details including preparation

Pretesting Meeting and Inspection

As with preconstruction meetings, a pretesting meeting allows for alignment of all parties before the start of testing. The meeting will ensure that all parties (including the owner, air barrier assembly contractor, and testing team) understand the boundaries of the test envelope, which equipment will be used, and the building preparation that will be required for the test to be performed properly. One key component of this meeting is determining who is responsible for disabling the HVAC systems as required and how the test area will be secured so preparation work is not compromised. Finally, there needs to be an understanding of what will happen if the test results do not pass the project requirements, including responsibilities and procedures for repairing deficiencies and retesting.

Submittal Requirements

The submittal requirements for WBAT should include the boundary sheets mentioned in the previous section along with a detailed test plan from the testing agency. The test plan should be submitted prior to the pretest meeting so that all parties are able to review it beforehand. Finally, the submittals should require proof of the test agency accreditation and that the individuals performing the test are certified in accordance with ISO 17024 to perform the required test methods.[11]

Equipment Requirements

It is the testing agency and certified technician's responsibility to clearly define which equipment will be used for the testing. This information will be included in the test plan submittals and discussed at the pretest meeting. However, the specification should include requirements for calibration of the equipment, such as how recently it was calibrated. Finally, it is recommended that specifiers call out the requirement for digital gauges instead of analog ones to ensure greater accuracy in the test measurements.

Testing Requirements

Different types of WBAT test methods are available, and the specification should be clear which type is required for the project. This will define the boundaries of the test and the test method that will be performed, such as ASTM E3158. The specification should include the requirement to perform testing both during pressurization and depressurization of the building enclosure and recording results separately. Additionally, the pass/fail criteria must also be included in the specification. These criteria may stem from the building code for the local jurisdiction or the owner project requirements.

It is helpful to define some of the preparation requirements for the testing within the specification. The test conditions for when the test can be performed will provide clarity for all parties as the test date approaches. Details such as closing and locking all exterior windows and doors, propping open internal doors, and having an explicit requirement for maintaining even pressure within the test envelope will prevent conflict.

If one is unfamiliar with all this terminology and the testing process, creating a specification from scratch can be a daunting task. There are sample specifications available to use as a starting template, including from industry associations such as ABAA.

CONCLUSION

The importance of whole-building airtightness cannot be overstated as a means to ensure energy-efficient and moisture tight buildings. The IECC and ASHRAE Standard 90.1 are both moving to more stringent requirements for buildings to achieve. However, meeting the new air barrier code requirements is achievable. The simplest way to meet the code requirements is to perform a WBAT on a project. WBAT may be a new test for many, but it does not have to be scary.

Multiple case studies from various parts of the country have shown that it is very reasonable to expect to pass testing at the airtightness levels required by the current IECC. Years of development and improvements have gone into the test methods as they moved from primarily using ASTM E779 to ASTM E3158. Trained and certified technicians have the proven techniques needed to perform tests, including the critical preparation procedures, such that buildings have a higher likelihood of passing.

However, testing cannot do it alone. All members of the construction team must pay attention to critical transition details throughout the design and construction process. This includes highlighting the critical areas in drawing sets as well as including all of the test requirements in the written specification. In the end, all these components work together to ensure a successful WBAT as one crucial part of ensuring a durable, energy-efficient building enclosure.

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The Current State of Embodied Carbon and Building Enclosures

ABSTRACT

In an effort to increase awareness and reduce the embodied carbon impacts of the building enclosure, this presentation will share research into current enclosure materials and systems, compare various enclosure systems to understand their relative carbon impacts from one to another, and highlight gaps in the critical data needed to calculate whole-building life-cycle assessments. The presentation will start by introducing embodied carbon, environmental product declarations (EPDs), and the product category rules (PCRs) that govern them and will conclude by giving a glimpse into where we are headed as an industry regarding future code and legislation requirements for low-carbon materials.

LEARNING OBJECTIVES

- Highlight the key documents used to track embodied carbon, including Environmental Product Declarations (EPDs) and Product Category Rules (PCRs), including an explanation of Scope 1, 2, & 3 emissions.
- Recall the main elements contributing to the building enclosure's embodied carbon.
- Identify steps to integrate presented research into enclosure material and systems, including hotspots for high-carbon materials, enclosure system types that are lagging in available product data, and various material and system benchmark comparisons.
- Discuss ongoing and upcoming carbon-focused code and legislation initiatives that are affecting building enclosure materials, as well as action items to improve the carbon tracking for projects.

SPEAKERS

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Nouha Javed, PE, LEED General Associate, is an engineer in the Diagnostics Group of Walter P Moore with more than seven years of experience in structural and enclosure evaluation and restoration, where she has developed work scopes, repair details, repair procedures, and technical specifications for waterproofing, restoration, and rehabilitation projects.

In addition to her engineering work, Javed actively leads the Sustainable Design task force for the Diagnostics Group at Walter P Moore. She effectively integrates the firm's SE2050 commitment with ongoing project efforts. Furthermore, she co-leads the Washington DC chapter of the Carbon Leadership Forum, showcasing her commitment to sustainability and environmental awareness.

Soar in 24
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INTRODUCTION

Buildings, bridges, roads, and other components of the built environment have historically been a significant contributor to global greenhouse gas (GHG) emissions. Though numbers may vary, it is estimated that the built environment is responsible for almost half of global emissions[1] on an annual basis. Typically, when discussing building emissions, particularly when looking at building enclosures, the focus tends to be on operational carbon and operational energy, terms used to describe the emissions created by a building when in use. However, embodied carbon from both the structural and enclosure systems plays a significant role in a building's emissions.

Every field of study comes with an industry-specific list of acronyms, shorthand terms, and seemingly endless definitions. When discussing embodied carbon, it's no different. These emissions are expressed in terms of metrics that reflect their potential effects on the environment. One such metric is global warming potential (GWP), which is typically quantified in kilograms of carbon dioxide equivalent (kg CO_2e), also known as a carbon footprint. The word "carbon" will be used in this paper as a shorthand term for carbon dioxide (CO^2) equivalent emissions when quantifying greenhouse gas emissions.

One commonly used term is life-cycle assessment (LCA), a methodology that quantifies the environmental impact of a component or system through a typical life cycle. LCAs are also commonly applied to a variety of building systems, such as structural, enclosure, mechanical, electrical and plumbing systems. When the LCAs of all components within the building are compiled, this is referred to as a whole-building life-cycle assessment (WBLCA). LCAs are critical during the design process as they allow the project team to weigh design alternatives against each other in an objective way. The tools and assumptions used to generate LCAs are constantly evolving as our understanding of embodied and operational carbon continues to mature. Fortunately, a variety of guides and software are available to designers to simplify the LCA process.

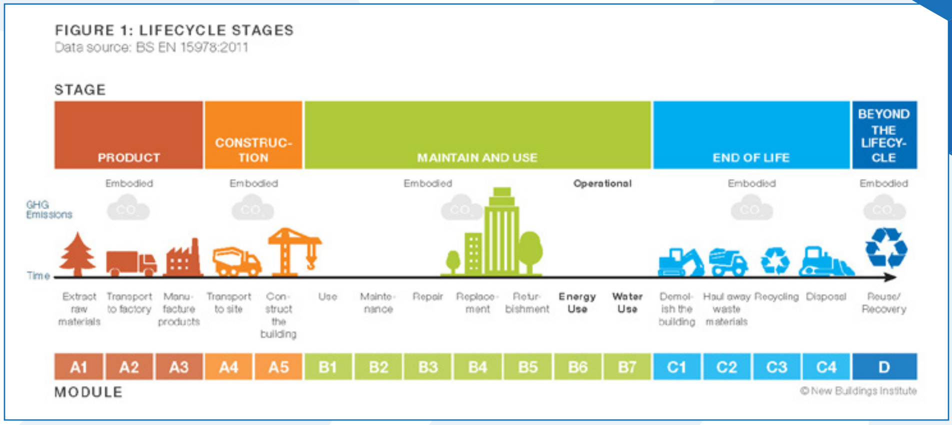

FIGURE 1. New Buildings Institute, *Lifecycle Stages*, **https://newbuildings.org/code_policy/embodied-carbon/.**

Generally, building material life cycles (**Fig. 1**) are tracked from production and construction (stage A), use phase (stage B), end-of-life (stage C), and any externalized impacts beyond the LCA's scope (stage D).[2] Beyond stage D, biogenic carbon, or the carbon that is produced by living organisms and not by burning fossil fuels, is tracked separately. The process of quantifying biogenic carbon is a complex calculation that is currently being evaluated; however, current guidance advises that biogenic carbon either be ignored or the potential benefits of carbon sequestration be included.[3]

As an example, stage A of a roofing membrane LCA would start at the extraction of raw materials and include material refinement and production, transportation to site, and construction installation. The impact of the membrane while in use might be accounted for in stage B, while the demolition, transportation to landfill, and ultimate disposal may be addressed in stage C. If, however, the membrane was recovered and

1 (Architecture 2030 n.d.)

2 (King and Magwood, Build Beyond Zero: New Ideas for Carbon-Smart Architecture 2022)

3 (The Carbon Leadership Forum 2019)

EPD TYPE	USE	SCOPE	DEVELOPED BY
Industry-wide	Industry-wide EPDs provide a benchmark for setting targets for policy or manufacturers seeking to reduce the embodied carbon of their product.	• Impacts for a product type (e.g., ready-mix concrete) • Includes data from multiple manufacturers within a geographic region.	Trade associations and based on data from member manufacturers.
Product-specific	Product-specific EPDs are used to compare functionally equivalent products or as a business benchmark.	• Impacts for a specific product • Includes data from a single manufacturer • Can encompass multiple facilities	Single manufacturers
Facility-specific	Facility-specific EPDs are used to compare functionally equivalent products at the highest level of resolution.	• Impacts for a specific product • Includes data from a single manufacturer • Captures the unique grid mix and fuel sources used at a single manufacturing facility	Single manufacturers

Source: RMI

FIGURE 2. Audrey Rempher, *Improving the Data and Disclosure of the Environmental Impact of Building Materials*, October 4, 2023, Rocky Mountain Institute, https://rmi.org/improving-the-data-and-disclosure-of-the-environmental-impact-of-building-materials/.

recycled, those impacts would be captured in stage D.

LCAs are most useful when material alternatives can be compared on a consistent, apples-to-apples basis. Environmental product declarations (EPDs) are commonly referred to as the nutritional labels for materials as an agreed-upon tool and methodology that is consistently used across material types. Product EPDs include information relevant to building system LCAs, including additional manufacturer and product data. Most standards require the use of a Type III EPD since they have been independently verified to be compliant with ISO 14025, have an unexpired validity date and are product specific. The most accurate EPD types are facility or plant specific (**Fig. 2**), since they are supply-chain specific rather than industry-wide and report a data uncertainty range.[4] Building Transparency's Embodied Carbon in Construction Calculator (EC3) is an open-access tool that allows a variety of EPDs to be evaluated.

When comparing two EPDs, consider if both documents are based on the same methodologies and if the materials are functionally equivalent. Both EPDs must refer to the same product category rules (PCRs), which define the requirements for developing EPDs for a particular material type. If we recycle the roofing example, the PCR for roof coatings is developed by NSFInternational, the program operator, who manages the development and publication of the document. The PCR sets a standard for roof coating LCAs, including guidance on scope requirements, system boundaries, calculation rules, and parameters.[5] PCRs may be published by industry groups or independent agencies; however, PCRs are reviewed by multiple stakeholders during the development process and are updated every five years to reflect any change in the product category.

With the use of LCAs, EPDs, and PCRs, the ultimate goal of any embodied carbon study is to quantify critical GWP impacts of a particular material component for a given project. GWP impacts per material unit are then multiplied by the quantity of a component used in a project to understand the total impact of that component across the scope of the LCA.

REDUCING EMBODIED CARBON: A PRIMER

Any effort to reduce embodied carbon in a building enclosure system should start with carbon quantification, establishing a baseline, and a target reduction relative to the baseline. Establishing a budget for the carbon footprint, or carbon dioxide (CO^2) equivalent emissions, for a project or particular project scope may also be used to help orient the project team towards a common end goal. Quantifying carbon is typically done through an LCA, which considers both the carbon footprint per material unit and quantity of a material. Strategies may be implemented to reduce the carbon footprint of a particular material in addition to reducing the quantity of the material itself in an effort to meet the overall carbon-reduction target of the project or scope.

Material reuse is one of the most effective embodied carbon strategies in a designer's toolkit, as reuse strategies can be used to both significantly reduce a material's carbon footprint and quantity needed. The carbon footprint required to renovate or upgrade a building system or component for current use is typically far lower than the impact of a newly manufactured one. For example, a product with a high percentage of recycled materials may have a significantly lower carbon footprint than one using primarily raw materials. Similarly, reusing existing building components, such as window systems in a facade upgrade, may significantly reduce the need for new window components.

Material reuse also addresses a critical consideration in reducing embodied carbon—the "time value of carbon", which is a phrase commonly attributed to Larry Strain,

4 (The Carbon Leadership Forum 2020)

5 (NSF Sustainability 2021)

FAIA. The concept can be summarized as "When you save matters; what you build matters; what you don't build matters more."[6] Due to the immediate nature of the climate crisis, all carbon emissions created today have a greater impact on the climate than any emissions created in the future, particularly when considering emissions added into our atmosphere after 2050. Another way of visualizing this concept is thinking of the climate impact as the magnitude of emissions multiplied by the time the greenhouse gasses will be present in our atmosphere—the earlier they are emitted, the greater impact they have. An important note to consider is that the time value of carbon affects all types of carbon—not just embodied carbon. For example, two window assemblies may be compared—one with high embodied carbon but with lower estimated operational carbon over its service life. Or as another example, a small reduction in energy costs by adding additional carbon-intensive, high-density insulation should be weighed against the current up-front carbon cost of that product.

Concrete and steel are the first materials that typically come to mind when it comes to building elements with high embodied carbon—and with good reason. The production of these two materials accounts for a large percentage of global emissions attributed to the built environment.[7] This is in part due to the vast quantities of concrete and steel produced and installed on a yearly basis around the world. Both materials also use large amounts of energy in production. Producing limestone based portland cement is an incredibly energy-intensive process and also produces carbon dioxide as a by-product. The calcination of limestone to create lime and carbon dioxide is an energy-intensive process and necessary to produce clinker; a core ingredient of portland cement. Similarly, the current production methods of steel and other commonly used metals in the built environment are energy-intensive and rely on the use of fossil fuels for much of the production process7. However, the global concrete and steel manufacturing industries are responding to the climate crisis and are changing. Cement alternatives, also known as supplementary cementitious materials (SCMs), are widely recognized and utilized in mix designs. Some major steel producers around the world are pivoting away from the use of fossil fuels and towards using alternative energy sources, such as green hydrogen, in the near future. Manufacturing innovations are being made in these industries on the path to reducing their embodied carbon impacts.

A critical component of the conversations around reducing embodied carbon in the concrete and metals industries is recycling. Both materials are well suited to reuse, especially steel, which is currently recycled around the world. However, not as well suited to reuse or recycling are most plastics and polymers, which would include many enclosure products such as insulation, sheathings, and waterproofing/roofing membranes. The vast majority of these polymer-based products are petrochemical products with significant GWP impacts across their life cycles,[8] particularly during the extraction of the fossil fuels needed to produce petrochemicals. Fortunately, many of these products are being redeveloped to reduce their carbon footprints, such as the development of bio-based plastics that are able to compost at the end of their service lives. Additionally, reuse and recycle initiatives are being implemented in an effort to reduce the quantities of waste plastic during the construction process.

The calculation and analysis of the embodied carbon of many enclosure systems is more complex than a concrete footing, for example, as many enclosure elements are assemblies, including multiple materials from different manufacturers. A curtainwall assembly will likely contain glass, aluminum, sealants, and polymers, all with different carbon footprints and impacts. With these complexities in mind, any effort to reduce the embodied carbon of enclosure systems should include a careful review of environmental product declarations in the product selection phase of design. A review is a critical component of recognizing materials with high embodied carbon and developing a strategy to substitute them, leading to effective carbon reduction strategies.

BUILDING ENCLOSURE MATERIALS

Typical Scope of Components

The scope of components to be included in the LCA of a building enclosure is not currently well standardized. If you dig into two common standards currently being used by many design teams, they state the following regarding the building enclosure scope:

- Per LEED v4 guidance: "The LCA must cover the complete building envelope … including … [the] structural wall assembly (from cladding to interior finishes)."[9]
- Per ILFI Zero Carbon Certification guidelines: "Calculations should list the estimated carbon impact of each of the final construction materials and processes associated with the foundation, structure, enclosure, and interior of the project."[10]

6 (King, The New Carbon Architecture: Building to Cool The Climate 2017)

7 (Fennell et al. 2022)

8 (King and Magwood, Build Beyond Zero: New Ideas for Carbon-Smart Architecture 2022)

9 USGBC Reference Guide for Building Design and Construction - v4, 2013.

10 (International Living Future Institute 2020, #)

These descriptions are not explicit in terms of inclusions and exclusions, and leave room for interpretation by those calculating the LCAs. This leads to challenges in comparing the results of WBLCAs from one to another due to misaligned scopes. Despite this lack of clarity, the EN 15978 standards give recommendations for the minimum extents of components to be included as follows:

- Components greater than 1% of the total system mass must be included.
- The sum of neglected components is not greater than 5% of the total system carbon equivalent or mass.
- Furthermore, the EN 15978 standards recommend designers should take care to ensure that components with a high carbon intensity, albeit low mass, are included where the inclusion significantly impacts the results of the assessment.

In general, experienced LCA practitioners have a general understanding of the typical enclosure materials to be included for a building enclosure LCA. These materials typically include:

Typical materials INCLUDED in building enclosure LCA	
Glazing systems	Sheathing (internal & external)
Aluminum sheet and extrusions	Masonry systems
Studs (metal and/or wood)	Air- & weather-resistive barriers
Insulation products	Roofing membranes
Cladding finishes, such as brick, terra-cotta, sheet metal, precast	Below-grade waterproofing membranes

On the other hand, there are also materials which are typically excluded from building enclosure LCA calculations. These could be excluded for a number of reasons, such as difficulty quantifying the amount of material, lack of EPD data for the systems, or the general understanding of their low impact to the total system's embodied carbon emissions. Materials typically excluded are:

Typical materials EXCLUDED in building enclosure LCA	
Fasteners	Flashing systems
Sealant and backer rod	Paints or coatings
Attachment brackets	Miscellaneous support metals
Accessories such as root barriers, drainage mats	Glues & adhesives

Data Availability

One of the large focuses within the industry has been the encouragement of transparency by material suppliers. The availability and accuracy of data is critical in order to calculate a WBLCA. As will be discussed later in this paper, various jurisdictions have enacted policies which have begun to require EPDs for certain materials, such as glazing and insulation. As design teams have gained more experience in calculating the embodied carbon of their designs, designers are now specifically searching out products that not only have product-specific EPDs but are also only using products on their projects that have EPDs available.

One of the main challenges with LCA calculations of building enclosures is the availability of products with LCA data, typically provided via EPDs. Last spring, our firm conducted internal research to verify if the products that we typically use have EPDs available. The results of that research were not promising. We found that certain materials such as insulation and roofing products have EPDs from a variety of manufacturers; however, many systems lack EPDs altogether. And within manufacturers' product lines, you will find that some products have EPDs while others do not. The below table is a non-exhaustive survey of building enclosure products to understand EPD availability from various systems.

# of Products with EPDs	Material
100+	» Carpet (interior) » Ceiling tile (interior) » Insulation
50–100	» Roofing membranes
5–10	» Processed glass products (IGUs, coated glass) » Aluminum extrusions » Below-grade waterproofing membranes » Air- & weather-resistive barriers
2 or fewer	» Joint sealant » Traffic coatings » Water repellents » Elastomeric coating

While it is somewhat discouraging to find whole sectors of the market where little to no products with EPDs are available, this highlights the need for designers to continue to encourage manufacturers to provide EPDs for their product. Transparency is critical to understand the relative environmental significance of these materials—without the data, we don't know what impacts are not being accounted for. Further, as the industry continues to request this transparency, manufacturers and suppliers will have no choice but to provide the transparency that is being requested, or risk not being specified on projects.

FUTURE TRENDS

"Buy Clean" Policies

The current momentum with respect to embodied carbon within the industry has begun to manifest itself in building codes and legislation. It seems every month another jurisdiction is announcing legislation

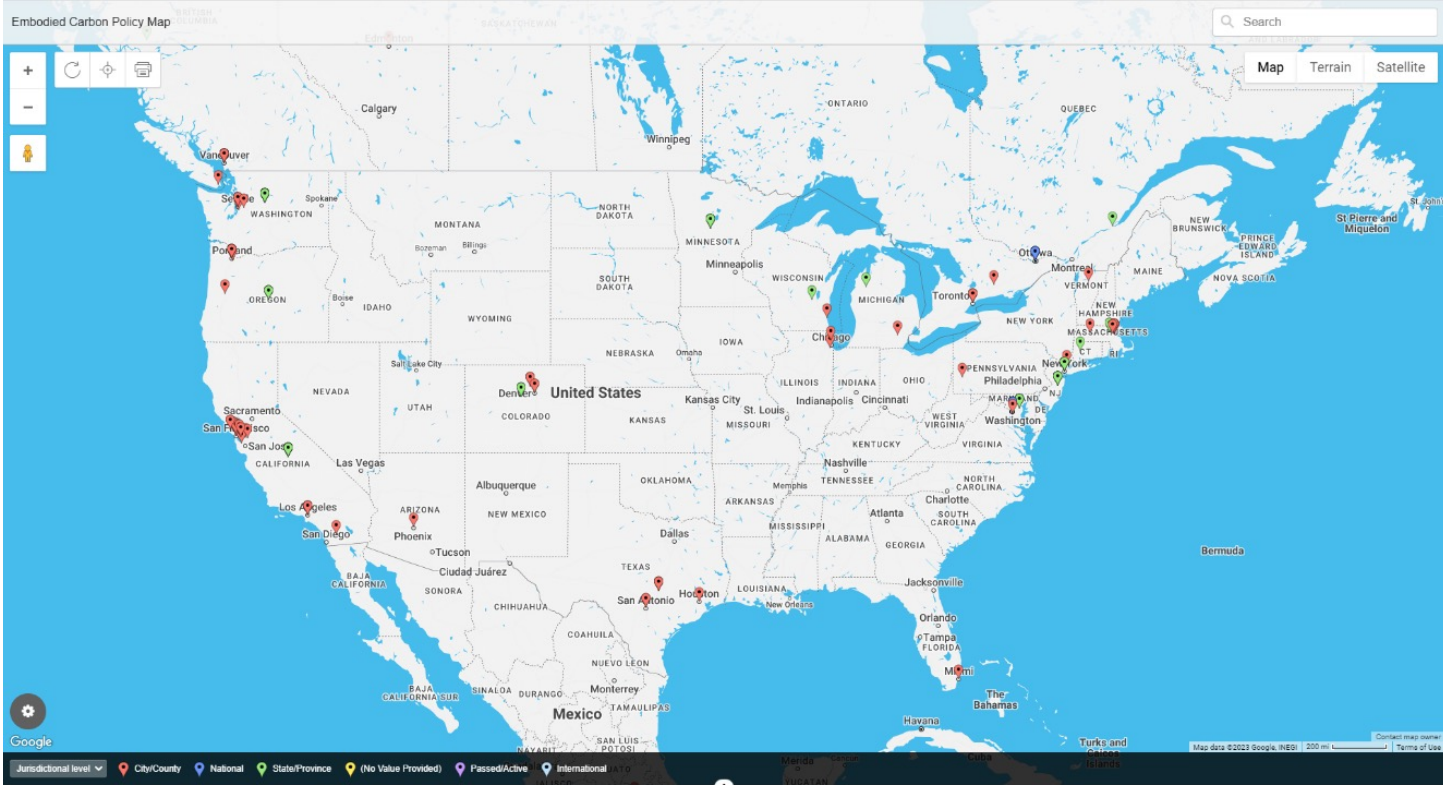

FIGURE 3. Carbon Leadership Forum. n.d. "Embodied Carbon Policy Map." BatchGeo. Accessed December 15, 2023. https://batchgeo.com/map/3cbe8e5a906a86a2978645ee09d8b958.

for embodied carbon limits. For the most part, this is being accomplished through "Buy Clean" policies, which are procurement policies in which limits are placed on the GWP of various materials. Numerous jurisdictions throughout the US have begun enacting Buy Clean policies, with perhaps the most well-known being the Buy Clean California Act (BCCA) legislation.

The BCCA was passed into law in 2017, with the mandatory requirements taking effect in July of 2022. While these requirements are only applicable to state-government new construction and major renovation projects of a certain size, BCCA has started by implementing GWP limits for cradle-to-gate emissions (A1 to A3 stages), applicable to structural steel (hot-rolled sections, hollow structural sections, and plate), concrete reinforcing steel, flat glass, and mineral wool board insulation.[11] To demonstrate compliance with the BCCA requirements, suppliers must provide ***facility-specific*** EPDs, typically considered the most accurate EPD data since the data is based upon impacts from products at a single facility location.

Since BCCA was announced, numerous other states and local governments have announced similar Buy Clean initiatives, some successfully enacted while others are still awaiting approval in their legislative processes. These include states such as Oregon, Washington State, Colorado, Minnesota, New Jersey, Maryland, and others. An excellent map of existing and proposed policies can be found on the Carbon Leadership Forum website here: https://carbonleadershipforum.org/clf-policy-toolkit/#map. (Refer to **Fig. 3**[12])

At the Federal level, the government has taken numerous steps toward the use of low–embodied carbon materials in the federal construction sector. This started with the December 2021 announcement by President Biden to form a Buy Clean Task Force within his administration. As a direct result of this task force, the 2022 Inflation Reduction Act included $4.5 billion to the EPA, GSA, and DOT to identify and procure low-carbon construction materials. For example, the GSA has announced their own version of Buy Clean standards in which GWP limits have been published for concrete, asphalt, flat glass, and steel, with requirements for insulation and aluminum being considered for future adoption. Given their purchasing power, the federal government is uniquely positioned to accelerate the growth of the low-carbon product market by implementing these federal Buy Clean programs.

To date, the GWP limits set in these various policies have mostly been based on industry average EPD data of the respective materials, aimed

11 ("Buy Clean California Act (BCCA)" 2023)

12 (Carbon Leadership Forum, n.d.)

at getting the highest emission manufacturers to improve their manufacturing processes to meet the thresholds. It's anticipated that the GWP limits will be decreased over time, with the aim towards achieving zero carbon goals on the horizon. By requiring (or encouraging) product-specific and facility-specific third-party EPDs for compliance, the policies are pushing manufacturers who have not yet created EPDs to get them published; otherwise, they are at risk of being unable to serve as suppliers for many projects. And as the saying goes, "*You can't improve what you don't measure*"—by requiring manufacturers to understand their own emissions through the publishing of EPDs, these policies of requiring granular emission data are inherently encouraging reductions in manufacturing emissions.

Embodied Carbon in the Building Codes

There are similar efforts taking place to include embodied carbon requirements within the building codes. For example, draft code language has recently been submitted within the ICC code adoption process (ICC Committee Action Hearings) to incorporate GWP limits into the International Building Code. Unfortunately, this attempt did not pass at the March 2022 ICC Committee Action Hearings, but this momentum continues.

A recent successful example took place in California. In August of 2023, California adopted requirements into the CALGreen code, effective in July 2024. The requirements apply to nonresidential projects over 100,000 ft^2 and school buildings over 50,000 ft^2, and compliance can be achieved by one of three paths, as follows:

- **Building Reuse:** Reuse at least 45% of an existing structure and exterior. When reuse is combined with new construction, the total addition area using this pathway is limited to double the area of the existing structure.
- **Performance:** Complete a WBLCA demonstrating 10% lower embodied carbon emission than a baseline project.
- **Prescriptive:** Document EPDs for listed materials (steel, glass, mineral wool, concrete) that are on average lower than a specified threshold of GWP.[13]

Carbon Standards

One of the largest areas for future development is the creation of embodied carbon standards. As it currently stands, there is not a well-established, uniform scope or requirements to conduct a WBLCA. The scope for which components must be included, the length of time for "whole life" carbon calculations, the minimum baseline when calculating performance-based improvements, or how maintenance and use emissions are calculated are not well defined and vary across WBLCA calculations. Due to these differences, comparing WBLCAs from one to another can be confusing. There is gaining traction supporting the use of a carbon use intensity (CUI) metric, expressed as kg CO_2e per square foot of building area, but practitioners ought to understand what building elements have been included or excluded from such numbers before comparing across projects. For example, what building enclosure systems and/or MEP systems are included in such a calculation. Further, differences in building usage types, climate regions, or building risk category also shall be considered when comparing a CUI metric.

Perhaps the most notable effort to create a standard to assess carbon emissions across the entire building life cycle is coming from ASHRAE. Named "ASHRAE/ICC Standard 240P—Evaluating Greenhouse Gas (GHG) and Carbon Emissions in Building Design, Construction and Operation," this standard is working to establish how to calculate the emissions of a building over the entire life cycle. The intent is to provide consistent procedures and data to be referenced by policies, codes, and other standards that address new and existing building performance.[14]

Future Trends to Impact Building Enclosure Embodied Carbon

When it comes to the building enclosure, there are several areas on the horizon for the embodied carbon of building enclosures. There has been criticism of recent GWP limits established by the Buy Clean California Act (and others) for implementing limits for glass but basing those limits on the flat-glass PCR. The flat-glass PCR only includes raw flat glass which has yet to be processed, including heat treatment, coatings, lamination, or fabrication into insulated glazing units. In today's construction, it is rare that projects utilize flat glass on its own. As a result, projects can avoid having to comply with the glass GWP limits within the policies.

We also anticipate that more materials will begin to fall under the GWP limits within various Buy Clean policies, notably aluminum and insulation materials beyond just mineral wool. Aluminum is one of the highest-emitting materials[15] used within the building enclosure, so it is natural for this material to begin to fall under GWP limits. And while establishing GWP limits for mineral wool is a great start, mineral wool falls within the lower range of emissions compared to some other insulation products.[16] Emissions limits for foam insulation materials, such as extruded polystyrene insulation (XPS), expanded polystyrene insulation (EPS), and spray foams, would be a logical next step to regulate some of the highest-emitting insulation products.

And lastly, as discussed previously,

13 (Malinowski 2023, #)

14 (Washington 2022)

15 (new buildings institute 2023)

16 (Carbon Leadership Forum, n.d.)

further transparency within building enclosure materials is a must. Manufacturers of glass, insulation, and aluminum have slowly come on board to produce EPDs for their products (and more EPDs are produced each month), but further transparency is required in many other parts of building enclosures.

CONCLUSION

The conversation around reducing embodied carbon in building enclosures comes at a critical time around the globe. This paper has aimed to educate building enclosure specialists regarding the terminology and importance of embodied carbon documentation within our industry, as well as shed light on the current state of enclosure materials and systems. Underscoring the need for transparency from the manufacturing industry, EPD data will inform decision-making in selecting building enclosure solutions that align with sustainability goals.

A key takeaway from this exploration is the crucial role of life-cycle assessments and EPDs in assessing and reducing embodied carbon. These tools provide valuable data into the environmental impacts of building materials. Addressing gaps in material data will be vital for further advancing our understanding and management of embodied carbon.

Looking ahead, the building enclosure industry is set to be impacted by recent and forthcoming codes, legislation, and standards specific to building enclosure embodied carbon. We can anticipate more detailed requirements for low-carbon materials, including increasingly more materials to be included within established carbon requirements. This transformation reflects a collective commitment to reducing our carbon footprint and fostering a more sustainable built environment. Architects, engineers, and building enclosure specialists shall be prepared for the new requirements by ensuring they understand the array of carbon and LCA terminology.

While this paper has primarily focused on embodied carbon, we must not forget that the enclosure sits at the intersection of both embodied and operational carbon impacts. This adds a challenging, yet important, complexity to the design of the enclosure. This is an exciting time to be involved with building enclosures, and the technical knowledge and understanding of carbon is critical to reducing our carbon footprint and fostering a more sustainable built environment. By leveraging the knowledge shared in this paper and embracing the forthcoming changes in codes and legislation, we hope to collectively work towards a future where low-carbon materials are the norm, creating healthier, more environmentally responsible, and resilient built environments for generations to come.

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Avoiding Pitfalls with Large Skylight Design and Maintenance

ABSTRACT

Modern skylights are complex building envelope elements that function both as roofing and fenestration systems. They must be designed for aesthetics, energy efficiency, structural loads, and water penetration resistance. However, skylights do not last forever and their maintenance can be complicated and expensive if not planned right.

Common skylight designs include simple drained frames, modern drained systems, and face sealed structural glass. Although each of these systems has varying price points and performance levels, designers need to consider the durability and maintenance implications of less costly systems, which often rely on inaccessible hidden seals.

Typical skylight maintenance includes cleaning, sealant replacement, and intermittent localized glass replacement. Simple skylight cleaning can often be undertaken without the need to access the skylight system, whereas more intensive maintenance such as sealant replacement often requires access across the skylight systems glazing, necessitating a safe working surface for the tradespersons. Skylight maintenance can be further complicated by skylight designs with hidden seals, which oftentimes necessitate glass replacement to properly fix leaks. Glass replacement typically requires both a crane to lift the glass into place, and safe working platform for the contractor.

Skylight access methods typically include one of the following: A permanent engineered moveable platform (such as a gantry system), temporary working platforms (scaffolding), or glass design for maintenance loads. Both temporary working platforms and permanent engineered platforms are very expensive to install on a per-use basis and can make skylight maintenance prohibitively expensive for some owners.

In order to reduce these maintenance access costs, it is becoming more common for modern skylights to be designed to support maintenance loads directly. Although the design of glass as a work platform requires complex structural glass analysis, the cost premium can be more than offset by maintenance savings. Recent improvements in materials and glass design have allowed the same approach to be used for retrofit projects with older skylights, allowing owners of existing buildings to reduce their maintenance costs. One additional benefit of this approach is that it also reduces the risk to unknowledgeable trades that may be working near skylights — whether it be sitting on, falling or tripping onto the skylight, there is a reduced risk to other workers.

In summary, there are many solutions available for maintenance and access of large skylight systems, but their costs and limitations must be considered by skylight designers. Although the industry has developed retrofit and temporary solutions to undertake skylight maintenance, the most cost-effective approach is to consider skylight maintenance from the start.

LEARNING OBJECTIVES

- » Discuss the various types of skylight design strategies, including their benefits and limitations.
- » Identify different types of skylight access strategies, used for maintenance, including seals and leaks.
- » Review the different skylight access strategies for glass replacement.
- » Review case studies for the concepts “simple framed drained systems,” “modern framed drained systems,” and “face-sealed structural glass systems” to provide context and understanding of the different skylight designs.

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Soar in 24
IIBEC International Convention & Trade Show

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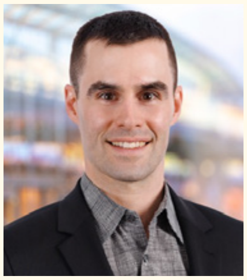

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DISCLAIMER

This paper includes commentary on skylight design and access that may not be applicable to all jurisdictions or situations, and purely for educational purposes. It is imperative that any persons working on or around skylights obtain documentation on the relevant hazards and requirements from local authorities having jurisdiction and engineers.

INTRODUCTION

Modern skylights are complex building envelope elements that allow natural light to enter buildings, while providing environmental separation for water, air, and heat. Beyond these basic functions, skylights offer the potential for architects and designers to blend interior and exterior spaces, transform atriums, and bring natural light into the core of large buildings. The impact large skylights have on the way a building feels and functions can be significant. However, the design of these complex systems can have costly and disruptive effects to building operations teams if they are not designed with maintenance in mind.

Skylights consist of three basic components, including the structure or frame, the glazing material, and the sealants. Skylight frames are designed to support and retain the glass, and in drained systems they are also designed to collect rainwater and drain it to the exterior. In cold climates the glazing materials almost always consist of sealed insulated glazing units, which eventually fail and require replacement. Skylight sealants also fail over time, and depending on the skylight design, they can sometimes require diligent maintenance to remain watertight. In order for skylights to function properly, they require maintenance, and good skylight design considers not only their aesthetics, but also their durability and maintenance requirements.

LARGE SKYLIGHT DESIGN

Large skylight systems can typically follow one of a few common industry principles to remain functional and exclude water. These common skylight types include:

1- Face-sealed skylights, which have one layer of sealant to prevent water entry. These systems are often designed for easy access to maintain exterior seals,

2- Simple framed drained rainscreen skylights, which follow a dual barrier approach, but often rely on sealants at hidden joints without raised/shingled/continuous drainage channels. These systems utilize framing often found in commercial curtain wall systems, with little if any design changes to accommodate the increased rain loads that skylights experience.

3- Modern drained skylights with raised/shingled/continuous drainage channels, which follow an improved dual barrier approach and incorporate frame detailing to reduce reliance on sealants. These systems typically feature dual-barrier frame connections that are shingled and raised where one drainage channel connects to another.

Face-sealed skylight systems reduce complexity by relying on one seal at the outer face of the glass-to-glass surface. These joints do not offer redundancy, but they can be easier to diagnose and repair when

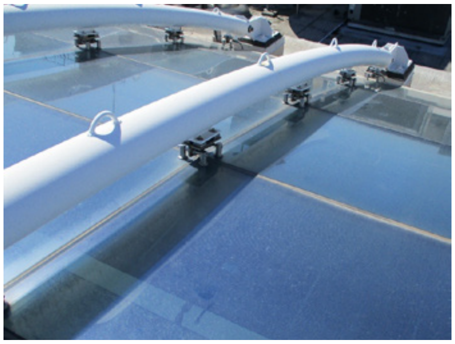

FIGURE 1. Face-sealed skylight.

water leaks occur. Because there is only one seal, the leak location can be traced at the interior, and the area requiring repair can be quickly diagnosed. These systems are often designed to support maintenance personnel loads, to permit sealant repairs to be readily undertaken.

Simple framed drained skylight systems utilize extrusions that have not been significantly modified or adapted from vertical glazing applications for use as skylights. The reason for their use is often related to manufacturing cost, as one simple extrusion profile can be used for rafters (verticals) and purlins (horizontals), but they do not include raised and overlapped drainage channels. The joints of these systems rely on difficult-to-access sealant, which requires maintenance to remain watertight and reduce leakage over time. Despite these limitations, simple drained skylights are not uncommon due to their low cost.

FIGURE 2. Simple framed skylight with curtain wall framing.

Modern drained skylight systems can be designed to include raised and overlapped drainage channels, where each layer shingles over the next, and is raised out of the drainage pathway below, providing a pathway for water to drain in the system, with minimal reliance on sealants. These framing systems are more expensive than adapted curtain wall frames, as different extrusions are used for rafters, purlins, and others, but can significantly improve long-term performance and reduce the frequency of leaks. In certain design situations, variations of these skylights have been used in bent profiles to eliminate joints in rafters altogether, such as the bent-rafter skylight design.

Detailing of skylight glass retention can also impact the risk of water entry. Low profile caps are common at skylight purlins to reduce the volume of water that can be trapped above each mullion as they impede drainage over the exterior skylight surface. Modern two-sided structural silicone skylight systems take this approach one step further, by eliminating the caps altogether. By eliminating the caps, structural silicone systems allow water to easily drain from one glazing unit to the next, without presenting a risk or water retention or entry at leading-edge gasket seals.

SKYLIGHT DESIGN FOR MAINTENANCE

Regardless of the skylight design implemented, all skylights will require some form of intermittent maintenance such as cleaning, sealant repairs, and sometimes localized glass replacement. Undertaking these procedures is often complicated by the fact that skylights are often in elevated, hard-to-reach places, and may present fall hazards to maintenance personnel. For that reason, the first step in designing skylights for maintenance should be to maximize the durability of the skylight system, to reduce its maintenance needs.

Minor cleaning and sealant repairs are often undertaken by the use of poles, with no access to the skylight required. High-slope skylights can

FIGURE 3. Skylight with overlapped raised drainage channels.

often be cleaned via bosun chairs or boom lifts. Use of bosun chairs or platforms that transfer load to skylights should always be reviewed by a qualified engineer to confirm that the skylight surface is designed to support anticipated loading. Regardless of the cleaning method, all personnel accessing the areas around skylights should be made aware of whether the skylight presents a fall hazard or can be used as a working platform.

Large skylight sealant replacement and leak repairs often require access to portions of skylight systems glazing, which can be difficult to reach. During this work tradespersons need to reach portions of the framing that cannot easily be accomplished from adjacent roof areas, and often require the use of an engineered scaffold, crane, or boom lift. The difficulty in working and accessing sealants for replacement are a good reason for designers to ensure that reliance on hidden sealants is

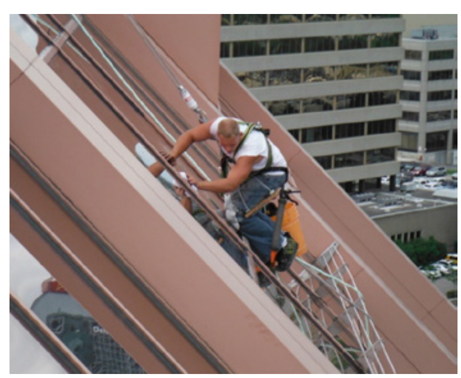

FIGURE 4. Leak repairs from bosun chair.

minimized. Replacement of hidden sealants frequently requires removal of glass, as the joint sealants requiring repair are at the back of the skylight framing sections.

Glass replacement typically requires both a crane to lift the glass, and a safe working platform for the contractor. Often the systems designed for personnel support are inadequate to support skylight glass on their own. In order to reduce the frequency of glass replacement designers should consider the durability of the components in use by considering the following:

1- Minimize water potential for reaching and sitting against edge seals or laminate interlayers. When detailing framing, ensure that there is adequate clearance for water to drain around the glass, drainage tracks are not filled with sealant, and glass setting- blocks do not restrict drainage.

2- Utilize durable edge-seal construction for insulated glass units. Skylight glazing unit edge seals undergo greater heat and loading stress than window glazing units due to their orientation and should be sufficient for their intended use case.

3- When specifying tempered glass ensure units are heat-soak tested. Specify materials and use manufacturers with a proven history of quality control and consider undertaking plant visits to confirm manufacturers are following fabrication standards.

SKYLIGHT ACCESS METHODS

Skylight access methods will depend on the work being completed, the skylight design, and local health and safety requirements of authorities having jurisdiction. When access to a skylight system is required, the method of access with depend on the skylight configuration, capacity, and type of work required. Common access methods will include one of the following: A permanent engineered moveable platform (such as a gantry system), temporary working platforms (such as scaffolding), or glass design for maintenance loads. In some situations, cranes can also be used for skylight access or to support skylight materials.

Gantry systems are engineered moving scaffolding systems, which can be used to allow regular access for skylight cleaning, maintenance, or inspections. These systems are typically designed by specialist structural engineers and should be incorporated from the outset of the skylight design. The high initial cost of gantry systems is often justified based on the high cost of repeated temporary scaffolding, or in situations where structural support conditions are too complex for temporary scaffolding to be installed. These systems are typically not sufficient or designed to support loads of glass replacement, and separate scaffolding or craning is often required in those situations.

Temporary scaffolding work platforms are expensive if used on a repetitive basis and although they can often be designed to suit the specific repair, they are time consuming, and have limitations in their configuration. Scaffolding systems can be designed to support glass and personnel loads and may be designed so the use of a separate crane is not required during glass replacement. As a result, temporary scaffolding is a very common method of access used for glass replacement work.

The cost of installing temporary scaffolding work platforms or a permanent moveable gantry system can be a considerable expense when considered on a per-use basis, which we have observed exceed $40,000 CAD for a single glazing unit. In order to reduce access costs, it is becoming more common for modern skylight glass to be designed to support maintenance loads directly. Although the design of glass as a work platform requires complex structural glass analysis, the cost premium can be more than offset by maintenance savings. By designing glass for maintenance loads, the expense of separate access systems or temporary scaffolding access can sometimes be eliminated, saving money and reducing the financial burden of skylight maintenance.

New glass designed as a working platform is typically designed to support a single worker per glass unit, and not the load of replacement glass, which is typically supported by a crane. One additional benefit of this approach is that it also reduces the risk to unknowledgeable trades that may be working near skylights–whether it be sitting on, falling, or tripping onto the skylight, there is a reduced risk to other workers.

Glass designed for maintenance loads can vary in its design applications, but it is commonly used in face sealed structural glass systems where regular access is anticipated. It has been our experience that many older skylight designs have the potential to be retrofitted to accommodate personnel loads, by analyzing and upgrading glazing components with modern high performance laminates that are compatible with fully tempered glass. In northern climates where snow loads are significant the base skylight structures are often adequate to support personnel loads, and it is often the glass that is the limiting factor in supporting maintenance loads. Structural glass analysis and design can confirm whether this is a practical solution, and the limitations of this approach should be confirmed with a qualified engineer.

CONCLUSION

In summary, there are many solutions available for the durable design, maintenance, and access of large skylight systems. Commercially available skylight systems vary significantly in their performance, cost, and longevity, and it is important for the correct skylight system to be chosen for each application. Although the industry has developed retrofit and temporary solutions to undertake skylight maintenance, the most cost-effective approach is to consider skylight durability and maintenance from the start.

Trust the Process: The Nuances of BECx

ABSTRACT

While commissioning of building systems has existed for many years, building enclosure commissioning (BECx) is relatively new to the design and construction industries. This presentation offers an overview of the BECx practice, its benefits, and the process as defined by industry standards. BECx designations, such as the CBECxP, will be discussed as they relate to providing this service as a distinguished and educated professional on the topic. Common misconceptions of BECx are discussed to help learners understand the nuances related to providing this service. Additionally, four case studies are presented to highlight the challenges, successes, and pitfalls of delivering modern BECx projects. The information presented will give BECx providers tools to help owners and clients trust the BECx process.

LEARNING OBJECTIVES

- Review the different phases of the building enclosure commissioning process.
- Identify the various codes and standards bodies that have incorporated BECx.
- Recognize 10 common misconceptions of BECx and list best practices for successful building enclosure commissioning.
- Discuss real-project case study examples on how building enclosure commissioning can be successful or improved.

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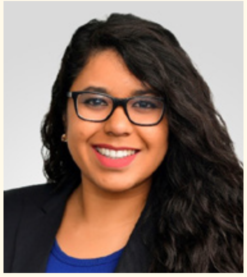

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Building enclosure commissioning (BECx) is a quality-focused process that provides the most value for owners of modern buildings with complex systems. BECx providers require technical proficiency with building science, enclosure system products, and detailing. Additionally, and arguably more importantly, they require nuanced skills to encourage positive and effective communication among members of a project team. A key component of getting owners, architects, and general contractors to "trust the process" is educating clients and project participants about BECx before and during the project.

INTRODUCTION TO BUILDING ENCLOSURE COMMISSIONING

BECx is a process that incorporates the core principles of building science throughout all phases of the building, from predesign through design and construction, and into occupancy. It involves evaluating the four control layers that are essential to building enclosure assemblies, across all six sides of a typical building (the floor/foundation, roof, and the four walls). Control layers are materials that limit or prevent the transmission or movement of air, water, heat, and vapor.[1] Some materials can serve as more than one control layer. For example, most air/water barrier membranes prevent the passage of air and bulk water, and if the membrane is vapor impermeable, it can block the passage of water vapor as well. The scope of BECx encompasses both the high-level overview, ensuring that there is continuity across the control layers, and the detailed work of reviewing material compatibility and sequencing at important transitions in the building enclosure assemblies.

Involving professionals who understand building science on a project, whether as the building enclosure consultant, building enclosure commissioning authority (BECxA), or Certified Building Enclosure Commissioning Provider (CBECxP), can be valuable because they will holistically apply the fundamentals when evaluating whether the waterproofing, exterior walls and fenestration, and roofing assemblies are appropriate for the project site. A BECxA or CBECxP is typically hired directly by the Owner.

Every site and building is unique in how it interacts with its specific surrounding environment. Some buildings extend deep into the groundwater table or are situated in high wind speed zones. Others endure harsh winters and repetitive cycles of freezing and thawing.

The goals of BECx are centered around constructability, durability, longevity, and safety. The process verifies that the building enclosure is designed and constructed using appropriate and compatible materials for the project-specific climate, which affects its performance and long-term durability. The building enclosure also influences interior conditions and the building's mechanical systems, with consequences for thermal comfort as well as occupant health and well-being.

When enclosures are appropriately designed for the climate, we can avoid "sweaty building syndrome," where condensation forms on interior surfaces, potentially leading to material degradation and biological growth, negatively affecting the health of the building's occupants.

BECx is performed to verify that the owner's interests and priorities related to the building enclosure are maintained throughout the various stages of a project. Some owners engage BECxA because that is the company or institution standard; these owners have previous experience with or knowledge of the BECx process and understand its value. Commissioning can also be a state-level requirement for state-funded projects, or it could be selected as part of a green building certification process such as LEED or Green Globe certifications.

BUILDING ENCLOSURE COMMISSIONING FOR MODERN BUILDINGS

Modern buildings have increasingly complex enclosures (**Fig. 1**). As material innovations continue to develop and new products come to market, it becomes more and more difficult for owners (and others without a background in building enclosures or building science) to understand the applicability and impacts of these materials within a building enclosure assembly. There are countless options for types of waterproofing, roofing, air/water barriers, and insulation, and it can be daunting to navigate through the process of selecting the right products and installation methods. Given this complexity, the engagement of a separate, professional entity independent of the design and construction teams, such

FIGURE 1. Modern building enclosures incorporate many different materials for the exterior walls, fenestration, roofing, and waterproofing system.

as a BECxA, can help ensure that the owner's interests remain the focus of the project.

There are many risks as projects enter construction, and installation of the building enclosure components begin. Contractors rely on various crews to complete the installations, who may have varying degrees of experience with the specified products or systems. Tight schedules and the impending pressure of maintaining critical paths or achieving dry-in can lead to hasty work with occasional deficiencies. An engaged BECxA assists in verifying the installations are compliant with contract drawings and specifications, project submittals, manufacturer's guidelines and instructions, and the owner's requirements, and they can identify the issues requiring correction at key milestones and periodic intervals throughout construction.

BUILDING ENCLOSURE COMMISSIONING GUIDELINES

Until the mid-2000s, the commissioning guidelines available in the construction industry were primarily written for building mechanical HVAC systems. In 2006, the National Institute of Building Sciences (NIBS) released NIBS Guideline 3-2006, *Exterior Enclosure Technical Requirements for the Commissioning Process*,[2] which was one of the first guidance documents to dedicate focus to enclosure commissioning. Over time, industry professionals with BECx experience were involved with refining and further developing documents to advance this practice. The BECx process and practice are currently outlined by the following documents and standards:

» NIBS Guideline 3-2012, *Building Enclosure Commissioning Process*[3]

» ASTM E2813-18, *Standard Practice for Building Enclosure Commissioning*[4]

» ASTM E2947-21a, *Standard Guide for Building Enclosure Commissioning*[5]

The above documents provide information on responsibilities, tasks, key documents, and deliverables throughout the project life cycle. Other useful resources include:

» Section 4, Definitions, of ASHRAE Guideline 0, *The Commissioning Process*[6]

» Section 3, Definitions, of ANSI/ASHRAE/IES Standard 202, *Commissioning Process for Buildings and Systems*[7]

» ASTM E631, *Terminology of Building Construction*[8]

» CSA Z320, *Building Commissioning Standard*[9]

» CSA Z5000, *Building Commissioning for Energy Using Systems*[10]

» CSA S478, *Guideline on Durability in Buildings*[11]

Additional commissioning resources and relevant documents have been published by ASHRAE, American National Standards Institute/Illuminating Engineering Society (ANSI/IES), and the International Organization for Standardization (ISO).

If BECx is being pursued as part of LEED or Green Globes, it is necessary to demonstrate that specific requirements for tasks and deliverables were completed and to submit the correct documentation to receive the desired points, whether for Fundamental or Enhanced levels of commissioning. BECx certifications and accreditations have been developed for professionals to demonstrate their experience and knowledge in this line of commissioning. One notable example is the Certified Building Enclosure Commissioning Provider (CBECxP®) designation from IIBEC.

PHASES OF BUILDING ENCLOSURE COMMISSIONING

To increase the probability of a successful building enclosure project with minimal issues, the BECxA should be involved from the early stages of the project. Each phase has its important tasks, and it is critical for the BECxA to stay engaged with the design and construction teams on all matters and decisions related to the building enclosure. This section provides an overview of the key pieces to the BECx puzzle, and is not intended to comprehensively discuss each task/item listed in NIBS Guideline 3,[3] ASTM E2813,[4] ASTM E2947[5] and other commissioning-related documents.

Predesign Phase

Similar to constructing a building, BECx starts with laying a solid foundation. The predesign phase establishes a framework for the building enclosure systems, against which the design, construction, and occupancy phases will be evaluated. The owner's project requirements (OPR) and the BECx plan are two of the most important project documents that will be generated by the BECxA in this phase.

The OPR outlines project criteria that are necessities to the owner, including, but not limited, to the durability or anticipated service life of building enclosure materials, building codes and standards, sustainability considerations, insurance, and the owner's overall vision. Meeting with the owner's team, including the direct client as well as other staff such as the facilities and/or maintenance employees, to discuss the project and collect the relevant information for the OPR can be very valuable. Some owners have design standards, and if these standards are available, they should also be reviewed while developing the OPR. For example, university campuses may have standards limiting which materials can be used on new buildings, whether for aesthetic, durability, or sustainability reasons.

In the predesign phase, the BECx plan is set up to become the go-to document summarizing the commissioning process for the duration of the project. As such, the plan should identify the various teams involved in the process, describe their roles and responsibilities, and document the process's scope, expectations, and timeline. Over the course of the project, the BECx plan evolves as more decisions are continually made, and changes to the plan should regularly be communicated to all parties on the team.

Design Phase

During the schematic design process, a basis of design (BOD) narrative is generated for the building enclosure to clarify the proposed exterior wall, waterproofing, and roofing systems applicable to the project. The BECxA or CBECxP should compare the BOD to the OPR document, as the BOD serves as the starting point from which the building design will be developed.

The BECxA or CBECxP should review the design documents, including architectural drawings and specifications, during the schematic design, design development, and construction documents phases, as outlined in ASTM E2813.[4] The reviews should be technically focused, covering overall control layer continuity across the building enclosure, and should evaluate the primary and accessory materials being proposed. Hygrothermal analysis of the building enclosure assemblies should be integrated into these technical reviews, as this analysis can provide insight into the suitability of the designs for the climate and building use. Comment logs for the document reviews are a helpful way to centralize the BECx items so the design team can easily address and respond to those items.

Reviewing the technical specifications also provides an opportunity for the BECxA or CBECxP to comment on many relevant aspects of the project, in addition to the materials and products, such as submittal requirements, mock-ups, and field-testing procedures. To centralize the building enclosure commissioning and testing information, a BECx specification section should be provided by the BECxA or CBECxP for inclusion in the project manual. As more specific details for the building begin to emerge throughout the design phases, the OPR and BECx plan will need to be updated periodically to reflect the design advancements.

Bidding and Negotiation Phase

The BECxA or CBECxP may be involved with reviewing bids and qualifications for the various subcontractors who will be installing the building enclosure assemblies.[5] They may also be involved with evaluating the testing agency qualifications and testing scope to ensure that the proposals meet the requirements of the BECx and technical specifications.

Preconstruction Phase

The BECxA or CBECxP should lead a preconstruction BECx kickoff meeting with the owner's team, design team, contractors, trades, and testing agencies to help coordinate and outline each party's responsibilities related to BECx, expectations, tasks, key milestones, schedule, and testing activity. The design-phase specifications typically include mock-ups, whether in the field or at a laboratory facility, as a design verification process (see **Fig. 2** for an example of a mock-up). Mock-ups allow the team to confirm whether

- the specified products can be installed as intended,
- different materials coming in contact will adhere and bond to each other,
- the building enclosure details can be constructed and in the proper sequence, and

FIGURE 2. Example mock-up of fenestration system.

» the building enclosure details meet the project requirements in effectively keeping air and moisture out.

To verify this last item, there are air and water leakage test methods that can be performed on the mock-up, following ASTM standards.[4] These tests need to be included in the design specifications and BECx plan to account for associated costs in the project budget, and responsibilities must be clearly communicated to the contractor and owner. This is especially important for laboratory mock-ups and testing, if required, as fees for these items can be significant. Any revisions to the building enclosure design following mock-ups and testing should be reflected in updates to the BECx plan and specification, as well as drawings and specifications by the design team. Oftentimes, coordination of testing among the various project participants must be reiterated more than once.

As submittal packages and shop drawings are submitted, the BECxA or CBECxP should review them for compliance with the contract documents and BECx documents. The BECxA or CBECxP may occasionally need to review submittals by other trades if those submittals affect or interface with the building enclosure assemblies. Communication of the submittal review workflow from contractor to BECx to architect, as well as planned use of any construction software tools, should be clearly spelled out during the preconstruction phase to avoid mix-ups later on.

Construction Phase

The construction phase is where everything comes together. The thorough attention paid to tailoring the BECx documentation and reviewing the design documents in the previous phases, along with the diligence in coordinating the work of the different project stakeholders, will pay dividends in the construction phase. Project specific checklists should be developed for each building enclosure system that will be reviewed by the BECxA or CBECxP and should be distributed to the general contractor and subcontractors for their use. Examples of checklists are provided in NIBS Guideline 3.[2] The BECxA or CBECxP should attend relevant preinstallation meetings as the meetings offer another opportunity for in-depth coordination among trades, inspectors, consultants, and the design team.

The importance of staying well connected with the contractors and well informed about construction progress cannot be overstated. There are critical stages at which the BECxA or CBECxP should be on site to review the installation of the building enclosure systems. Earlier is typically better than later so as to avoid situations where the key elements that need to be reviewed are already covered up by other materials. For example, the quality and detailing of an air/water barrier will be difficult to verify once installation of the exterior insulation and cladding is underway. Once the ship has sailed, it is unlikely that the general contractor will reverse progress for the BECxA or CBECxP to retroactively review the installation.

Throughout the periodic site visits, the BECxA or CBECxP and the project team should discuss any issues, deficiencies, or deviations from the construction drawings, specifications, and BECx documents at the earliest opportunity, and an issues log should be maintained and updated as the contractor addresses each item.

Similarly, the field testing should be scheduled and performed at the milestones listed in the project specifications. The BECxA or CBECxP should observe the field testing and any required retesting to ensure that all testing is performed in accordance with the applicable testing standards from ASTM International, the American Architectural Manufacturers Association, or another standards organization. The testing methodology, frequency, and locations should be monitored for compliance with the specification requirements. Updates to the BECx plan and OPR should be made, if applicable.

Occupancy and Operation Phase

At this stage, the owner and/or tenants have moved into the building, and the BECxA or CBECxP should be gathering all relevant documentation from previous phases into a final package, along with a final BECx report. The focus for the building enclosure shifts to warranties and maintenance, so a product-specific maintenance manual and ongoing BECx plan should be provided to the owner and facilities staff. The BECxA or CBECxP should perform a warranty visit at the 10-month mark. The objective of the visit is to take a site walk with the contractor, facilities staff, and owner to review for potential warranty items.[2]

COMMON MISCONCEPTIONS ABOUT BUILDING ENCLOSURE COMMISSIONING

While the BECx process just described may seem simple and straightforward, we frequently encounter several misconceptions in the construction industry related to BECx. The following sections identify some of these misconceptions and provide clarifications to help emphasize the true scope and purpose of BECx.

Misconception #1: "Commissioning is the same as consulting."

While there are similarities between the tasks involved in commissioning and consulting, consultants and commissioners serve different purposes. Consultants are typically contracted to the architect's team, assisting with the building enclosure design, and they are typically involved with product recommendations or selection. In contrast, the BECxA or CBECxP is contracted to the owner, and their mission is to ensure that the building enclosure design and construction meet the owner's overall requirements. The BECxA's or CBECxP's reviews of the design documents should be performed with **a perspective independent from that of the architect or general contractor, with the goal**

of identifying items that may not fit the owner's vision or requirements. The BECx process includes significantly more responsibility and involvement with coordinating and overseeing building enclosure related activities throughout the project's lifecycle than consulting.

Misconception #2: "Commissioning adversely affects budget."

BECx is a preventive process that aims to block potential issues from snowballing into larger, more expensive headaches. In many cases, water intrusion or condensation issues early in a building's service life could have been avoided if the building enclosure had been properly commissioned. The investigations and repairs later down the road can outweigh the costs of commissioning from the start.

Misconception #3: "Commissioning adversely affects schedule."

Proper commissioning keeps projects on schedule by establishing clear requirements and milestones to guide the project team. BECx may introduce additional steps, but it is a team effort to coordinate key tasks and ensure that they are completed on time. The BECxA's or CBECxP's periodic reviews of construction and testing aim to proactively identify potential issues and address them before they evolve into to larger-scale concerns. This BECx process helps prevent rework and lengthy investigations toward the end of construction, when the discovery of problems can significantly derail the project and extend the overall schedule.

Misconception #4: Commissioning is just an inspection process during construction."

BECx should begin well before the construction phase—the earlier it starts, the better! While one major component of commissioning does include observing installation and testing of assemblies during construction, **all commissioning services have the most value when BECx starts in the predesign phase**. In BECx, early planning and selection of the proper systems plays a large role in the final performance of the building enclosure. BECx happens during the predesign, design, preconstruction, construction, acceptance, and post-construction phases.

Misconception #5: "The architect and general contractor will handle all the design and construction issues."

The architect and general Contractor have a lot of stuff going on. While both have their own levels of quality assurance and quality control that are beneficial, neither entity is solely dedicated to building enclosure design and construction issues. In contrast, **BECx providers focus only on the building enclosure**, paying particular attention to the long-term success of the asset on the owner's behalf. By improving coordination between all parties on a project, the ultimate goal of BECx is to ensure that the owner's requirements and expectations are met. For today's modern and complex buildings, the BECx process helps to fill the gaps (pun intended).

Misconception #6: "The general contractor will resolve any post-construction issues with the building enclosure systems during the warranty stage."

Warranties are limited. According to warranty data and statistics collected by Warranty Week, the average claims rate in the building industry has been less than 1% over the last 20 years.[12] Meanwhile, the US Environmental Protection Agency reported that 85% of US office buildings have experienced past water damage or current leaks.[13] In general, manufacturer warranties tend to cover only specific defects from manufacturing of the building materials. Labor or "workmanship" warranties typically cover work that was installed incorrectly or with major defects. However, building enclosure problems can be caused by a variety of issues that may not neatly fall into either category.

Misconception #7: "It will cost us less to fix building enclosure defects after construction than during construction."

It is more expensive (and less effective) to address issues after they've been covered up. Take damage to an air barrier membrane behind metal wall panels as an example (which is based on a true story). After one round of air leakage testing near the start of installation, our team discovered air leakage through abandoned holes in the air barrier that occurred during installation of the metal wall panels. A small section of metal panels already installed was removed to address the air barrier penetrations. During installation, remediation can be as simple as applying an extra layer of fluid-applied material or a strip of flashing membrane. However, if building air leakage were found at the damaged air barrier locations at the end of construction, significantly more metal panels would need to be removed and reinstalled. Installers may have already demobilized from the site and would need to return. Further, the extent of damage across other locations on the building would have remained unknown as conditions could no longer be easily observed without further removal of panels. The owner's support of our services led to success in this case.

Misconception #8: "Another enclosure consultant on the project can complete the same tasks as the BECx provider."

Building enclosure consultants are great, but **they don't follow the specific guidelines or process that BECx standards provide**. Enclosure consultants may be hired on a project by the architect, general contractor, or owner to provide various services that are geared toward their client. BECx is adopted by owners to verify and document that the performance of the building enclosure assembly meets defined objectives and criteria set in the OPR, per the process outlined in NIBS Guideline 3,[3] ASTM E2813,[4] ASTM E2947.[5] Additionally, when owners seek LEED v4 Green Globes credits for Envelope Commissioning, projects require a commissioning authority and specific BECx documentation must be submitted.

CASE STUDIES

The following case studies are presented to highlight the nuanced ways that delivering BECx projects can be more challenging than they may seem.

University of North Carolina Surgical Tower

The University of North Carolina Surgical Tower, located in Chapel Hill, N.C., is a seven-story, 357,000 ft2 medical facility that houses modernized surgical spaces (**Fig. 3**). The building construction, which was completed in 2023, was phased into three distinct sections: construction of the main tower plus construction of two basement-level connectors to existing buildings, all designed by the same Architect. As part of the university's bidding process, the three phases were bid and awarded to separate contractors. Our firm was retained for BECx services at the start of construction. We were not retained during the predesign or other design phases.

We quickly became aware that the coordinating the work of the three contractors would be no small feat, especially considering the critical below-grade transitions between new and existing basement construction. To make matters more interesting, the contractors for each phase were planning to install different manufacturers' products and different types of below-grade waterproofing membranes, rendering the detailing between each transition even more complicated. In this case, the BECx process was heavily used toward the start of construction to help manage and align multiple parties on specific vulnerabilities at the basements. As construction progressed vertically, managing the subconsultant enclosure testing agency also became more time consuming than was initially expected due to conflicting schedules and retesting complications. As BECx providers, facilitating cooperation between people on a project is as much a challenge as overseeing the technical enclosure aspects of the commissioning process.

FIGURE 3. Rendering of the University of North Carolina Surgical Tower. *Photo Credit: University of North Carolina at Chapel Hill School of Medicine.*

The performance of BECx tasks helped ensure that the following project needs were met:

- Proper documentation of below-grade waterproofing transition details between each phase of new and existing construction
- The acquisition of manufacturer letters verifying product compatibilities and where warranties extended at product transitions
- Adequate testing of multiple air barrier penetrations behind rainscreen panels and effective remediation solutions on a wide scale

Nuanced BECx lessons learned from delivering this project include the following:

- Retaining BECx earlier during the design phase may have eased the stress of difficult waterproofing details and avoided the use of multiple manufacturers.
- Development of BECx testing in conjunction with the owner and architect is important.
- The BECx scope and fees should always include the work of managing subconsultant testing agencies.
- People management can be as important as technical management for BECx providers.

BECx proved vital to safeguarding the construction of watertight basement levels and airtight walls for the university's newest medical facility.

University of Miami Centennial Village Student Housing

The University of Miami Centennial Village is a five-building, 540,000 ft2 student housing complex that will serve as a hallmark for the campus when it is completed in 2025 (**Fig. 4**). The owner is seeking LEED Gold certification for the project and engaged our firm to provide BECx services during the early design phase in 2019.

It soon became apparent that the owner was primarily focused on BECx as a means to obtain LEED points and tended to be rather hands-off in the process. Thus, the main point of contact for the BECx team shifted to the architect, who was helpful, cooperative, and invested in the BECx activities during design. These positive interactions allowed for several enclosure design concerns to be addressed in an effective and timely manner. Then, at the start of 2020, the project, which was in the middle of the design phase, was placed on

FIGURE 4. Rendering of the University of Miami Centennial Village. *Photo Credit: VMDO Architects.*

hold due to the COVID-19 pandemic. When it picked up again after several months, several redesigns were now planned. The existing BECx scope and fee structure could no longer realistically accommodate new design reviews, and smart negotiation skills were required to update the scope of BECx activities to include design changes. As the project progressed, coordination with other building enclosure consultants on the project became increasingly difficult. When dealing with these challenges, we have been careful to respectfully communicate our stance while remaining flexible and open to opposing opinions. This soft skill is vital to keep parties on good terms and the project progressing efficiently.

Nuanced BECx lessons learned from delivering this project include the following:

- Collaboration with cooperative architects who understand the purpose of BECx has a positive impact on success of the project.
- Importance of confirming testing budget with Owner is critical.
- BECx teams must push for the scope of work to include additional services when design changes occur.
- Coordination with other building enclosure consultants should be handled tactfully.

Navigating changes as they occur on a project is a skill that BECx teams must master to be effective and successful.

Savannah Convention Center Expansion

The Savannah Convention Center is a 330,000 square foot event complex on the Savannah River waterfront in Georgia (**Fig. 5**). The event space has been undergoing an expansion to include a vast new ballroom and all-glass facade entrance; the project is scheduled to be completed in 2024. Walter P Moore was retained by the owner in 2019 to provide BECx services, and the design phase for the project was completed that year.

Near the start of construction in 2020, the owner requested that our firm retain a subconsultant testing agency to perform mock-up and field performance verification. Fast forward to 2022: multiple schedule extensions have occurred, but the scope of work has not been adjusted for additional BECx fees or services. During this two-year period, the owner and the BECx project management team had both changed. The original testing scope was questioned by the new owner and ultimately revised.

When curtainwall chamber testing for water and air leakage (ASTM E1105[14] and ASTM E783,[15] respectively) on a standalone mock-up was finally performed in late 2022, the results of the testing indicated failure but those results were questioned by contractor's building enclosure consultant, who noted minor discrepancies in the BECx field report and the testing agency's test report related to chamber construction, test pressures used, and calculated air infiltration values. While those comments were ultimately dismissed after further clarification, this interaction led to strained communication among the general contractor, BECx team, and testing agency. The parties struggled to agree on the costs and schedule for retesting the mock-up, but our team held firm that it was necessary to provide the owner with a verified curtainwall system before in situ construction continued.

Nuanced BECx lessons learned from delivering this project include the following:

- Accurately document all testing setups and criteria to instill confidence in the results.
- Be mindful of the effects of employee turnover on long-term projects and document/confirm the agreements made by parties, such as testing requirements.
- When facing challenges, remain steadfast on your stance to verify performance.
- Selecting and managing the testing agency can be challenging to coordinate.

FIGURE 5. Rendering of the Savannah Convention Center expansion. *Photo Credit: TVS Design.*

Proper BECx documentation and coordination of mock-up and field testing can give owners assurance their building will perform as intended.

Confidential Theme Park Project

The owner of a new theme park retained our firm to provide BECx near the start of construction phase. When we first joined the team, the confidential nature of the project made it cumbersome to obtain information needed for commissioning activities—a trend that would continue throughout the project. Documents as simple and essential as building drawings in PDF form took multiple steps and weeks to procure. Our team's communication and follow-up skills were put to the test in new ways that demanded patience.

The unique, fast-paced nature of construction led our team to deliver BECx services in a nontraditional way. During several of our site visits, documentation for many components being installed had not yet been finalized. Given this lack of full documentation, it was necessary to have multiple on-site detailing coordination meetings involving subcontractors, the contractor, the architect, and the owner, and field orders and changes happened rapidly. Because the means and methods for some proprietary products used (such as the cement plaster mixture design) were confidential, we had to ask unique questions to understand how detailing would work best. Fluid-applied air barrier detailing at complicated geometries, transitions, and structures behind the cement plaster became critical to keeping the buildings airtight in a way that preserved the owner's aesthetic vision.

Nuanced BECx lessons learned from delivering this project include the following:

- Unique buildings and construction conditions require flexibility in BECx delivery methods.
- Use of any proprietary products should be understood early in the project.
- The owner's requirements for the project's visual aesthetics must be taken into account when recommending enclosure detailing.

BECx providers must adapt to the particular challenges of commissioning of unique and fast-paced projects.

CONCLUSION

Building enclosure commissioning is a beneficial, quality-focused process for modern buildings with complex systems. In many cases, the distinguishing factor of an excellent commissioning agent is not their technical proficiency with building sciences, specific building enclosure systems or detailing, but rather their ability to adapt as changes occur and to foster communication on a team. Owners, architects, and general contractors can learn to trust the BECx process with help from savvy BECx providers who excel at navigating the nuances of delivering this service.

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Glass Distortion:
Not Such a Clear View

ABSTRACT

A funhouse mirror can provide endless entertainment simply by distorting the reflected image of an object. This effect can also be achieved by utilizing computer software or social media applications on a smartphone. It is all fun and games unless a true reflection is the desired outcome. This article discusses distortion of heat-treated architectural glass and how to perform an objective and quantifiable means for evaluation.

LEARNING OBJECTIVES

» Explain the heat-treating process of architectural glass.

» Recognize the different types of glass distortion.

» Explain how glass curvature affects the image quality that is reflected on the glass surface.

» Discuss criteria for specifying an objective and quantifiable means for evaluating the aesthetics of architectural glass.

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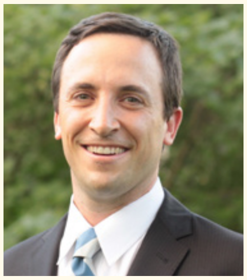

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Eric Hegstrom
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Eric Hegstrom has led the development of glass inspection equipment for LiteSentry (now LiteSentry/Softsolution) for more than 20 years. He has more than 30 years' experience in software engineering, the last 22 of which were spent designing and developing industrial vision, control, and automation systems for glass fabrication. He is active in developing industry standards and was most recently on the ASTM subcommittee for C1901 "Standard Test Method for Measuring Optical Retardation in Flat Architectural Glass." His previous experience includes work with Apple, Applied Materials, and Perkin-Elmer.

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GLASS DISTORTION

When utilizing heat-treated architectural glass, reflected images on the glass surface will have some degree of distortion. High-quality glass fabricators strive to produce "flat" glass, but achieving perfection is not possible. Glass distortion is inherent to the fabrication process and is discussed in ASTM C1048, *Standard Specification for Heat-Strengthened and Fully Tempered Flat Glass*.[1]

There are circumstances in which glass distortion is not a high priority, allowing the contractor to competitively price shop between different glass fabricators. On the other end of the spectrum, there are projects that necessitate minimal glass distortion; this limits the selection pool of qualified glass fabricators who are capable of consistently producing a high-quality product. A certain level of glass distortion is generally tolerable on a project. However, unless the project specifications require specific and quantifiable criteria, the acceptability of the glass distortion remains in the eye of the beholder.

A rudimentary check could include gauging the reaction of a casual observer. If the glass distortion is noticeable, but only after bringing it to their attention and soliciting specific feedback, then presumably there is not a quality concern. Conversely, if their first impression of the building is overwhelmed by an egregious distortion of reflected images, there is likely a glass quality issue. Obviously, this would be considered an informal, subjective, and reactionary approach to quality assurance, which could be a very costly proposition for the project team.

TRADITIONAL GLASS DISTORTION EVALUATION METHODS

The glazing specification section of a project manual will usually include glass quality requirements. In addition to ASTM C1048,[1] other glass quality standards generally include ASTM C1036, *Standard Specification for Flat Glass*,[2] and ASTM C1376, *Standard Specification for Pyrolytic and Vacuum Deposition Coatings on Flat Glass*.[3]

It is common for architects to specify the roll wave pattern of heat-treated glass to be parallel to the ground. Beyond that, the specifications will usually vary from project to project for glass distortion requirements.

Prior to the advent of modern electronic glass scanning technology, glass fabricators relied on a "zebra board" for a subjective visual evaluation of the glass distortion (**Fig. 1**). Zebra boards are composed of straight lines (alternating black and white) and are positioned at the back end of the oven's cooling section. This quality-control tool allows the operators to evaluate the glass right after it has been heat treated, and before it is unloaded for the next step of the fabrication process. It should be noted there are limitations associated with this visual inspection technique, as it is not a reliable means for identifying all potential distortion anomalies associated with the heat-treating process.

FIGURE 1. Zebra board visual evaluation of glass distortion on heat-treated glass.

A common type of distortion inherent to glass that is heat-treated in the horizontal position is a roll wave pattern (**Fig. 2**). This is the result of the glass being transported through the oven on rollers, becoming "soft"

FIGURE 2. Example of roll wave pattern in heat-treated architectural glass.

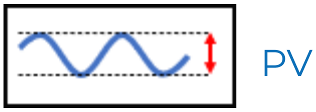

FIGURE 3. Representation of peak-to-valley roll wave distortion.

as it heats up, and then sagging between support points. When the glass is cooled, the deformation to the glass process becomes permanent. Roll wave distortion can be quantified by measuring the depth of the valleys relative to the peaks (**Fig. 3**), using a flat-bottom gauge (**Fig. 4**). There are no industry quality standards for roll wave pattern, though a common criterion for architectural glazing applications is a maximum of 0.003 in. (0.076 mm) in the center of glass and a maximum of 0.008 in. (0.20 mm) at the leading or trailing edge of glass. While this can be a useful guideline to identify an excessive roll wave pattern, there are other types of distortion this evaluation method cannot detect. In addition, there are physical limitations associated with this tool as it relates to obtaining an absolute measurement of the roll wave pattern along the entire glass surface. Further, the use of a flat-bottom gauge is an operator-performed quality check, usually at a predetermined frequency of time or production throughput, and thus it would be impractical to expect a measurement on every lite of glass.

OPTICAL DISTORTION

Project stakeholders will undoubtedly expect a higher level of quality in high-visibility commercial building applications compared with glass used in shower doors, handrails, and storefront applications. For those instances in which glass "flatness" is a critical design consideration, another way to communicate glass curvature is in terms of optical power (aka optical distortion). This provides an objective and quantitative means for evaluation, which also is a direct correlation to how the human eye perceives glass distortion (**Fig. 5**).

Glass curvature can be shaped either convex or concave, both of which will distort how an image is perceived. For the purposes of this article, only the effect of visible light being reflected on a glass surface (i.e., mirror-like) will be discussed (**Fig. 6**). Optical distortion describes the severity (or magnitude) of the glass curvature; the following summarizes how it is described and quantified.

- Optical distortion is measured in units of diopters.
- A higher diopter measurement indicates more severe glass curvature, which ultimately results in more optical distortion.
- Optical distortion is inversely proportional to the focal length[6] (equation 1), which is where all the light rays are focused.
- A positive diopter measurement indicates a concave glass shape, which magnifies an image (when the viewer is inside the focal length). Conversely, a negative diopter measurement indicates a convex glass shape, which demagnifies an image.

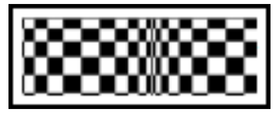

FIGURE 5. Representative reflected image of a checkerboard on distorted heat-treated glass.

Equation 1: $\Phi = 1/f$, where Φ = optical distortion in diopters and f = focal length in meters.

An alternative means for correlating optical distortion to focal length is to quantify the glass curvature (**Fig. 7**). The following summarizes how glass curvature correlates to optical distortion.

- A complete circle can be extrapolated out when reviewing the curved portion of a glass sample.
- The radius of glass curvature is two times the focal length (equation 2), and thus the relationship between optical distortion and the radius of glass curvature can be simplified by equation 3.
- As the radius of glass curvature decreases, the optical distortion increases (see **Table 1** for a select few data points).

Equation 2: $R = 2 \times f$, where R = radius of glass curvature in meters and f = focal length in meters.

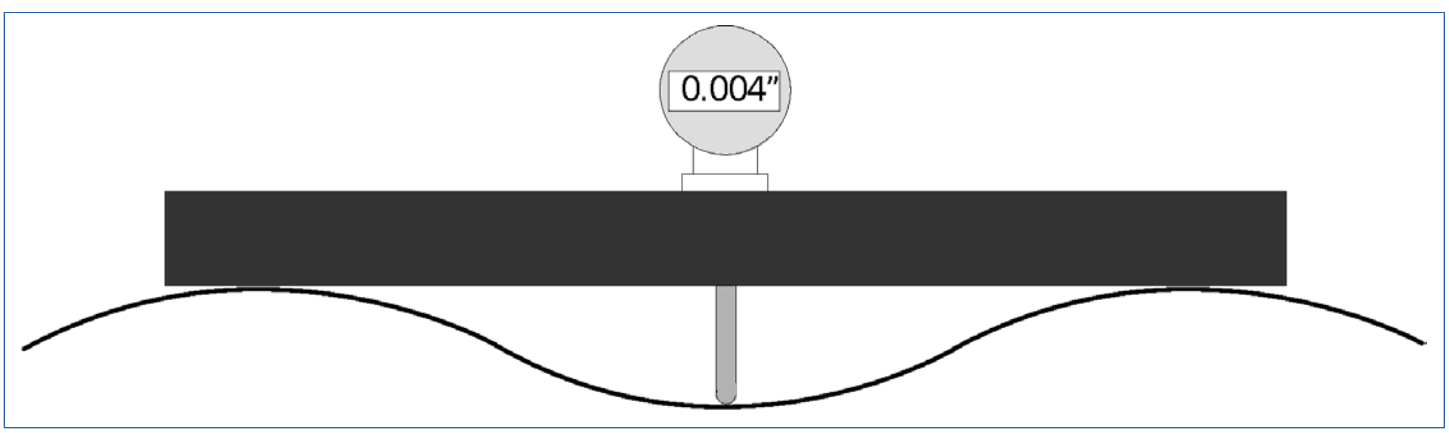

FIGURE 4. Example of flat-bottom gauge measurement.

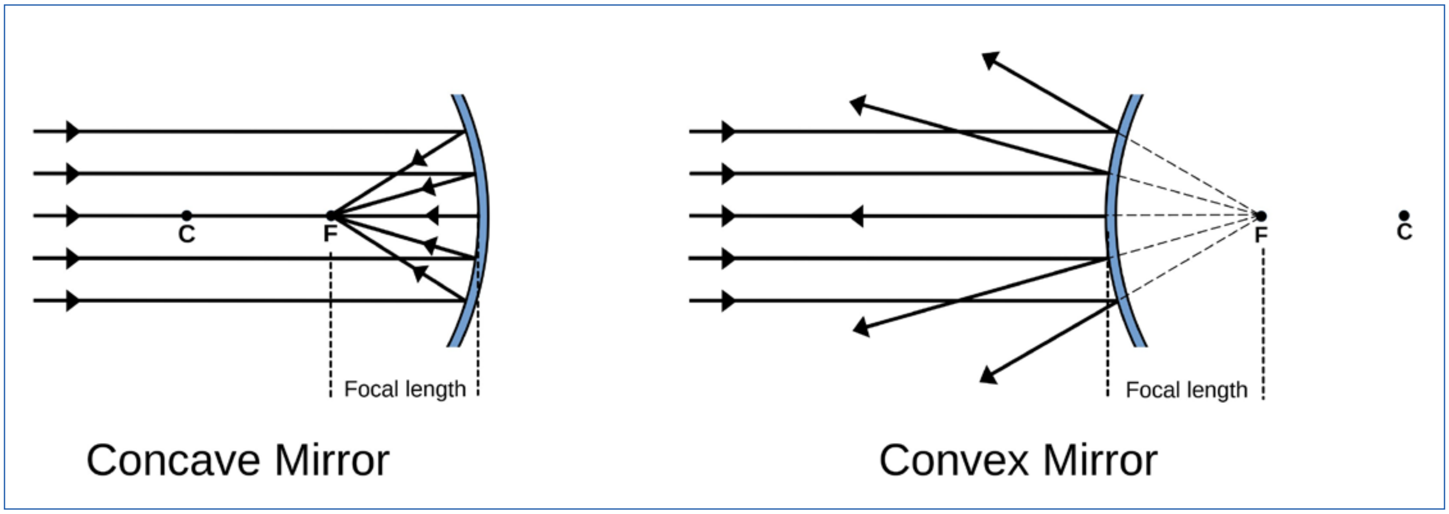

FIGURE 6. Illustrative examples of focal length with respect to concave and convex glass curvature, when viewed in reflection.

Equation 3: $\Phi = 2/R$, where Φ = optical distortion in diopters and R = radius of glass curvature in meters. Note, optical distortion is typically expressed in units of millidiopters (1,000 millidiopters = 1 diopter).

ASTM C1651-11(2018), *Standard Test Method for Measurement of Roll Wave Optical Distortion in Heat-Treated Flat Glass*,[4] and ASTM C1652/C1652M-21, *Standard Test Method for Measuring Optical Distortion in Flat Glass Products Using Digital Photography of Grids*,[5] are industry standards that includes equations for calculating optical distortion based on measuring peak-to-valley roll wave distortion. It should be noted this standard assumes a theoretical perfect sine wave for the equations (**Fig. 8**). However, **Figure 9** shows the same wavelength and peak-to-valley roll wave distortion measurement even though there is a drastically different amount of glass curvature. Thus, it is possible this standard may not provide an accurate value to convey how the human eye perceives the severity of the optical distortion.

ENHANCED EVALUATION FOR HIGH-QUALITY ARCHITECTURAL GLASS

Today's technology allows for the distortion of every lite of glass to be electronically scanned and measured during the fabrication process

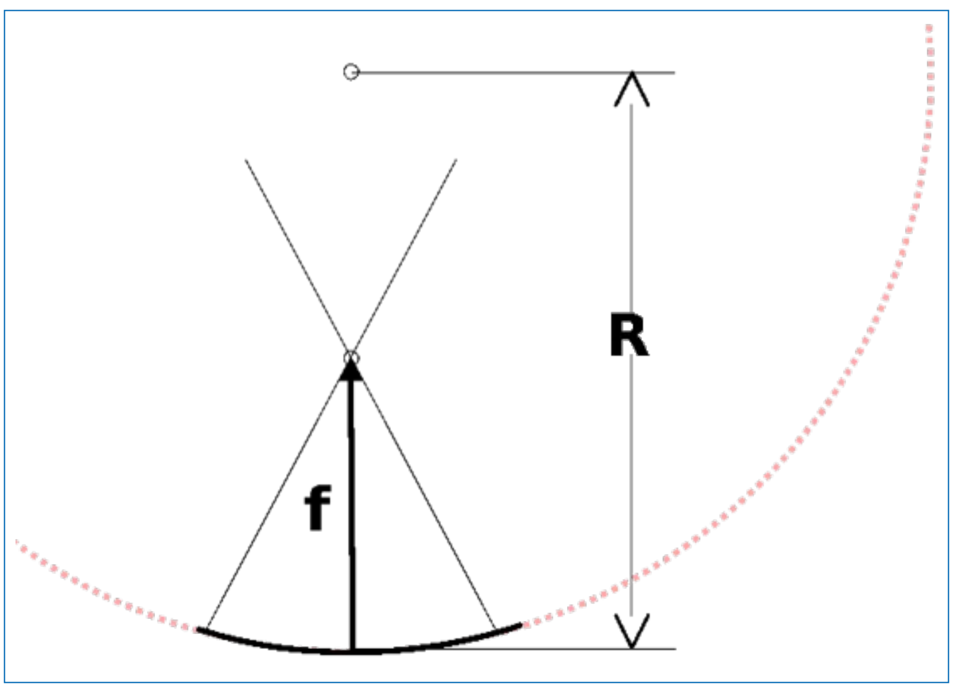

FIGURE 7. Representative relationship between radius of concave glass curvature and focal length.

TABLE 1. Comparison between radius of glass curvature and optical distortion.

Radius of glass curvature (R), meters	Optical distortion (Φ), millidiopters
∞ (flat glass)	0
100	20
40	50
20	100
10	200
6.67	300
5	400
4	500

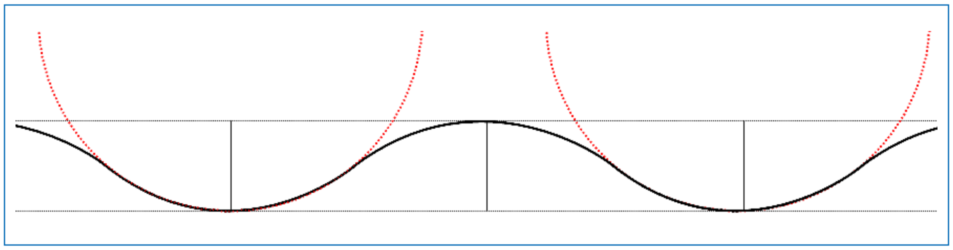

FIGURE 8. Roll wave pattern where both valleys have the same radius of glass curvature.

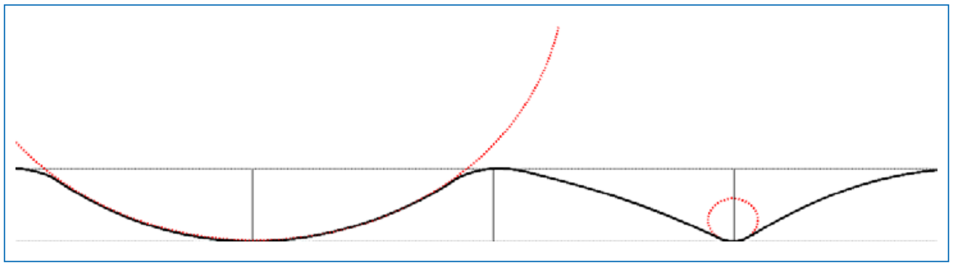

FIGURE 9. Roll wave pattern with one valley (left) having a large radius of glass curvature (low optical distortion) and the other valley (right) having a small radius of glass curvature (high optical distortion).

(some limitations apply based on substrate/coating type). This provides a quantifiable and objective means for evaluation, which includes the entire glass surface. The distortion measurements can then be tallied and sequentially ordered from least to greatest, expressed in terms of percentile (**Fig. 10**). Architects specifying high-quality architectural glass typically request that the output be summarized and communicated in either one (or both) of the following:

- In terms of optical distortion in units of millidiopters (mD) at a specific percentile measurement of the glass area. For example, 303 mD is the 95th percentile measurement of the entire glass surface.
- In terms of glass surface area (%) in which the optical distortion is less than a specific measurement. For example, the optical distortion for 90% of the entire glass surface is less than 239 mD.

Although no national standards exist regarding allowable optical distortion, float glass suppliers have attempted to differentiate the fabricators that can produce high-quality heat-treated glass for commercial glazing applications. As a point of reference, the authors of this article are aware of a float glass supplier that requires their certified fabricators produce glass with a maximum optical distortion of +/-100 mD for over 95% of the glass surface.[7]

However, looking solely at this output can be misleading because it may not reveal all glass-distortion-related issues. For example, **Figure 11** shows a heat-treated glass sample with a vertical distortion streak. Because this piece of glass has a relatively large area compared with the localized distortion issue, the vertical streak is not overly apparent when looking at the overall glass distortion data. There are multiple manufacturers of electronic glass scanning equipment, some of which have developed their own propriety algorithms to identify and quantity different types of localized distortion.

CONCLUSION

There are various levels of quality for architectural glass, and at this point in time there is no comprehensive industry standard that

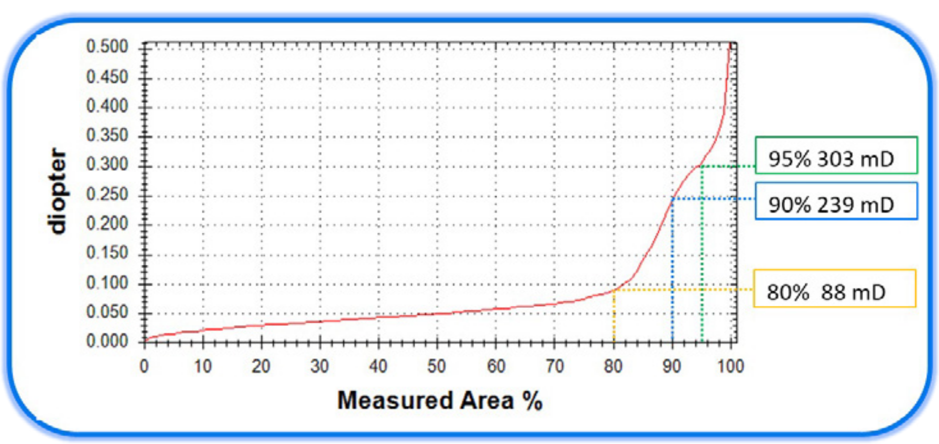

FIGURE 10. Optical distortion measurements over an entire piece of glass. Based on experience, the authors feel the above data is indicative of glass distortion that would likely be perceived as objectionable in a high-profile application.

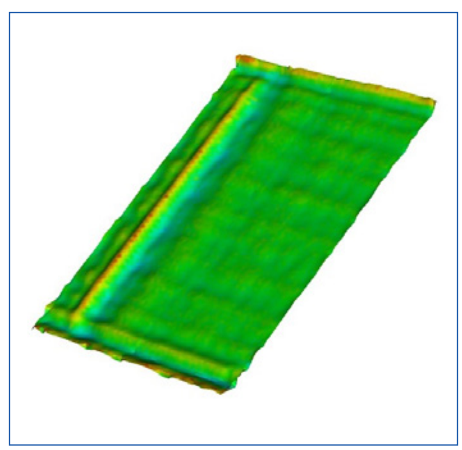

FIGURE 11. Three-dimensional electronic glass scan showing a vertical distortion streak.

addresses all the different types of glass distortion. For monumental projects having stringent expectations related to glass flatness, the authors recommend performing the following due diligence.

- Review the project's glass quality requirements. If there are no specific distortion guidelines, mutually agreed-upon criteria should be established prior to awarding a contract.
- Solicit a high-level summary of the glass fabricator's quality management system.
- Request a full-size mock-up for visual evaluation and approval by the project stakeholders.
- Require quality assurance/quality control submittal logs showing electronic distortion measurements during production of the project glass.

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An Updated Holistic Look at Old Assumptions:
Insights From Three New Studies on Roof Albedo

ABSTRACT

Ever since the Lawrence Berkeley National Laboratory published the first major study about roof albedo in 1988, the world has been comforted by the idea that mitigating urban heat islands and improving energy efficiency could be as easy as coating a roof with some white reflective coating. It is understandable that society could be so easily swayed by what seems like such a simple solution to such major problems.

If only it were that easy.

Over the past 30 years, there have been many studies done and articles written on roof albedo and its impact on energy efficiency and urban heat islands. While these studies accurately show promising results in certain areas of the country under certain conditions, new research funded by the ERA in the past three years indicates several nuances in the 30-year discussion of whether a black or white roof is better. This session will review three new research studies that have been completed in the past four years: a study by global consulting firm ICF on the impact of reflective roof mandates on urban heat islands, a study by ICF on the impact of roof albedo on energy efficiency, and a critical literature review by Clemson University of all previously published studies and articles on roof albedo.

LEARNING OBJECTIVES

- Define roof albedo, urban heat islands, and energy efficiency and their interaction within the built environment.
- Discuss factors to consider when determining the components of a roof system design as related to legislative or regulatory mandates, building codes, and voluntary guidelines.
- Identify inconsistencies and shortcomings of prior research on roof albedo and employ them when reviewing future studies.
- Summarize the benefits of various roof system choices with clients.

SPEAKERS

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EPDM Roofing Association, Denver, Colorado

Ellen is the Executive Director of the EPDM Roofing Association, whose members manufacture products for the roof and building envelope. As the leader of the 20+ year trade association, she has served as a trusted advisor and a pivotal leader who has positioned the organization for growth and strengthened its goal of representing the manufacturers of EPDM single-ply roofing products and their leading suppliers.

Ellen is an intentional collaborator who structures high-capacity coalitions to strengthen advocacy, outreach, and engagement initiatives for numerous organizations, regulatory agencies, and municipal governments.

Ellen has a bachelor's degree in political science and a master's degree in education policy and has earned the rigorous Certified Association Executive designation from the American Society of Association Executives.

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Jason P. Wilen, AIA, CDT, RRO, is an architect and building enclosure specialist with over 30 years of experience. Jason joined Klein & Hoffman (K&H) in 2018 and is now an Associate Principal. Before K&H, Jason served for 7 years as a director with the technical services section of the National Roofing Contractors Association (NRCA) and 18 years with architectural, forensic and roof consulting firms. He holds a Bachelor of Architecture degree from the Illinois Institute of Technology, Chicago, and is a licensed architect in Illinois.

Jason provides leadership and project management for K&H's roof system and waterproofing rehabilitation projects; participates with enclosure commissioning efforts, provides litigation support, and consulting for building and energy code development. Additionally, Jason is a member of ASTM Committees D08, C16 and E60, IIBEC, and has authored over 25 feature articles for local and national trade journals and magazines. In 2022, Jason was awarded IIBEC's Richard M. Horowtiz Award, honoring the best technical article published in its technical journal, *Interface*.

The growing awareness of climate change, as well as the related issues of urban heat islands and steadily increasing energy costs, has led to a growing interest in the effectiveness of reflective, or "cool" roofs (i.e., roofs that are designed to reflect more sunlight and therefore absorb less solar energy than a conventional roof). Proponents of reflective roofs have recommended their use throughout the U.S. to save energy and mitigate the effects of urban heat islands (UHIs), and some cities have moved toward mandating the use of white roofs on all new construction, roofing removal, and replacement as well.

Outline

Because EPDM Roofing Association (ERA) members make a variety of roofing membranes of various colors and roofing products used in countless geographic locations and building types, ERA's members believe it is incumbent on policymakers to verify the purported advantages of cool roofs and ensure that building owners and designers are free to decide how best to use EPDM roofing products to meet their roof performance and sustainability goals. ERA members contend that two fundamental questions should be answered before additional mandates are enacted. First, do reflective or cool-roof mandates in a given locality have the desired impact of reducing or limiting the development of UHIs? And second, to what extent is there sufficient certainty in the protocol by which UHI is quantified to determine this at all? Does roof albedo or insulation matter more in achieving improved energy efficiency?

Recently, ERA turned to researchers in Clemson University's Department of Construction Science and Management and ICF, one of the nation's foremost energy and environment consulting firms, to answer these questions. This research, which was conducted from 2019 to 2023, includes a critical review of the relevant literature by the Clemson University researchers titled "The Impact of Membrane Color and Roof Albedo on Energy Efficiency and Urban Heat Islands,"[1] and two original studies by ICF: "Assessing the Effects of Local Cool Roof Policies on Urban Heat Islands"[2] and "A Comparison of Code-Compliant Roof Insulation and Roof Albedo Impacts and Benefits on Energy Efficiency."[3]

UHI research lacks consistent methodology, hindering real world applications.

Based on the results of these studies, the ERA recommends that policymakers pause the implementation of policies that require reflective roofing mandates and calls upon government agencies, nongovernmental organizations, and other stakeholders to conduct additional research to assess the relative value of every tactic that could be used to diminish the impact of UHIs and increase building energy efficiency.[4]

As the research suggests, many questions need to be answered before the real-world implications of one-size-fits-all reflective roofing mandates can be understood and evaluated. This white paper aims to begin that process by presenting the current research on the presence of cool roofs as tools to mitigate UHIs and enhance the energy efficiency of buildings, identifying areas for improving cool-roof research, and predicting the policy implications of enacting one-size-fits-all roofing mandates.

LITERATURE REVIEW: THE IMPACT OF MEMBRANE COLOR AND ROOF ALBEDO ON ENERGY EFFICIENCY AND URBAN HEAT ISLANDS

The ERA contracted with researchers in Clemson University's Department of Construction Science and Management to conduct a critical review of the published data and literature about the impact of membrane color on energy efficiency and UHIs, synthesize the findings from that literature, and identify gaps in the existing research. After examining more than 2,856 references, 178 articles and papers, and 102 original research studies, the researchers identified questions about the use and benefits of cool roofs that require additional and deeper study.[5]

Overview of Research on the Impact of Cool Roofs on UHI and Energy Efficiency

According to the researchers, studies examining the impact of cool roofs on UHIs presented mixed results, as there are a range of factors, including landscape, density, geographic location and climate, and more, that contribute to the severity of UHIs. For example, many of the studies the researchers reviewed were dated (i.e., published at least a decade ago) and therefore failed to consider factors relevant to UHIs, such as the impact of high vehicular emissions on temperatures in areas with high density, the effect of hardscape asphalt surfaces compared to roofs, and the influence of building height. Further, the researchers reported instances in which more recent studies based their conclusions on these earlier studies, which now must be considered dated or offering incomplete information.[6]

The researchers observed that conclusions about the effect of membrane color on energy efficiency would benefit from additional and more timely research to support or refute currently held perceptions, such as the notions that increased levels of reflectivity increase the amount of annual energy savings, and that roof insulation is critical in all climates. New research, they suggest, should compare the impact of roof albedo on energy efficiency for real-world vs. simulation-based studies, for these simulation-based studies did not account for aging, soiling, and weatherability of the "cool" material during a building's life span.[6]

Research Gaps and their Impact on Implementation

Although there is an abundance of current research that examines the impact of cool roofs on building performance, energy efficiency, and UHIs, there are gaps and inconsistencies in their research methodologies that limit the application of their findings in real-world settings. The effectiveness of cool roofs in addressing these issues very much depends on a combination of factors that are unique to each city and/or geographic location, and thus incongruous with one-size-fits-all roof mandates.[6]

COMPARATIVE ANALYSIS OF THE EFFECT OF LOCAL COOL-ROOF POLICIES ON URBAN HEAT ISLANDS

To better understand the measurable impacts of commercial roofing surfaces on urban heat islands (UHIs), ERA contracted with ICF, one of the nation's foremost energy and environment consulting firms, to undertake a three-phase study designed to assess whether cool-roof mandates help mitigate UHIs (phase 1), determine whether the proliferation of cool roofs in a particular city positively impacts the UHI effect with improved analytical rigor (phase 2), and compare the strength and significance of daytime and nighttime UHIs to determine whether increases in cool roofs within help mitigate UHIs within particular cities (phase 3). The following is a summary of the methodologies used to conduct this three-part study and its conclusions.[7]

Phase I: Analysis of Select Cities with Reflective-Roof Mandates

In phase 1, ICF researchers analyzed ambient temperatures in three urban areas that have had cool-roof mandates in place, compared those temperatures to temperatures in three similar localities that have not imposed such mandates, and analyzed corresponding changes in urban land surface color in those localities to estimate the effect of commercial roof solar reflectance on UHIs. Experimental and control city pairs were selected to enable the comparison of impacts between cities with and without cool-roof mandates. Selection considered year of cool-roof mandate implementation and mandate coverage;

availability and resolution of air temperature and GIS (geographic information system) data, both before and after mandate implementation; and climate conditions, including a city's international climate zone and microclimate, to moderate impacts confounding weather effects. The selected experimental (or mandate) cities and control city pairs were New York City, NY (mandate city) and Newark, NJ; Chicago, IL (mandate city) and Indianapolis, IN; and Washington, DC (mandate city) and Baltimore, MD.[8]

COOL ROOF MANDATES & UHI — PHASE I
No decrease in daytime UHI was observed in any city pair after the imposition of a cool roof mandate.

Phase 1 Results

Comparison of the cities with and without mandates revealed no discernible correlation between the imposition of cool-roof mandates and UHIs. As the ICF researchers state:

- » None of the three city pairs exhibited a relative reduction in daytime UHI intensity after the experimental city imposed a cool-roof mandate.
- » Only one of three city pairs exhibited a relative reduction in nighttime UHI intensity after the experimental city imposed a cool-roof mandate.
- » Three out of 12 cases (daytime and nighttime UHI intensity for each of the six cities) showed a negative trend between UHI intensity and relative change in cool roof, indicating an uncertain, or at best, a low and localized impact on UHIs from the imposition of cool-roof mandates.[8]

Phase 2: Analysis of Cities with High UHI and Reflective Roofing Mandates

The aims of phase 2 were similar to those of phase 1: assess the relative impact of commercial cool roofs on UHIs. However, the second analysis was designed to improve analytical rigor; specifically, ICF proposed the use of higher-resolution imagery to enable more rigorous analysis of the areas of interest and yield results more meaningful to stakeholders.[9]

To accomplish these objectives, two cities, Chicago, IL, and Portland, OR, were selected for analysis because their high amounts of white roofing and UHIs made them good candidates for evaluating whether there are perceptible effects from the installation of commercial cool roofs on local UHIs. In addition, ICF's preliminary analysis of NOAA weather station and GIS data indicated that both cities have good availability of local weather stations with complete data and high-resolution GIS data complete with building layers for commercially zoned areas of interest.[9]

Phase 2 Study Results and Conclusions

Air temperature analyses conducted for Chicago and Portland for daytime UHIs were deemed inconclusive because they resulted in considerably lower estimates of UHIs than presented in the commonly cited climate science publication (CCCSP), and the scenarios analyzed exhibited variable trends with uncertainty. However, the researchers decided that their findings may be reasonable and accurate even if they contradict findings in the CCCSP from which the methodology to measure UHIs was taken.[9]

COOL ROOF MANDATES & UHI — PHASE II
UHI measurements for Chicago and Portland were significantly less than those cited in the CCCSP even though the same methodology was followed.

According to EPA, UHIs are often strongest at nighttime because the built environment cools and releases heat to the atmosphere much slower than the surrounding rural areas, and daytime UHI can even be negative as the rural landscape heats up faster than the urban environment. Similar impacts were noted in the ICF analysis, where the daytime day-to-day UHIs were highly variable with as many days exhibiting positive as negative UHIs.[9]

Because there is no standardized method for determining UHIs, the researchers found UHIs to be contextual and based on the needs and objectives of those performing the study. Therefore, while different teams of researchers used multiple definitions and methods to quantify UHI, the ICF researchers believed it was reasonable to conclude that Chicago's and Portland's daytime UHIs (as determined through air-temperature analysis) were less pronounced than indicated in the CCCSP, even though they followed its methodology.[9]

Phase 3: Comparative Analysis of Daytime and Nighttime UHI

In Phase 3 of the research, 13 cities—Albuquerque, NM; Baltimore, MD; Buffalo, NY; Columbus, OH; Denver, CO; Kansas City, MO; Las Vegas, NV; Louisville, KY; Minneapolis, MN; Philadelphia, PA; Portland, OR; San Diego, CA; and Washington, D.C.—underwent a temperature-based UHI analysis that evaluated daytime and nighttime changes in UHIs on an annual basis over a period of more than a decade. The researchers mirrored the CCCSP's methods by looking at the strength and significance of daytime and nighttime UHIs and assessing the probability of a UHI being as prominent through the use of alternate weather stations and summertime periods.[10]

COOL ROOF MANDATES & UHI — PHASE III

Daytime measurements in the 13 cities were highly variable, with consecutive days flipping between positive and negative UHIs.

Because confidence in estimating UHI is central to the objectives of this study, the researchers found the following notable:[10]

- Daytime UHI was found to be less pronounced and more variable when compared to nighttime UHIs, which tend to be significant and positive.

  Due to the absence of a standardized approach for assessing Urban Heat Island (UHI), its determination is contextual and depends on the specific requirements and goals of the researchers.
- Daytime UHI was not strong when compared to results from the CCCSP, and results vary greatly according to weather station selection.
- On a day-to-day basis, daytime UHI was highly variable, with instances where consecutive days flipped between positive and negative UHI.
- Air temperatures recorded at weather stations are influenced primarily by local conditions and rarely factor in surrounding areas.
- Daytime UHI also varied according to the quantity of weather stations and selected time period.

COOL ROOF MANDATES & UHI — CONCLUSIONS

1. Other major factors impact UHI, not just low-slope roofs.
2. The impact of cool roof mandates on UHI is inconclusive.

Overall Conclusions of the Impact of Cool-Roof Mandates on Urban Heat Islands

Given the results of the three-phase study, an increased presence of cool, white, or reflective roofs, whether by mandates or market occurrence, does not mitigate the effects of UHIs. As noted previously, as there is no established method for determining or analyzing Urban Heat Islands (UHIs), prior research on UHIs has been identified as context-dependent, shaped by the unique needs and objectives of the researchers conducting each individual study. As such, the ICF researchers noted that there is a great need among the scientific community to establish standardized and reproducible methods for defining and measuring UHIs that will yield reasonably consistent results.[11]

The researchers note that several themes remained consistent throughout all three phases:[12]

- There are many factors that impact UHI, only one of which is commercial rooftops.
- Daytime UHI was more variable and less pronounced than nighttime UHI.
- There is a need for stronger and higher-quality daytime UHI calculations.
- Air temperatures only reflect conditions near weather stations and not broader areas.
- Analysis of daytime UHI shows inconsistent results and is influenced by many factors.
  - The impact of cool-roof mandates on UHI is inconclusive and requires more research.

A COMPARISON OF CODE-COMPLIANT ROOF INSULATION AND ROOF ALBEDO IMPACTS AND BENEFITS

Cool roofs have become one of several accepted strategies for mitigating the impacts of urban heat islands and have long been a prescriptive requirement of American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 90.1-2022, *Energy Standard for Buildings Except Low-Rise Residential Buildings*[13] and the *International Energy Conservation Code* (IECC)[14] in Climate Zones 1, 2, and 3. These requirements generally mandate a white or high-albedo roofing surface material that reflects a portion of the incoming solar radiation away from a building's roof, before it is transmitted to and absorbed by the building.

Cool roofs are currently not required by ASHRAE 90.1-2019 nor the IECC in Climate Zone 4 and zones to the north, as the reduction in solar heat gain from cool roofs tends to increase the overall building energy use in cooler to cold climates.

To better understand and communicate where insulation and cool roofs provide the greatest benefits,

ROOF ALBEDO, INSULATION, & ENERGY EFFICIENCY

Researchers developed building energy models to calculate energy cost savings, produce lifecycle economic metrics, and develop emissions benefits.

ERA commissioned ICF to conduct a study designed to assess and quantify the life-cycle energy, economics, and emission benefits of code-compliant roof replacements and cool-roof projects for a select number of commercial building types constructed with low-sloped roofs and representative city/climate zone combinations. The following is a summary of how this study was conducted and its conclusions.[15]

To determine where insulation and cool roofs provide the greatest benefits, ICF developed a three-step approach designed to accomplish the following:[16]

» Develop building energy models to represent the baseline and intervention scenarios. Both sets of models were simulated to produce annual estimates of whole-building energy use and their energy use was subtracted to produce incremental energy savings.
» Calculate energy cost savings as the product of energy savings by fuel type and the corresponding price of fuel and then combined with secondary research on incremental material and labor capital costs to produce life-cycle economic metrics.
» Develop emissions benefits from energy savings as the product of energy savings by fuel type and the corresponding emissions factors.

ICF created baseline building energy models (developed from the Department of Energy's commercial prototypical building models) for the Medium Office, Hospital, Primary School, and Warehouse building types, in three primary and seven sub-U.S. climate zones. These selections represent nine U.S. cities and use the 2004 building energy model.[15]

Next, ICF developed intervention models from the baseline building energy models representing the three-year solar reflectance and thermal emittance values commonly used in modeling for building-level code compliance.[16]

Intervention (I1): The black roof with code-compliant levels of insulation intervention is identical to the baseline condition but with roof insulation levels based on the ASHRAE Standard 90.1-2019 minimum rated R-value building enclosure criteria given in the prescriptive building envelope compliance path for conditioned nonresidential opaque roof (exterior) elements for insulation entirely above deck.

Intervention (I2): The cool roof with baseline levels of insulation intervention is identical to the baseline condition but with three-year-aged solar reflectance and thermal emittance values of the ASHRAE 90.1-2019 standard for cool (or white) roofs.

Intervention (I3): The cool roof with code-compliant levels of insulation intervention is identical to the black roof with code-compliant levels of insulation but with the three-year-aged solar reflectance and thermal emittance of the cool-roof intervention (I2).

With their intervention models in place, the researchers then performed energy use and economic benefit (i.e., energy-cost savings, incremental material and labor costs) analyses on each of the intervention scenarios to determine which offered the greatest energy savings and economic benefit.[16]

The results of these analyses were mixed, as the benefits offered by the three interventions were determined by the characteristics of the four building types. 15As the study notes:

» Intervention 1 offered the greatest energy savings with buildings that had larger conditioned floor areas and space heating and cooling requirements, and was cost-effective for almost all building types and climate zones.
» Intervention 2 offered less than 2 percent energy savings (the impacts of cool roofs alone, if and when they were positive, were small) and was cost-effective in some scenarios, but the lifetime net benefits were small compared with those offered by increased insulation.
» Intervention 3 offered the greatest energy savings with larger conditioned floor areas and space heating and cooling requirements, and was cost-effective in some building types and climate zones.

ROOF ALBEDO, INSULATION, & ENERGY EFFICIENCY

1. Black roof with code-compliant insulation.
2. Cool roof with baseline insulation.
3. Cool roof with code-compliant insulation.

The study comparing code-compliant roof insulation and roof albedo concluded the following:

» Code-compliant insulation provides greater net benefits than the cool-roof intervention in all cases.
» Insulation levels are equally as or more effective than "cool roofs" in achieving energy-saving goals.
» Cool roofs tend to provide only a marginal or slight reduction in energy use across all modeled climate zones when installed with traditional levels of insulation. These findings applied to most commercial building types with low-sloped roofs and insulation installed entirely above deck.

ROOF ALBEDO, INSULATION, & ENERGY EFFICIENCY

In all cases code-compliant insulation yields greater net benefits than cool roofs.

Insulation is as (or more) effective than a cool roof for energy savings.

The findings suggest code-compliant insulation in most cases provides significantly greater net benefits than cool-roof intervention in all but a few rare cases where the insulation intervention is not cost-effective. And despite a modest reduction in cool-roof impacts when combined with code-compliant insulation, the combination of code-compliant insulation and a cool roof provides greater benefits than either alone. This finding suggests that when there is an equal opportunity to either increase the roof insulation to be code-compliant or pursue a cool-roof project, one would be remiss to not elect the insulation intervention, after which the incremental economics of installing a cool roof tend to be lessened.[16]

STUDY LIMITATIONS AND AREAS FOR IMPROVEMENT

The researchers noted challenges and limitations that impacted their findings. For example, in phase 1 of the ICF study "Assessing the Effects of Local Cool Roof Policies on Urban Heat Islands,"[12] researchers noted that, although the study met the objective of developing a replicable and scalable framework to assess the relative role of commercial cool roofs on local urban heat islands, these results were influenced by limitations, including control of confounding environmental factors, spatial separation between urban areas, and low correlations between weather station air temperature and urban density.[8]

Further, weather station air temperature and urban density are the two variables used to determine UHI intensity over the analysis period. The lack of correlation between these two variables has several implications.

- First, it suggests air temperatures recorded at weather stations are influenced primarily by local conditions, and to a lesser degree (or if at all) by the nearby surrounding areas.
- Second, it implies that urban density alone is not a good proxy for air temperature as anthropogenic and environmental factors, such as tailpipe emissions and the color of impervious surfaces, also influence temperature.
- Third, it implies that the margin of error in the temporal UHI intensity analysis is significant in most cases to negate trends observed in UHI over the analysis period.

Limitations pertaining to the quality and coverage of satellite imagery also contributed to inconclusive results.

- Satellite data was limited to 30-meter resolution and provided less granularity for classifying imagery, discerning between objects, and distinguishing between land surface colors than higher-resolution (0.5- and 1.0-meter resolution) data.
- The geographical boundary assessed for changes in land surface color includes cool roofs as well as other land-use changes, such as an increase in landscape vegetation and possible increased urban tree canopy. Both options are well known and effective strategies for UHI mitigation.
- The lack of trends directly relatable to cool roofs can be attributed to the geographical area of coverage and satellite resolution and could be a result of differences in cloud cover between selected satellite imagery, changes in urban land use other than from cool roofs, or loss of reflectivity or darkening of white surfaces (including roofs) due to surface degradation.

In phase 2, the study limitations were related to conclusions that can be drawn from the analysis results due to environmental factors rather than study design. These include the following:[9]

- **Control of confounding environmental factors**—Two aspects common to the referenced cities are the prevalence of local ordinances and double-digit population growth, both of which have potentially interactive and/or confounding, but opposite impacts with UHIs. Vegetative roof mandates and tree planting, for example, are complementary UHI mitigation strategies to cool-roofing ordinances. While the impacts of complementary UHI policies may moderate the impacts of population growth, after city selection, the best course of action to reduce potential bias is to select analysis periods that both cover significant installations of cool roofs and limit the change in environmental conditions from related UHI policies.
- **Representative weather stations**—While there is a sufficient quantity of available weather stations, the analysis is limited both by the geographic availability of those used in the CCCSP, which consisted of those generally to the south that are in nonmountainous areas; the number of weather stations used in the Climate Central study, which is limited to one urban and three rural stations; and location of the weather stations. While the airport station has a high urban density, it is located close to a body of water (river) that may exert influence over the air temperature in a way that counters the analysis.

RECOMMENDATIONS FOR FUTURE RESEARCH

As part of their studies, the researchers identified issues in which further study could increase understanding of the benefits cool roofs might have on UHIs and energy efficiency. They include the following:[9]

- Comparing cool roofs with other strategies for reducing the creation and impacts of UHIs, such as increasing vegetation area and improving the albedo of paved surfaces. Both of these approaches have been shown to reduce the effects of UHIs beyond that of low-albedo commercial roofs.
- Assessing the strength and significance of daytime UHIs for the top 10 U.S. cities following the methodologies outlined in the CCCSP study. For each analyzed city, researchers should assess the magnitude and timing of impact from other environmental factors that influence UHIs over the analysis period.
- Using high-resolution GIS data to evaluate building-level changes in white roofs as well as changes in landscape vegetation, as both may influence the creation and impacts of UHIs.
- Analyzing the variability of air temperatures over time in cities where the majority of roofs are white to see if it has a positive impact on the occurrence of UHIs.

POLICY IMPLICATIONS AND CONCLUSION

The decisions by cities and building code governing bodies to mandate reflective roofing in certain climate zones have preempted the economic and science-based individualized design decisions predicated upon critical factors such as local geography, building use, or the roofing materials' carbon footprint. Focusing on the reflectivity of roofing materials as a means of addressing the impacts of UHIs is misplaced and unproven.[15]

Therefore, the ERA recommends that federal, state, and municipal governments refrain from mandating policies that require reflective-roofing mandates until the presumed benefits of cool roofs are compared with other strategies for increasing energy efficiency and reducing the effects of UHIs. Further, these comparisons must use consistent and robust methodologies for evaluating other strategies known to mitigate UHI impacts, such as increasing landscape vegetation and improving the albedo of paved surfaces, both of which account for many times the total area of low-albedo commercial roofs.[4]

Meeting these requests would result in the broader, more rigorous, and consistent real-world analysis needed to assess the value of cool-roof mandates within a larger, more comprehensive plan for addressing the impacts of climate change.

The strategies for reducing the impact of UHIs and boosting energy efficiency vary widely and the impacts of cool roofs compared with other approaches, such as installing cool pavement, increasing landscape vegetation and tree planting, and implementing smart growth policies and regulation, have not been determined.

The Clemson University review of current literature on cool roofs found questions that need to be examined in depth to understand the benefits and implications of cool roofs: How does seasonality impact UHI and cool-roof efficacy? How do different locations, roof types, and climate zones impact UHIs and energy efficiency? Should cool-roof implementation focus on roofs with the largest surface area? To what degree does material degradation impact the effectiveness of cool roofs? And what are the economic and life cycle benefits of cool roofs?[5]

Further, although there is an abundance of current research that examines the impact of cool roofs on building performance, energy efficiency, and UHIs, there are notable gaps and inconsistencies in their research methodologies that limit the application of their findings in real-world settings. These gaps and discrepancies are significant, for the effectiveness of cool roofs in addressing these issues depends on a combination of factors that are unique to each city and/or geographic location, and thus incongruous with one-size-fits-all roof mandates.[5]

Similar conclusions were reached in the three-phase ICF study "The Impact of Cool Roof Mandates on Urban Heat Islands,"[7] which found that commercial rooftops, including cool roofs, are only one of many factors impacting UHIs, and that the impact of cool-roof mandates on UHI is largely inconclusive and requires more research. This is important information for policymakers who may view cool roofs as a silver bullet they can use to defend citizens against the threats of climate change.[4,6]

Further, the ICF study "A Comparison of Code-Compliant Roof Insulation and Roof Albedo Impacts and Benefits"[15] reached a similar conclusion: there is a proper location and usage for every roof membrane available, and the use of cool roof does not yield the greatest benefits in all cases. As the ICF researchers note, "When there is an equal opportunity to either increase the roof insulation to be code-compliant or pursue a cool roof project, one would be remiss to not elect the insulation intervention, after which the incremental economics of installing a cool roof tend to be lessened."[16]

ROOF ALBEDO, INSULATION, & ENERGY EFFICIENCY
White roof mandates constrain sustainable roof design options.

All too often, mandates like those some U.S. cities have been enacting in regard to 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 system, the roof assembly. 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.

Because ERA members make a variety of roofing membranes of various colors that are used in countless geographic locations and building types around the country, ERA's members believe that the fundamental questions about cool roofs raised in this white paper be answered before additional mandates prohibiting building owners from using the roofing products of their choice are enacted.

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Hygrothermal Efficiency of Retrofit Wall Cladding System for Existing Buildings

ABSTRACT

The global population surge and increased housing construction development have led to a soaring demand for energy. Many existing buildings were constructed without sustainability in mind, making them highly energy inefficient. In the US, for example, buildings consume over 40% of the nation's energy, mainly for heating and cooling. To address this issue, energy conservation retrofits are essential to reduce energy consumption and associated operational carbon footprint.

Most buildings from the 1980s lack proper insulation, but optimizing their thermal design, along with choosing appropriate insulation and exterior cladding materials, can significantly cut energy consumption and reduce CO_2 emissions. However, increasing insulation and similar products can lead to higher embodied carbon due to their production, installation, and disposal.

This study focuses on retrofitting commercial building rainscreen envelopes using WUFI, a hygrothermal software. An ongoing project involving a school building from the 1990s, plagued by moisture issues and structural risks, seeks to enhance energy efficiency while preserving the existing structure. Objectives include improving thermal efficiency and reducing condensation within the building envelope.

Simulation results on the existing assembly predicted moisture damage and mold/mildew risks. Retrofit simulations, however, indicated drying of the building envelope and energy savings. Smart rainscreen retrofits offer a cost-effective solution for commercial buildings, decreasing embodied carbon, reducing landfill waste, enhancing comfort, and increasing energy efficiency.

The study acknowledges the limitations of 1-D analysis and suggests the need for comprehensive whole-building analysis to incorporate factors like HVAC systems, further advancing this research.

LEARNING OBJECTIVES

- Discuss the importance of air barriers, vapor control, and thermal control in wall assemblies.
- Recognize the potential source of energy and water leaks in existing wall assemblies.
- Measure and model existing wall assemblies in WUFI.
- Illustrate rainscreen design principles to manage moisture, air, and vapor.
- Model redesigned wall assemblies to forecast potential environmental risks.

SPEAKER

Jonnie Hasan, PE, M.Eng (Sustainable Smart Cities), BECxP, CxA+BE

Director of Engineering, Norcross, Georgia
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Jonnie Hasan, M.Eng (Sustainable Smart Cities), PE, BECxP, CxA+BE, has more than 25 years of experience in commercial construction, design-build, and cladding industries. He holds a structural engineering PE, Six Sigma green belt, 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. Mr. Hasan is an active member of ASTM, BEC (local chapter), PCI, ACI, and ASCE.

AUTHOR:
Qumrul Hasan (Jonnie), PE, BECxP, CxA+BE

LITERATURE REVIEW

Depletion of natural resources and the association of anthropogenic carbon dioxide with climate change highlight the need for reducing carbon-based energy consumption globally (IPCC 2014). Buildings contribute 40% of global greenhouse gas emissions, with commercial buildings consuming 80% of their energy during operations (DOE 2011). To achieve carbon neutrality by 2050, a four- to tenfold increase in energy efficiency is required (IPCC 2014). This presents an opportunity for sustainable construction sector, potentially boosting demand for smart construction materials and employment related to sustainable developments (IPCC 2014).

The US Department of Energy's Deep Energy Retrofits (DERs) program emphasizes retrofitting to reduce greenhouse gas emissions (DOE 2011). Passive retrofitting, which focuses on building envelopes, insulation, and airtightness, can effectively lower the operational carbon footprint (Straube, Ueno and Schumacher 2021). Passive strategies are preferred for their potential to conserve energy (DOE 2011).

Retrofitting existing buildings can improve occupant comfort and reduce environmental footprints. Studies show that effective insulation and cladding can increase building system performance by up to 40% (DOE 2016).

Retrofit wall assemblies are crucial for energy efficiency. "Rainscreen" assemblies, such as those studied by the Pacific Northwest National Laboratory, can achieve hygrothermal balance for moisture management (Antonopoulos, et al. 2019). This paper focuses on existing wood- or steel-framed insulated walls (DOE 2016).

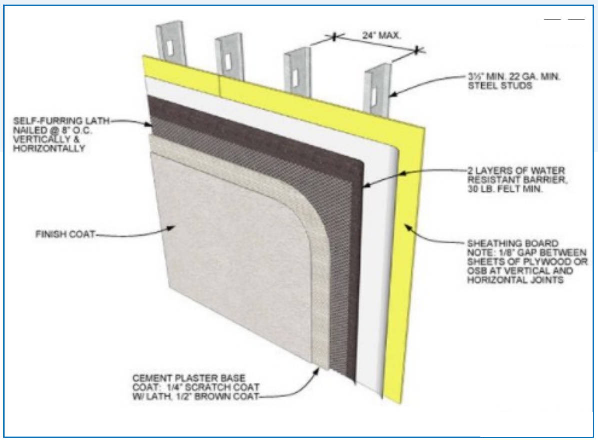


FIGURE 1. Typical Metal-Stud-Framed Wall.

Retrofit rainscreen assemblies consist of four layers to manage air, moisture, heat, and vapor: exterior cladding, cavity/drainage, insulation layer, and an air, water and vapor membrane.

Two types of rainscreens defined by the American Architectural Manufacturers Association (AAMA) include back-drained and pressure-equalized systems (508 2007) (AAMA 509 2009).

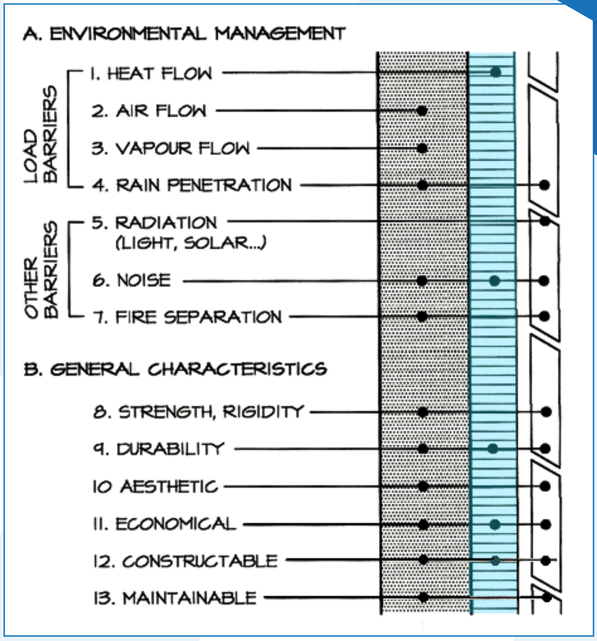


FIGURE 2. Rainscreen control layers (Strube 2019).

This paper aims to analyze these wall assemblies for cost-effective back-drained, ventilated rainscreen system retrofit construction using hygrothermal efficiency and reducing reliance on HVAC systems.

Existing Metal-Framed Wall Assemblies

In its research report (Lstiburek 2010), Building Science highlights the mold and mildew risks linked to cold-formed steel studs with only cavity insulation and no exterior insulation. The US National Energy Code (IECC) offers thermal efficiency guidelines for walls but overlooks interior comfort. While interior wall cavity insulation may meet code requirements, research by BSC (Lstiburek 2010) and DOE (Brennan and Iain 2015) emphasizes the potential for cavity condensation. Unlike mass walls with CMU, cold-formed steel

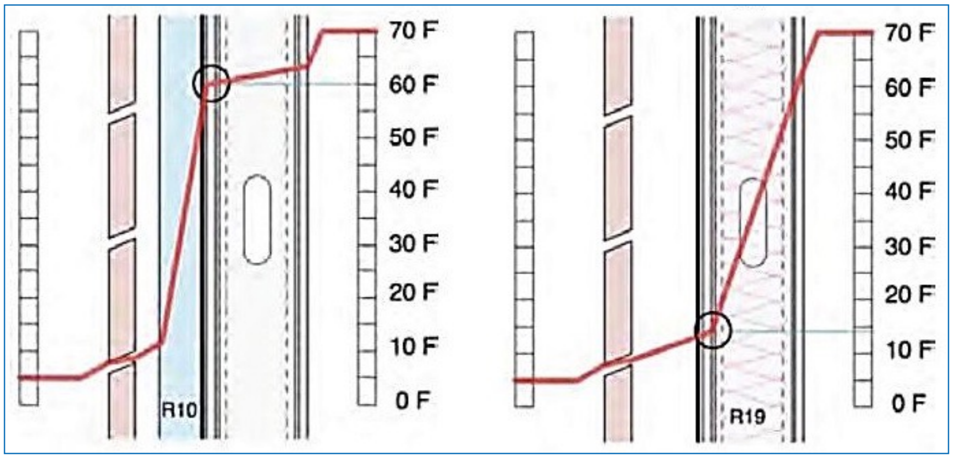


FIGURE 3. Pre- and post-retrofit of CFSS wall with exterior insulation (Lstiburek 2010).

stud (CFSS) walls contain gypsum boards, making them susceptible to mold and mildew growth due to condensation, humidity, and temperature factors. BSC conducted an analysis of the dew point diagram before and after retrofitting this system, as depicted in **Fig. 3**.

Lstiburek suggests that adding exterior continuous insulation to CFSS wall assemblies can mitigate condensation risk within the cavity. However, proper design of insulation thickness and selection of air-/water-resistive barrier are crucial to ensure the assembly's dew point occurs outside the envelope or exterior cavity. Equally critical is designing a ventilated cavity to facilitate continuous drying of the system.

Potential Impact on Sustainable Design

As revealed in the literature review, research gaps exist in previous methodologies. In the US, a significant proportion of commercial buildings use either CMU or CFSS wall assemblies with minimal insulation, contributing to increased energy consumption and operational carbon footprint (Richard Pallaids 2016). Previous studies indicate that incorporating insulation and an air-/water-resistive barrier can substantially enhance energy savings in these buildings. However, these studies do not consider the effectiveness or hygrothermal characteristics of proposed retrofit assemblies.

Energy-efficient retrofits are essential for reducing carbon footprint, provided that adding insulation does not lead to condensation issues. This case study's focus is to develop processes for analyzing typical building wall envelopes and recommending best practices for retrofit assemblies with minimal insulation (while minimizing thermal bridging) and optimal hygrothermal outcomes. These recommendations can guide efforts to minimize the operational and embodied carbon footprint of existing buildings, aligning with the 2030 goals set by DOE.

CASE STUDY OBJECTIVES

- Establish existing thermal benchmark of the existing wall assemblies using 1-D hygrothermal modeling software.
- Investigate smart passive retrofit option(s) to provide cost-effective solutions that will reduce dependency on active retrofits such as HVAC systems.
- Recommend cost-effective retrofit option that will increase overall energy efficiency of the building and reduce risk of condensation within the building envelope.

Methodology Process

A hygrothermal process diagram was developed and proposed by Dr. John Straube (Straube and Schumacher, The Role Of Hygrothermal Modeling in Practical Building 2002) to investigate existing building envelope assemblies. However, this simpler process doesn't benchmark existing conditions and may not be suitable to compare energy and hygrothermal performance. A slight modification of the process outlined by Dr. Straube can be used as a methodology for the objectives of this paper. Figure 4 below shows the proposed process that will be used for decision-making methodology. The process can be divided into three categories with input, simulation, and output.

Sustainable Building Retrofit Evaluation

Initial Assessment

Understanding existing conditions is crucial. Drawing from DOE and Straube methodologies, we will take the following steps.

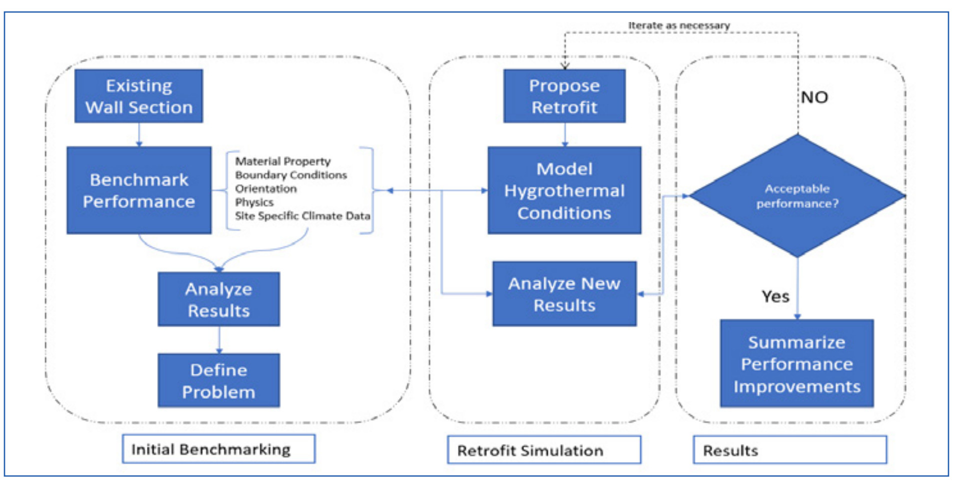
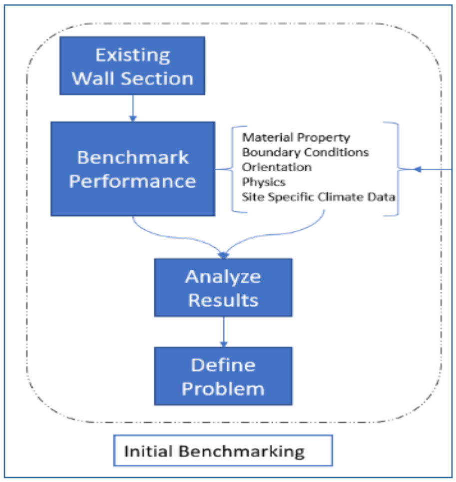


FIGURE 4. Proposed investigation process.



Existing Wall Evaluation:

1. Examine existing wall conditions through on-site investigation, thermal imaging, and reviewing as-built drawings.
2. Consult with occupants and owners to identify issues like water infiltration, vapor problems, hot spots, mold/mildew.
3. Assess available resources—human, budget, and their significance.
4. Establish a timeline for proposed solutions.

Benchmarking Performance:

1. Analyze each part of the exterior wall assembly.
2. Obtain material properties from records or industry documents.
3. Document exterior and interior boundary conditions, considering US market climates (i.e., IECC Climate Zones 1–7).
4. Define enclosure cross sections for modeling with orientation.
5. Identify existing problems such as visible mold, condensation, heat/cold spots.
6. Analyze existing conditions using hygrothermal modeling software.
7. Record and tabulate existing condition results.

Defining the Problem:

1. Understand the benchmarked enclosure's response to condensation under different conditions and consequences of exceeding limits.
2. Verify analysis against visual or destructive investigations (e.g., visible condensation, decay, mold).
3. Project the enclosure's response over time without action, considering energy usage, loss, and structure lifespan.
4. Assess the risk of HAMM (Heat, Air, Moisture-Liquid, Moisture-vapor) issues impacting building life, causing total loss of occupancy, land contamination, waste, and carbon footprint if new construction is needed.

Retrofit Simulation

Established energy flow through the existing building section allows simulating retrofit impact with rainscreen systems. Steps mirror the initial phase but include the proposed rainscreen assembly, rerunning hygrothermal analysis.

Proposed Retrofit

Model existing wall assemblies with different retrofit materials, following rainscreen principles. Redesign for improved energy efficiency, comfort, minimal embodied carbon impact, and resilience to future climate extremes. Refer to **Fig. 5** for proposed retrofit material layers:

1. Implement an air/water barrier with various vapor profiles.
2. Apply exterior continuous insulation (mineral wool) with varying depth to meet code and benchmark requirements.
3. Review structural framing supporting new cladding material for thermal bridging and condensation risk.
4. Add aluminum metal panel cladding for weather protection, emphasizing reusability, resiliency, and potential 50% energy savings.

Reanalysis

Conduct hygrothermal modeling for each retrofit, considering various materials and climates. Evaluate:

1. Performance over 10 years (thermal, condensation risk, resiliency).
2. Lifespan of existing materials before and after retrofit.
3. Added embodied carbon from new materials.

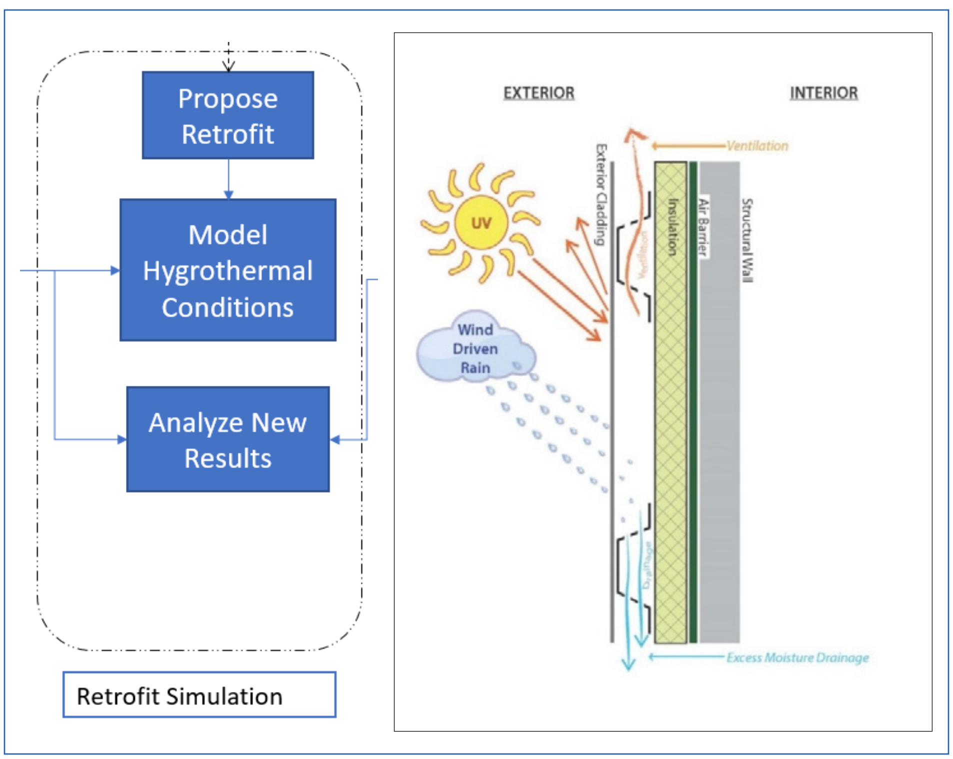


FIGURE 5. Proposed rainscreen retrofit.

Results/Discussion

Hygrothermal modeling results measure retrofit performance against regulatory standards and benchmark improvements. Three categories require assessment (Collins 2018).

Thermal Performance
Review the retrofitted wall assembly's R-value, comparing it to International Energy Conservation Code requirements. Aim for minimal insulation to reduce embodied carbon by mitigating thermal bridging.

Air and Water Infiltration
Evaluate air changes per hour (ACH) to gauge drying potential. Enhance airtightness with an exterior air barrier to reduce energy loss due to infiltration.

Total Embodied Carbon
Assess the total embodied carbon of existing cladding post-retrofit, considering life cycle analysis (LCA) of building materials. Detailed embodied carbon evaluation for each retrofit isn't covered, but preliminary research suggests the proposed retrofit has the least global warming potential.

In summary, this paper's procedures and tools demonstrate building cladding retrofit effectiveness. Smart retrofit methods can extend existing building life and apply to most US commercial building wall systems, offering a sustainable guide tailored to climate zones.

PROJECT NAME: SUZANNE M. SMITH SCHOOL, 169 S LEVANT RD, LEVANT, ME 04456

Suzanne M. Smith School, ME, has proceeded with multiple wall assembly repairs. Improvements have been made over the preceding three years to replace rotting siding and repair areas of rotting sheathing. Constructed around 1998, the structure was built with multiple building materials, including wood siding and brick using metal studs, and has a standing-seam metal roof. For the purposes of this study, we are focusing on the wall assemblies utilizing wood siding on the exterior.

Initial Benchmark/Current Issues

Based on the field report, the following observations and issues were noted:

- A large percentage of siding is deteriorating.
- Areas around penetrations and perimeters showed signs of extreme rotting.
- The sections of trim were rotten, allowing facers to peel away.
- Areas behind the siding and building wrap showed signs of organic growth and rust (fasteners and washers/plates).

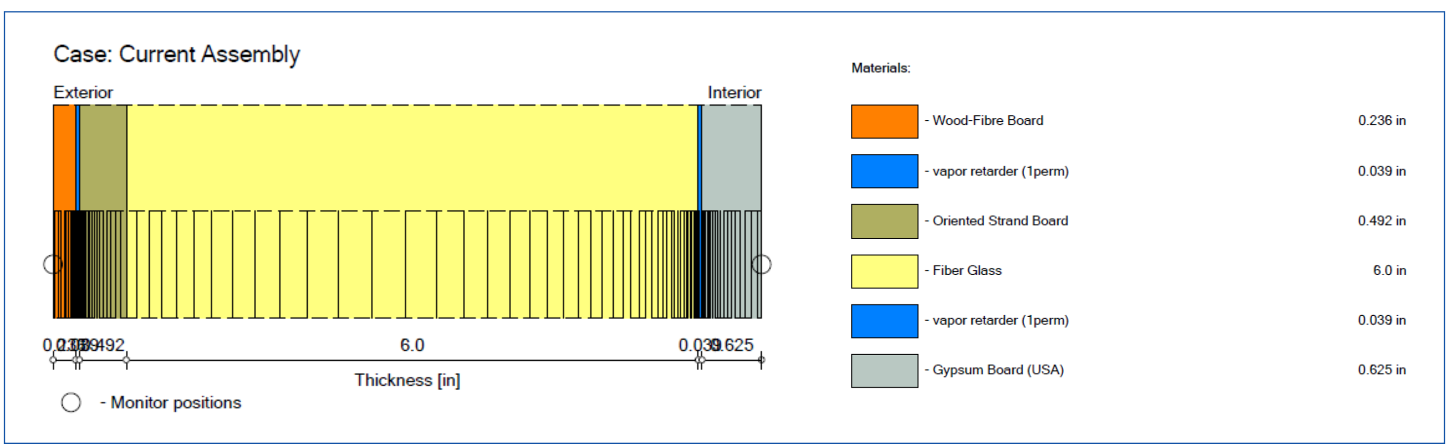
The owner has indicated that the plan was to demo the existing building completely and replace the whole building with new construction. This requires multiple years of planning, design, and disruption to the occupants. As an alternative, a revive and reclad plan was developed that would investigate the root cause of building deterioration. The scope of work would be as follows:

- Investigate and analyze existing wall assembly.
- Model existing wall assembly and simulate for the past 26 (from 1998 to 2024) years of use under normal climate condition. This will give us the results needed to compare the simulation to actual field condition and finalize the boundary condition inputs.
- Based on initial results, summarize the root causes of condensation and energy loss.
- Provide sustainable rainscreen facade retrofit that can mitigate current condensation causes and improve thermal efficiency of the overall building envelope.
- Summarize overall project scope without extensive demolition to existing building.

Hygrothermal Model of Suzanne M. Smith Elementary School (1998–2024)

Existing wall assembly construction (from inside to the exterior): interior gypsum board, vapor retarder, wood studs with fiberglass insulation infill, exterior OSB sheathing, vapor retarder and wood fiber board cladding. The assembly in this case was modeled using WUFI for the period of 1998 through 2024. The input for each of the materials used was based on ASHRAE properties. The following initial inputs were used.

(See graph below.)



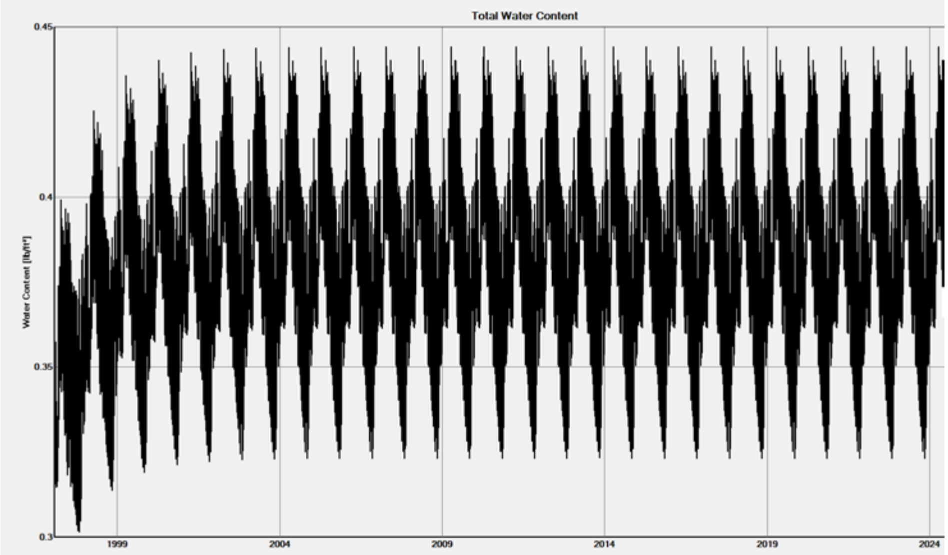


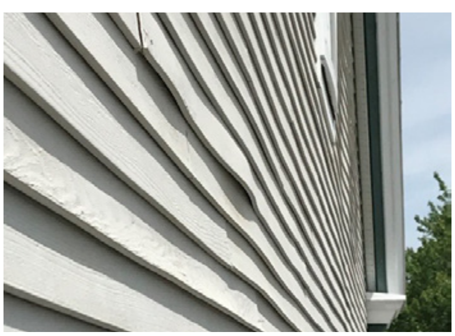
FIGURE 6. Existing condition: moisture buildup, year over year.

Mildew found on the surface of the OSB sheathing behind the building wrap.

Rusting nail head behind the building wrap.

High moisture content within the siding trim.

High moisture content within the siding trim.



Warped and wavy siding from high moisture content. A large percentage of siding looks like this around the building.

High moisture content within the siding trim.

FIGURE 7. Existing Condition, moisture reading of cladding assembly.

Climate Data: The closet climate data to Levant, ME, was used for boundary conditions. The interior conditions were simulated per WTA guidelines as noted in ASHRAE 160 guidelines. Based on the weather rose (most exposed and severe wall), the north-east wall was used for modeling.

Discussion of the Outcome: The model was simulated from 1/1/1998 through 1/1/2024 for existing condition (as is). The result of the simulation shows that the overall water content in the envelope (year over year) increased (water content vs. time graph shown in **Fig. 6**). This finding from the simulation collaborates with the site investigation evidence, and the moisture reading taken (**Fig. 7**). Some of the exterior cladding shows extensive warping and interior structural damage.

For healthy buildings, wall envelope materials should decrease in moisture content after construction and should stabilize. However, this building's current construction traps moisture within the cavity. The amount of moisture trapped is alarming. Per **Fig. 8**: The clapboard moisture content is almost 5 lb/ft³ and the exterior OSB moisture content is almost 8 lb/ft³, which exceeds the materials life span (as was evident from the inspection) and has become a structural concern and air quality hazard.

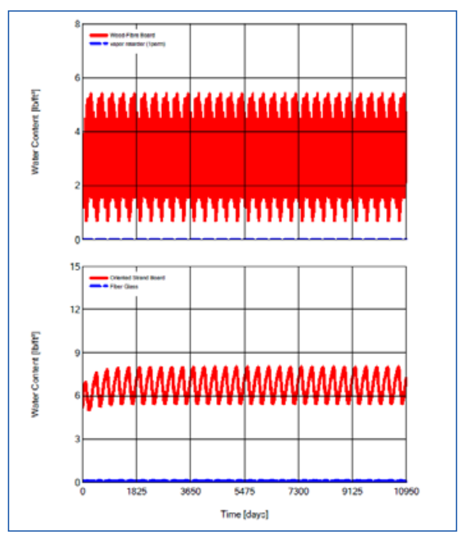


FIGURE 8. Existing OSB and cladding moisture content.

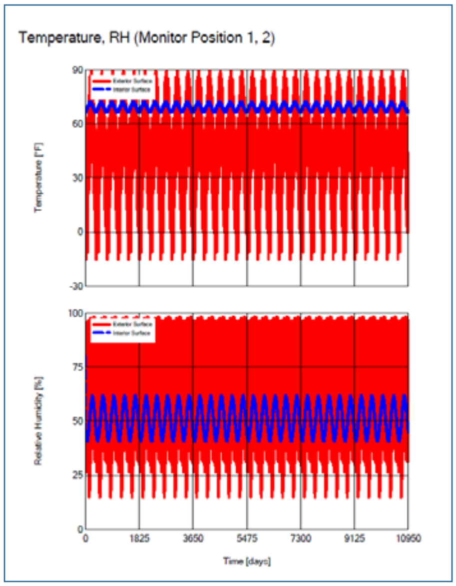


FIGURE 9. Existing assembly: relative humidity and temperature.

Additionally, with high relative humidity and high temperatures at the exterior sheathing (**Fig. 9**), the potential for mold/mildew growth is extremely high. The Isopleths graph (Appendix B) points at the exterior OSB shows high probability of mold growth as the building reaches levels that both ASHRAE and the EPA list as high potential for mold growth. The inspection of these areas (**Fig. 10**) shows great mold and mildew growth, confirming the simulation.

Existing Assembly Summary

As noted through simulation and site inspection, the current wall assembly as is has suffered significant deterioration. If nothing is done, the simulation projects high risk of continued deterioration that could result in structural deficiency through rotting, major indoor air quality issues through mold/mildew growth, and higher loss of energy (energy consumption will keep going up as materials deteriorate).

Proposed Smart Retrofit

To mitigate and correct the deficiencies, a rainscreen wall assembly is recommended and will require removing all clapboard siding, trim, and building wrap to expose the OSB sheathing. All areas of sheathing showing rot and mold growth will be removed and replaced in kind. Any areas of framing and wall insulation that are wet and deteriorated will be replaced in kind. A vapor-permeable self-adhered air barrier will be installed directly to the sheathing and manufacturer-approved flashing tapes and sealants will be installed to create a complete air barrier. It is recommended that the air barrier is inspected by a third party to approve in writing its condition before any additional work can be performed. Over the air barrier a 2 in. layer of mineral wool rigid board insulation will be fastened to the sheathing as well as a vented hat channel installed horizontally. Twenty-four-gauge steel siding will be installed to the vented hat channels with air vents at all sill and head details to allow for air movement between the cladding and insulation to promote seasonal drying as needed.

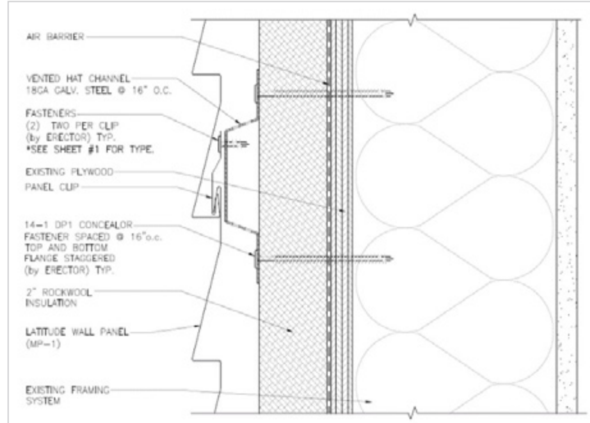


FIGURE 11. Proposed smart retrofit assembly.

This high moisture reading was taken in an area that was replaced in 2021. The reading was taken in 2019 at the trim and the photo to the right shows the condition of the sheathing behind the air barrier that was uncovered prior to a new rainscreen wall assembly system being installed.

A large percentage of sheathing was rotten and had mold growth from high moisture content stemming from the wall assembly. Additionally, insulation within multiple bays and some wall studs was wet and saturated. This wall assembly is the same as the rest of the school.

FIGURE 10. Existing Condition, moisture reading of cladding assembly.

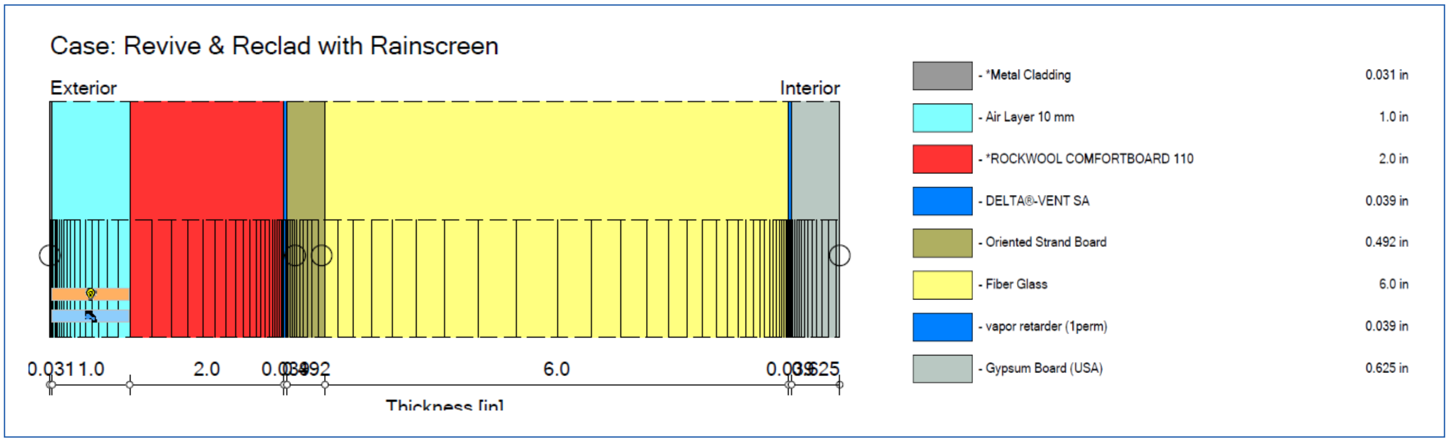
Hygrothermal Analysis of Proposed Retrofit System

Using the above proposed retrofit wall assembly, numerous WUFI models were run to project the condition of the assembly for the next decade. ASHRAE building material properties were used for retrofitting assembly in the model. The assembly is noted as follows:

(See graph at the top of page 19.)

Climate Data: The closet climate data like Levant, ME, was used for boundary conditions. The interior conditions were simulated per WTA guidelines as noted in ASHRAE 160 guidelines. Based on the weather rose (most exposed and severe wall), the northeast wall was used for modeling.

Discussion of the Outcome: Based on running the model from 1/1/2021 thru 1/1/2031 with the addition of new AWB, insulation, vented cavity, and panels: the simulation shows that the



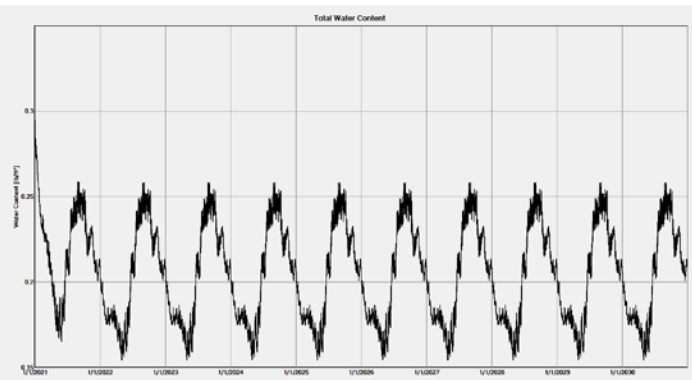


FIGURE 12. Retrofit: total water content.

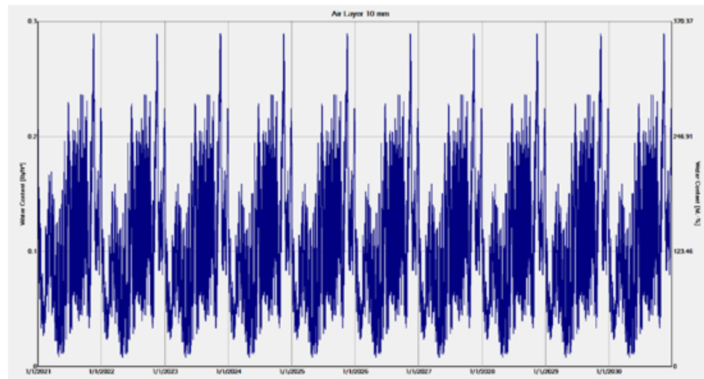


FIGURE 13. Retrofit vented cavity moisture capacity.

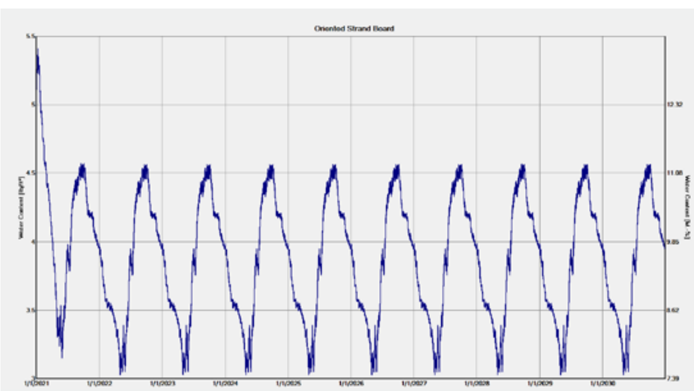


FIGURE 14. Retrofit Solution: Water content in OSB in 10 years.

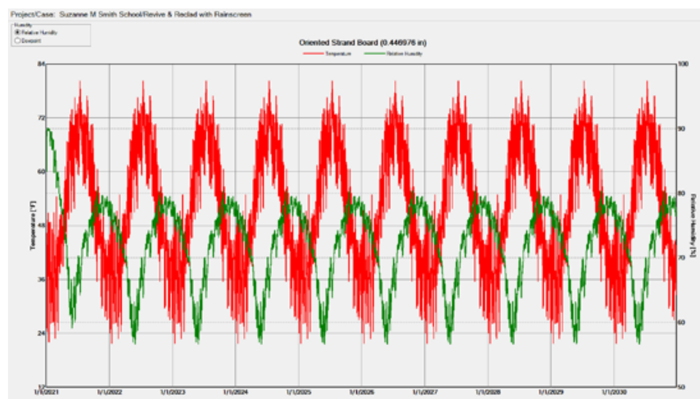


FIGURE 15. Retrofit relative humidity and temperature over 10 years.

overall water content in the envelope (year over year) decreases or stabilizes at an amount that doesn't exceed the hygric capacity of the materials. The building envelope with the proposed rainscreen system dries down to around 0.25 lb/ft³ and reaches equilibrium. It is important to understand that building wall assemblies will never dry out to zero and that the goal is to keep vapor/moisture to a point which doesn't damage/rot the materials within the assembly. The projected water content in the assembly is an acceptable amount to achieve this objective. Further, maximum moisture content is projected to be contained within the vented cavity. (**Fig. 13**), allowing the existing assembly to dry out. With the addition of exterior insulation and a vapor permeable AWB, the exterior OSB drastically dries out jumping down from 5.5 lb/ft³ to almost 2.5 lb/ft³ and stabilizing at 4.5 lb/ft³. Year over year through various seasons, the OSB can dry out and not exceed its hygric capacity (**Fig. 14**). Based on these projections the proposed retrofit will allow the assembly to minimize moisture retention and retain structural integrity of the wall framing system.

Per ASHRAE guideline 160 and EPA, there is a high probability of mold/mildew growth when relative humidity is above 90% and temp is above 80°F. The proposed retrofit decreases the risk of mold growth significantly. According to the WUFI projections shown, the inside of the exterior OSB monitor shows that as the temperature rises, the relative humidity goes down, creating an adverse environment for any kind of biological growth.

SUMMARY OF RETROFIT SOLUTION

The proposed smart rainscreen solution is projected to meet the goals outlined by the owner of the project. Based on the modeling:

- It is projected that the overall building will not require complete demolition and reconstruction. The added assembly mounted to the existing wall will allow the existing condition to dry out over time.
- The retrofit solution provides an increased effective median R-value of 36 compared to an R-value of 26 for the existing assembly. This is an increase of almost 38% in energy efficiency of the wall system, which could lead to a lower energy bill and carbon footprint.
- The air circulation in the vented cavity continuously removes moisture from the interior of the wall assembly, thus lowering the relative humidity and the risk of mold/mildew growth.

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Integrated Enclosure Detailing at the BIDMC New Inpatient Building

ABSTRACT

The new Beth Israel Deaconess Medical Center (BIDMC) Inpatient Building was designed and constructed from 2017 through 2023; the project includes development of a new 12-story hospital totaling about 384,000 ft2. The building facade includes a mixture of unitized and stick-built curtainwall, terra-cotta cladding, and metal panels, and it includes various locations of low-slope membrane roofing and a large green roof plaza treated with fluid-applied waterproofing. The building abuts and connects to an existing hospital building. This presentation will explore the challenges and design considerations for a new modern clinical hospital building within the city, including waterproofing over highly sensitive spaces, expansion joint detailing to adjacent existing unitized construction, and new unitized curtainwall detailing. We will discuss the marriage between the architectural design and the envelope detailing, as well as constructability challenges throughout the project.

LEARNING OBJECTIVES

- Understand considerations for waterproofing over a highly sensitive space.
- Discuss challenges associated with integrating expansion joints from new to existing buildings.
- Learn about considerations for unitized and stick-built curtainwall construction.
- Understand the relationship between the architectural design and envelope detailing.

SPEAKERS

Jensen Ying, AIA, LEED AP BD+C
Senior Associate, Payette, Boston, Massachusetts

Jensen Ying, AIA, LEED AP BD+C, joined Payette in 2013 and has over 10 years of experience in large-scale lab and healthcare projects, including specializing in exterior shell and core design. He has a growing knowledge of the design, analysis, and detailing of highly complex enclosure systems. His experience includes complex parametric facade sun shading systems, unitized and stick-built systems, and masonry rainscreens. He was instrumental in the design and execution of the Northeastern University ISEC building and the Beth Israel Deaconess Medical Center's new Klarman Building.

Mary Arntzen, PE
Senior Project Manager, Simpson Gumpertz & Heger Inc., Waltham, Massachusetts

Mary Arntzen, PE, joined Simpson Gumpertz & Heger Inc. (SGH) in 2015 after several years of providing project and field engineering services in the construction industry. At SGH, she is frequently involved in designing, investigating, and rehabilitating building-enclosure systems, and has served as the project manager for various large and complex projects, often working directly with owners, architects, construction managers, and developer clients. She has extensive experience reviewing glass-and-metal curtainwall systems, windows, roofing, plaza waterproofing, cladding, and below-grade waterproofing systems. She is a board member of the IIBEC New England Chapter.

AUTHORS:
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1.0 GENERAL

The new BIDMC Inpatient Building in Boston, MA (**Fig. 1**), was designed and constructed from 2017 through 2023; the project included development of a new 12-story hospital totaling approximately 384,000 ft^2. Payette Associates served as the architect of record for the building, and Simpson Gumpertz & Heger Inc. (SGH) served as the building enclosure consultant and structural engineer. This paper will present some of the challenges and design considerations for the design and construction of this new modern clinical hospital building.

The building facade includes a mixture of unitized and stick-built curtainwall and terra-cotta and metal panel rainscreen cladding. There are several levels of low-slope membrane roofing and a large green roof terrace. One of the major features of the building design is that the building abuts and connects to an existing operational hospital building, leading to the need to integrate the new envelope with the existing building envelope while the existing building remained in full use and operation.

FIGURE 1. View of Completed BIDMC Inpatient Building – *Credit Robert Benson.*

With a large and complex building with many moving parts, the team aimed to break down the facade and roofing elements into various sections during both the design and construction process. While there were several different conditions that were explored and detailed at the facade, this paper will highlight the integrated detailing at three major elements of the building that connect to one another (**Fig. 2**):

- Level 6 Healing Garden terrace (**white arrows; Fig 2**)
- Expansion joints between the new and existing building (**purple line; Fig 2**)
- Connector facade "fly-by" (**red line; Fig 2**)

This paper will aim to describe some of the major considerations that drove design and construction decisions for the above elements.

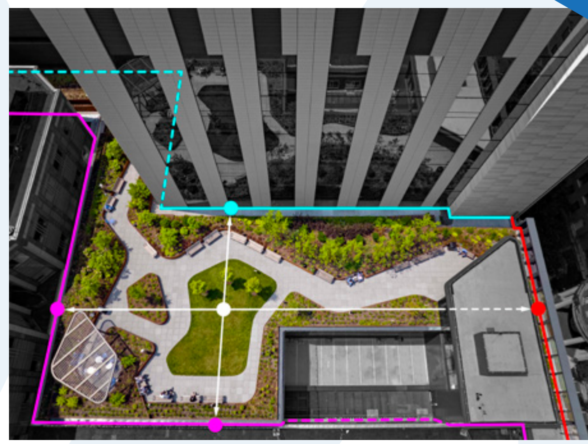

FIGURE 2. Overall View of Healing Garden, Expansion Joints, and Connector – *Credit Payette Associates and Robert Benson.*

Building Massing & Programmatic Constraints

The project site is situated in the western region of the Longwood Medical Area (LMA), on Beth Israel's west-side campus. Just in view of the institution's west-side campus lies the Muddy River and Riverway greenway. This area separates Boston from Brookline but also serves as a link within a larger chain of parks and waterways called the Boston Emerald Necklace. Naturally, the views provided by the Emerald Necklace would be a key driver in the siting, massing, programming, and to the orientation of the new inpatient tower.

The new inpatient building is constructed on a brownfield site, sharing its parcel directly adjacent to the institution's existing inpatient hospital with a 24-hour emergency department (ED). The existing ED is a single-story structure that projects from the L-shaped footprint of the hospital with an array of outdoor ambulance parking bays. Interruption of the ED's operations and services would be a nonstarter to the enabling and construction of the new inpatient tower. Therefore, the new building's design had to effectively utilize the area between the new inpatient tower and the

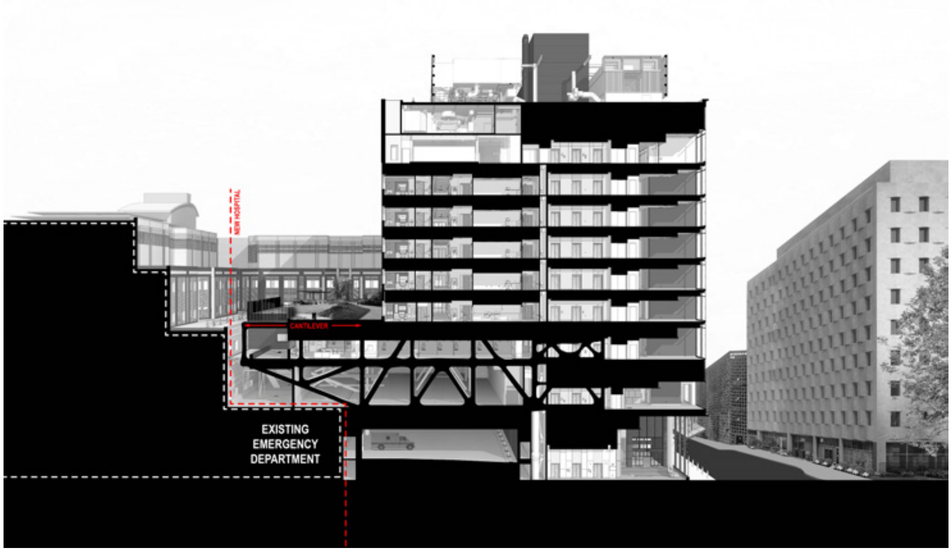

FIGURE 3. Overall Section Showing Building Cantilever – *Credit Payette Associates*.

existing ED while minimizing impact. The resultant design called for a cantilevered portion of the new radiology (Level 3) and perioperative (Level 5) floors over the existing ED roof (**Fig. 3**). The roof of the perioperative floor (Level 6) hosts the new roof garden. In addition, two floors of elevated connector corridors were laminated across the north face of the new inpatient building as well as the existing hospital. These "sky bridges" integrated the imaging and perioperative programs of the new hospital with the existing network of services provided in the west campus. At the head of the Level 5 connector was a fly-by curtainwall screen designed as a fall deterrent and to serve as a wind screen for the garden. Integrating the waterproofing in a manner that would maintain the connector design to read as a seamless plane of glass was another task that involved various iterative design study.

The Healing Garden, an outdoor terrace available for staff and patients, created conditions in which waterproofing was of utmost importance—for performance and aesthetic reasons. Proper waterproofing over sensitive spaces, such as operating rooms, was vital to the project's success and longevity. In addition, the areas along the perimeter of the roof garden abutted the facades of the existing hospital. These facades, built in the early 1990s, varied in their systems and construction. As a result, extensive exploratory work was conducted as well as the subsequent waterproofing measures. Many of these measures will be discussed in this paper.

General Project Delivery: Design Assist & Collaboration

The project delivery utilized a design-assist process where the architect, facade contractor, envelope consultant, and structural engineer collaborated during the design development phase to review and discuss detailing early on while the project design was still in development. The goal of this process was to help guide the design of the facade in conjunction with the architectural design intent as well as the relevant structural and envelope conditions at these locations.

This process allowed for the architect, envelope consultant, structural engineer, and facade installer to meet approximately 10 times during the design phase to discuss the sections of facade and determine the required detailing at each location. In particular, the process included the following:

- Decisions between unitized and stick-built facade systems
- Understanding of required structural support and design tolerances for facade elements
- Development of thermal models for typical facade conditions
- Coordination between roofing and waterproofing element detailing and adjacent facade items
- Review of major cost and trade coordination items

The team also incorporated an enclosure commissioning process to meet LEED v4 BD+C Healthcare. The commissioning process identified the performance goals for the project (target thermal performance, relevant air and weatherproofing metrics, etc.) and implemented a quality control process during the project to perform and document testing as well as in-place mock-ups. The project design-assist process, enclosure commissioning, and testing protocol all helped the team to achieve the complex architectural exterior expression, select appropriate system types, design the desired high-performance envelope, and integrate the new systems across the facade.

1.1 WATERPROOFING CONDITIONS

Level 6 Healing Garden Terrace

One of the major project components is the Level 6 Healing Garden, which includes a vegetative ("green") roof and paver walkways over the waterproofed composite concrete deck. The Healing Garden serves as both an extension of nature into the hospital, drawing its inspiration from the adjacent Emerald Necklace Riverway, as well as a node of respite for both patients and staff in the new inpatient building. The Healing Garden is placed directly over the operating rooms of the new hospital building, which is a space highly sensitive to water and air penetration; this area required a high level of attention to the selected materials and detailing.

During the design phase, the team reviewed this area with the goal of selecting the most robust waterproofing system, appropriately detailing the conditions between said waterproofing system with adjacent waterproofing systems

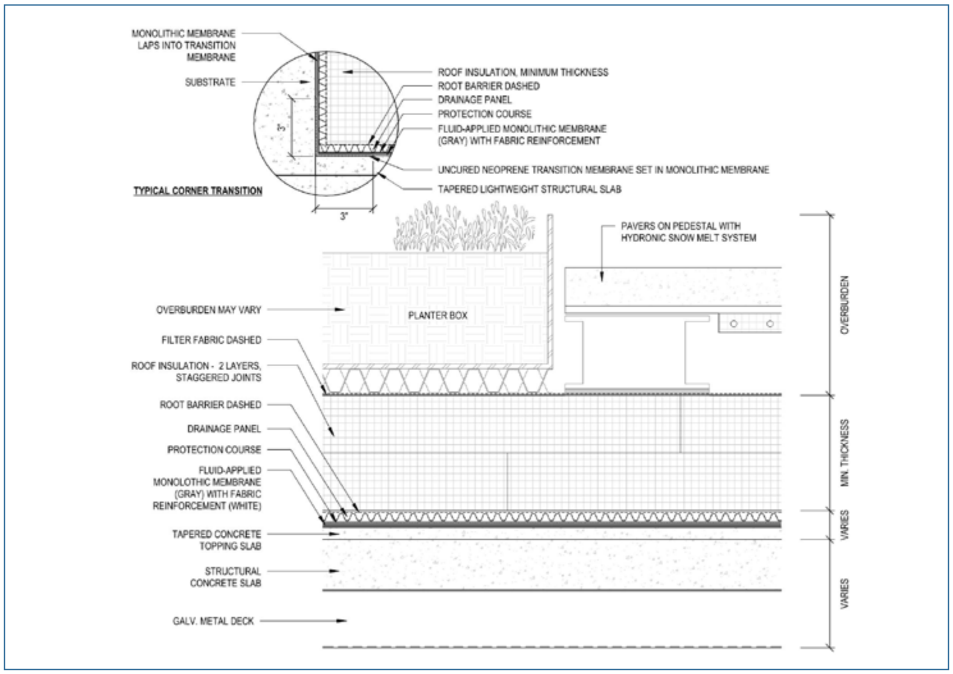

FIGURE 4. HRA Waterproofing Section Detail – *Credit Payette Associates.*

and coordinating the selected waterproofing system with adjacent rising wall and facade conditions. The team discussed the possibility of a conventional membrane roofing option in this space versus a protected membrane system with fluid-applied waterproofing. Ultimately, the team decided an inverted roofing membrane assembly (IRMA) with fully reinforced hot fluid-applied waterproofing (HRA) placed directly onto the concrete slab would be more appropriate and robust than a single-ply conventional roofing system due to the potential for damage from the large amount of materials and overburden above (**Fig. 4**). During the design-assist process, the construction team raised concerns about odors from a fluid-applied waterproofing assembly impacting hospital operations at the existing active hospital directly adjacent to this space; the team included odor-mitigating measures in the project specifications (such as odor-mitigating additives and filters at all intakes and penetrations) to limit odor impact on the adjacent building.

While the project team had success utilizing fully reinforced hot-applied rubberized asphalt waterproofing, during the construction phase, the owner and construction team expressed the desire to improve the durability of the waterproofing assembly further. The team elected to reinforce the hot-applied waterproofing with two layers of fabric reinforcing (and three layers of waterproofing encasing the fabric) to increase the assembly thickness and improve the overall durability of the system (**Fig. 5**). The team also considered a permanent electronic leak-detection monitoring system incorporated into the assembly; this was not incorporated into the design, as it would be placed directly above the waterproofing assembly in the wet zone, and the team was unsure how successful this application would be for this project.

Due to the space programming, the Level 6 terrace is placed directly above an approximately 62 ft. cantilevered truss structure with concrete slabs. This cantilever condition is sensitive to additional weight and deflection considerations. The structural engineer worked closely with the envelope consultant, architect, and construction team to discuss the expected deflection and weight requirements. The waterproofing needed to be coordinated with the structure prior to installation; while the team intended to incorporate some slope into the terrace, the additional build-up of concrete topping was limited due to weight considerations. Prior to waterproofing installation, the team reviewed the concrete deck for locations of potential low spots and ponding water and addressed these prior to waterproofing installation.

FIGURE 5. HRA Installation in Progress – *Credit Jensen Ying.*

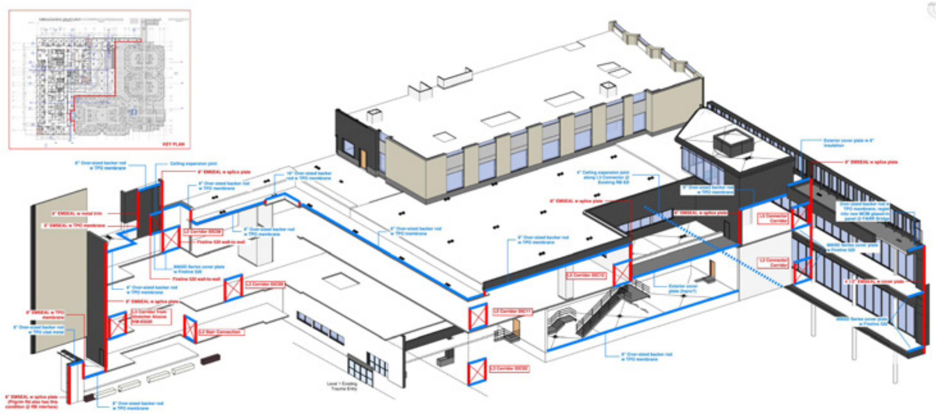

FIGURE 6. Diagram of Building Expansion Joints – *Credit Payette Associates.*

Since the system was reinforced with an extra layer of reinforcing fabric and waterproofing, the installation took longer and the installer installed a smaller area of waterproofing per day than in a typical project which created some initial challenges in making sure all layers were installed in one day. The team incorporated on-site third-party review of the waterproofing during the initial first week of installation and throughout the installation process. Due to the weight concerns noted above, the concrete slab was formed from lightweight concrete; the team waited at least 60 days after slab placement to install the waterproofing and tested various locations for moisture prior to installation. The team also incorporated regular adhesion testing of the waterproofing throughout the process.

After installation was complete, the construction manager anticipated that there would be a large amount of foot traffic, equipment, and other materials over the top surface of the waterproofing. The system was protected with several layers of plywood and insulation after installation. Prior to overburden placement, the system successfully underwent flood testing and electronic leak-detection testing.

Sections below will explain additional considerations for integration with the HRA assembly and the adjacent systems.

Expansion Joints and Integration with Existing Building

The Healing Garden, as well as the Level 6 roofing spaces, connect and integrate with the existing adjacent building. Expansion joints are often needed where new buildings connect to existing structures to accommodate movement between the two buildings; expansion joints also need to integrate the air and weather barrier between the new and existing buildings to create a weathertight transition. The BIDMC New Inpatient Building incorporated complex expansion joints that jogged across several floor levels, in and out across the roofing areas, and across several different building envelope systems **(Fig. 6**).

The project included an investigation phase to review the existing conditions at the adjacent building. While initial test cuts revealed that some areas of the existing building included a weather barrier over stud-framed structure that could be integrated with the new roofing, other exploratory openings revealed an existing unitized wall construction with granite cladding over aluminum rails with a metal backpan as the air barrier (**Fig. 7**). It is critical to understand where the air and water lines exist on the existing facade to understand where to tie new waterproofing assemblies into, and to understand where drainage may occur. The existing unitized facade appeared to rely primarily on the sealed granite facade as the barrier for the facade, though there appeared to be occasional drainage provisions (through-wall flashings at some levels below where the new roofing would integrate, etc.).

The original design included detailing that integrated the new waterproofing and roofing materials with the (assumed) air barrier behind the existing building facade, and a new through-wall flashing above. Once the exploratory phase unveiled a unitized facade at some locations, the original detailing became challenging to implement. The team

FIGURE 7. Existing Unitized Curtain Wall and Glazed in Granite Panels – *Credit Jensen Ying.*

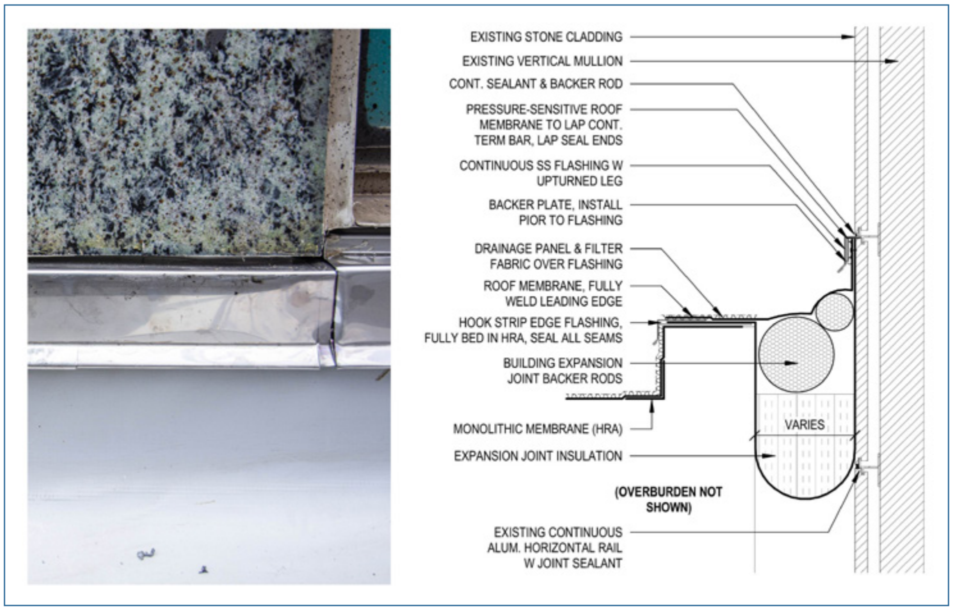

FIGURE 8. Typical Building Expansion Joint Details at Granite – *Credit Payette Associates.*

discussed various options for tying in with the expansion joint, which ranged from complete removal and modification of the existing facade to surface sealing new materials to existing materials. Complete removal would require substantial investigation and alterations of the existing structure and disruptions to the existing hospital across several floor levels. Surface sealing the waterproofing system to the adjacent structure did not provide the reliability and performance the team desired. Ultimately, the team discussed an option of providing some water management at the existing facade via new reglet-set stainless steel flashings by integrating the new expansion joint system into the granite face of the facade (**Fig. 8**). At locations where there was a back-up wall and air barrier at the existing facade, a through-wall flashing was incorporated and integrated with the new assembly. While the team was able to develop a detail for integrating the two systems, the project team was concerned about especially sensitive areas beneath some portions of the expansion joint; therefore, the project incorporated a sheet metal gutter at the interior as a secondary means of water management should some water bypass the expansion joint tie-in.

The team discussed options for integrating the existing facade with the hot-applied rubberized asphalt waterproofing assembly at the Level 6 terrace. The team reviewed the locations where the existing building would interface with the new facade; the expansion is accommodated at locations between new and existing structure and included jogs across different floor levels and different envelope systems. The team discussed options between field-fabricated expansion joints and shop-fabricated joints. Given the extensive changes in conditions across the site and the expected movement, a field-fabricated expansion joint formed from TPO roofing membrane was deemed most appropriate to accommodate the variations in the existing facade. The integration between the TPO expansion joint and the adjacent HRA occurred via a curb present across the Healing Garden and existing building roof, which included foil-faced membrane to provide a transition layer between the HRA and the roofing membrane (**Fig. 9**). The TPO material could integrate with the TPO roofing assemblies at other locations and with the silicone sheet at glazing assemblies. The field-formed expansion joint was designed to accommodate the required movement while also promoting drainage via a metal flashing above. The team reviewed these conditions on various dates after installation to inspect for locations of leakage/discontinuities, and the final condition was successful in providing a weathertight assembly.

1.2 EXTERIOR FACADE

The exterior facade detailing had to be integrated successfully with the expansion joint and waterproofing conditions noted above, particularly at the connector facade. This section includes some considerations for the typical facade areas abutting the Level 6 Healing Garden.

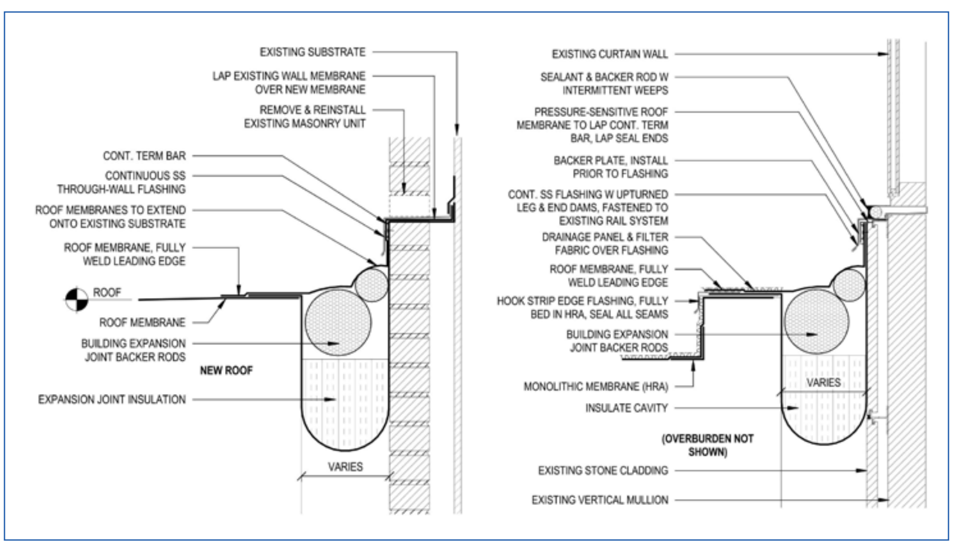

FIGURE 9. Typical Building Expansion Joint Details – *Credit Payette Associates.*

Typical System Considerations

During the design-assist phase, the team discussed options between unitized and stick-built curtainwall systems for the facade. The type of system selected would ultimately affect the detailing and integration with the adjacent systems. Unitized facade systems presented an opportunity to reduce construction schedule for the facade (improving time to close up the building and make it watertight), allow for a higher level of quality control in the fabrication shop (rather than sealing joinery on site), and less storage of materials on site. Stick-built systems could be used for localized areas of ribbon curtainwall where there was less need for unitization since it was localized with less repeatable conditions.

A hospital space can include higher relative humidity at some interior spaces, particularly at operating rooms. The project team reviewed thermal models early on to review the expected surface temperatures for critical details to confirm performance was coordinated with expected interior conditions. The team also largely placed areas with high relative humidity within the interior footprint of the building (i.e., not along exterior walls) to help reduce the risk for condensation.

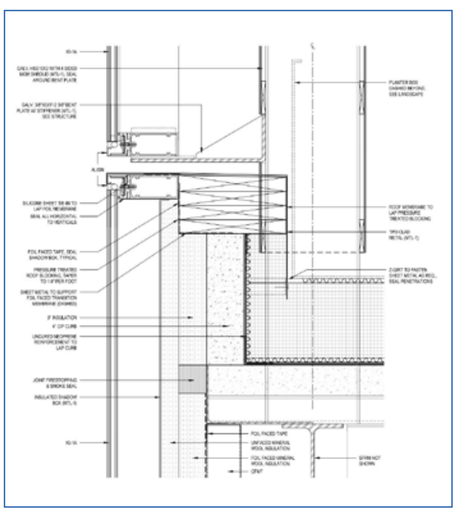

FIGURE 10. Section Detail at Fly-By Curtain Wall – *Credit Payette Associates.*

Connector Facade "Fly-By"

The connector system connects the new inpatient building to the existing adjacent building. The connector system includes a unitized curtainwall system that extends up to the Level 6 Healing Garden and "flies by" the slab, creating a condition that needs to be reliably sealed and waterproofed, and integrated with the adjacent waterproofing at the Healing Garden.

When a curtainwall assembly extends past a slab, there are several ways that this can be detailed. The team determined that the most reliable detail for this condition would be to totally separate the curtainwall that extends above the roof slab from the curtainwall system below. This allows for the system above the slab to be exposed without leading to a thermal bridge to the system below and allows for the waterproofing to be made continuous over the lower portion of the curtainwall before the curtainwall above is placed. This is achieved by structural column support penetrations through the roof that have structural elements that support the curtainwall system above the roof slab (**Fig. 10**).

The lower section of curtainwall terminates just above the roof level. There is a parapet/curb inboard of the curtainwall that is insulated and waterproofed. The waterproofing is integrated with the top of the curtainwall via a silicone sheet product, which is capped off by a sheet metal coping. This detailing needed to be sequenced and coordinated with the adjacent Level 6 waterproofing so that it could be completed prior to installation of the curtainwall above.

This section of facade is made more complex by the fact that it is bisected by a vertical facade expansion joint, as a portion of the connector is supported off the existing building structure and the other portion is supported off the new building structure. The facade systems incorporated a silicone sheet expansion joint that integrated with the waterproofing at the terrace. Similar to the systems noted above, a field-fabricated TPO expansion joint was utilized at the horizontal portions of the expansion joint and integrated with the silicone sheet at the vertical portions and utilizing double mullions.

This section of facade and waterproofing illustrates the need to understand movement capabilities of different materials, identify coordination between adjacent materials, and provide a reliable termination of facade conditions that extend past the roofing assemblies.

Performance Testing

Projects can incorporate performance testing into a free-standing performance mock-up prior to the start of construction, or testing can be done on the building ("in-situ" testing). It would have been challenging to incorporate all of the various facade systems into an off-site mock-up, and at a large cost to the project. The systems being used in the project were assemblies that were not custom and had been tested on previous projects as well. Instead, the team pursued in-situ testing of each facade system, early on in the construction process, to confirm actual performance. The team reviewed various on-site mock-ups of first installations of the facade systems, and reviewed fabrication of the unitized system at the fabricators shop.

Performance testing included a mixture of chamber (ASTM E1105) testing and nozzle (AAMA 501.2) testing and was performed on the typical facade systems. The project team coordinated the sequencing of the facade so that systems were tested as early on as was feasible during the installation process. This testing was overseen and performed by third-party testing companies and helped the team to confirm actual installed performance. The combination of on-site mock-ups and testing allowed the project team to work through some of the challenging conditions on the facade.

1.3 CONCLUSION

Detailing of a complex new hospital building requires a collaborative team effort to identify major systems and potential challenging items early on. Some considerations for complex buildings such as these include the following:

- Target high-performance materials to use in the primary enclosure systems and ensure continuity and integration across adjacent systems.
- Review sensitive interior-space locations and conditions above and adjacent to these locations.
- Coordination is needed between the structure, enclosure, and aesthetic design goals early on, particularly at waterproofed terrace assemblies.
- Waterproofed terrace assemblies need to consider design tolerances, movement, drainage, material type, and overburden above.
- A design-assist process can help the team to collaborate, particularly with the relevant facade subcontractors. Encourage detailing across different systems (between facades and waterproofing systems, etc.).
- Incorporate mock-ups and performance testing to confirm expected performance. Test early on during the construction schedule. If in-situ testing and on-building mock-ups will be the accepted path, then there should be the understanding with the owner, architect, and all trades that the process may lead to the need to make modifications to future fabrication/details.

Ultimately, the project required a hands-on design and construction team that was collaborative and all pursuing the same goal of a high-performance enclosure to ensure the design and performance goals were met.

Dimension Stone Testing and Evaluation—The What, Why, When, and Where

ABSTRACT

Dimension stone is frequently specified and used in our built world as exterior wall cladding, interior wall cladding, paving, and flooring. To ensure the expectations of performance are met, standardized testing for compliance with minimum physical properties, to assess durability, and to estimate in-service capacities for stone assemblies is routinely specified. Testing can not only ensure quality but also guide designers with respect to appropriateness of use and detailing considerations such as anchor types and stone thickness. Various ASTM International standardized testing procedures for stone products will be described and discussed, along with suggested testing regimens for each stage of the building process.

LEARNING OBJECTIVES

- Review which testing standards are most appropriate to each application .
- Discuss which testing standards are most appropriate to each application .
- Specify appropriate stone testing by the phase of the construction.
- Describe new stone testing standards that are under development and their purposes.
- Determine if a particular stone type complies with the appropriate ASTM stone specifications.

SPEAKERS

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Natural stone is recognized and used as a construction material throughout our built world because of its visual and textural diversity, timeless beauty, sense of permanence, and association with quality. Design professionals (including architects, landscape architects, and interior designers) rely on natural stone to create the environments in which we live, work, commune, and even memorialize past events and individuals of significance from our history. The considerable demand for "new" stone, in combination with globalization, has opened opportunities for suppliers from around the world, many of whom have only recently developed their natural stone resources for commercial use. This rush to market can create healthy competition and increase the volume and diversity of stone available. However, the lack of historical experience with some stone types and inconsistent documentation of their physical properties can lead to the selection of unsuitable products and unsuccessful outcomes (see **Fig. 1** and **2**). For example, well-intentioned vendors may not realize that a stone used for interior flooring will not perform adequately in an exterior cladding application.

FIGURE 1. Permanently stained interior flooring from moisture exposure.

OVERVIEW OF NATURAL STONE CLASSIFICATIONS[1]

Geologically, natural stones generally fall into three categories based on the influences of their formation: igneous, metamorphic, and sedimentary. Stone is formed through the application of heat and pressure over time on minerals within the Earth's crust, or through deposition of degraded rock. The formation process imparts certain inherent aesthetic, structural, and performance characteristics. Because the formation process is subject to a wide range of heat, pressure, and time, all stone in a given category will not have the same characteristics and may most accurately fall between two of the three categories.

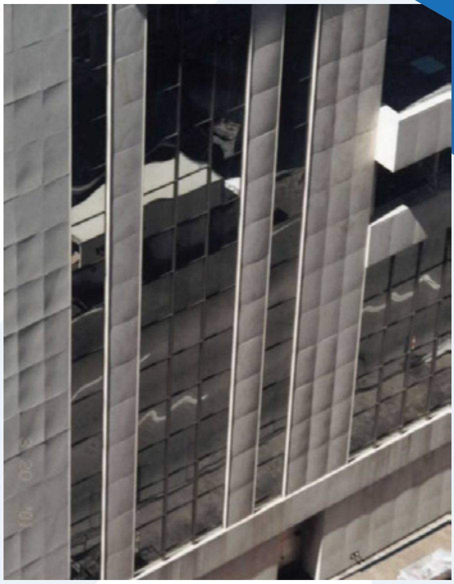

FIGURE 2. Bowing of marble cladding panels due to hysteresis.

Igneous stone is formed from underground volcanic activity that produces molten material, which moves to the surface as lava under high temperature and pressure and then cools to form rock. Principal minerals are silica, mica, and feldspar.

Sedimentary rock is formed by the constant layering of marine organism fossils and weathered igneous or metamorphic rock as sediment. Over time, the pressure of the material weight and natural binders (such as iron oxide, clay, calcium, and silica) bond the materials together to form stratified stone formations or bedding planes.

Metamorphic stone forms from accumulation of sedimentary or igneous rock that continues to be exposed to extreme temperature and pressure for long periods, during which time they can be broken down and reformed or mixed with fluids or other materials.

From a mineralogy standpoint, stone can be divided into two general categories: those that contain silica (siliceous) and those containing calcium carbonate (calcareous).

ASTM International is responsible for industry-recognized standard specifications for building materials, including the most commonly used natural stone types in the building construction industry. The following are the ASTM specifications for seven commercial classifications, each of which include minimum physical properties:

- » ASTM C503, *Standard Specification for Marble Dimension Stone*[2]
- » ASTM C568, *Standard Specification for Limestone Dimension Stone*[3]
- » ASTM C615, *Standard Specification for Granite Dimension Stone*[4]
- » ASTM C616, *Standard Specification for Quartz-Based Dimension Stone*[5]
- » ASTM C629, *Standard Specification for Slate Dimension Stone*[6]
- » ASTM C1526, *Standard Specification for Serpentine Dimension Stone*[7]
- » ASTM C1527, *Standard Specification for Travertine Dimension Stone*[8]

Table 1 contrasts the ASTM classifications with the traditional geologic and mineralogic categories.

WHAT ARE THE CURRENT STONE TEST STANDARDS?

The standard specifications for each stone classification include minimum values for physical property testing that are directly relevant to the engineering of that stone in most building applications. Each test set includes 5 specimens that are each fully dry, saturated, cut parallel to the stone rift (the direction the stone is most easily split), and cut perpendicular to the rift, for a total of 20 specimens to bracket the likely range of values that could occur in service. ASTM C1799, *Standard Guide to Dimension Stone Test Specimen Sampling and Preparation*,[9] describes the conditions under which physical testing is performed and provides guidance on the frequency of testing based on the volume of stone used for a project.

The following are tests that are directly relevant to actual stone engineering in each standard stone specification:

- » ASTM C97, *Standard Test Methods for Absorption and Bulk Specific Gravity of Dimension Stone*.[10] The specific gravity portion of this testing method provides a convenient and accurate means of calculating the unit weight of natural stone. Specimens are typically 2 in. (50 mm) cubes, but cylinders or prisms of specific dimensions can also be used.
- • ASTM C99, *Standard Test Method for Modulus of Rupture of Dimension Stone*.[11] Modulus of rupture provides a value that can be used in bending calculations and anchor design in the absence of ASTM C880 testing (described below). This test method incorporates a single load application point, which is typically also the point of breaking stress. The specimens are a standard size, independent of project-specific dimensions.
- » ASTM C120, *Standard Test Methods for Flexure Testing of Structural and Roofing Slate*.[12] Given the prolific use of building slate for roofing, the slate industry relies on a single test standard for shingles as well as structural slate. The specimens are a standard size, independent of project-specific dimensions. The breaking load is determined for shingles, and the modulus of rupture is the test value for structural slate.
- » ASTM C170, *Standard Test Method of Compressive Strength of Dimension Stone*.[13] Surprisingly, compressive strength is not typically considered critical in stone engineering, except when stone elements are stacked. Stone compressive strength is typically relatively high when compared with other building materials and rarely controls a stone design. Specimens are typically 2 in. (50 mm) cubes, but cylinders of specific dimensions can also be used.
- • ASTM C880, *Standard Test Method for Flexural Strength of Dimension Stone*.[14] This method measures

TABLE 1. Stone classifications by geology and mineralogy

Geologic category	Mineralogic category	ASTM classifications	Common types of building stones unclassified by ASTM
Sedimentary	Siliceous	Quartz-based (sandstone, bluestone, quartzite and similar)	
	Calcareous	Limestone, travertine	Onyx
Metamorphic	Siliceous	Slate, serpentine	Schist, gneiss, soapstone
	Calcareous	Marble	
Igneous	Siliceous	Granite	Basalt

FIGURE 3. Stone specimen tested in accordance with C880 to determine flexural strength.

flexural strength used in bending calculations, among other design checks (**Fig. 3**). The testing uses specimens of project-specific stone thicknesses, with the length and width determined as a ratio of the thickness. It also incorporates two load application points, thereby exposing a wider area of the specimen to stress and providing a more accurate value of flexural strength for a specific project application. For these reasons, stone engineers typically prefer this test method over modulus of rupture for cladding and paving design. The standard specifications for limestone (ASTM C568), quartz-based stone (ASTM C616), and slate (ASTM C629) are the only standard specifications that do not include requirements for flexural strength (ASTM C880). The specifications for these three classes of materials require the use of modulus of rupture for bending calculations; however, stone engineers may require flexural strength testing for these stone classifications.

- ASTM C1354, *Standard Test Method for Strength of Individual Stone Anchorages in Dimension Stone*.[15] Strength of the stone is only part of the information necessary to design a successful stone installation. The interaction between the proposed anchorage system and the stone is arguably as important. There are countless ways to secure stone cladding to a substrate, and ASTM C1242, *Standard Guide for Selection, Design, and Installation of Dimension Stone Attachment Systems*,[16] discusses many of those methods. The ASTM C1354 test method determines the capacity of the stone and anchor assembly, which is particularly important for unique anchor designs, or for highly variable stone types where standard calculation assumptions or analytical modeling may be overly conservative or insufficiently accurate.

Predictive Testing and Evaluation1[7]

In addition to physical property testing that is necessary to engineer stone for a specific application, there are several common tests for natural stone that are predictive regarding long-term performance. The following test methods can help the designer determine whether the stone will be appropriate for a given application from a serviceability standpoint, and whether it will remain structurally sound over the intended service life of the project:

- ASTM C97, *Standard Test Methods for Absorption and Bulk Specific Gravity of Dimension Stone*.[10] The absorption portion of this test method is used as a predictive indicator of stain resistance and is sometimes used to predict resistance to distress from cycles of freezing and thawing. Specimens are typically 2 in. (50 mm) cubes, but cylinders or prisms of specific dimensions can also be used.
- ASTM C217, *Standard Test Methods for Weather Resistance of Slate*.[18] Exclusively required for slate dimension stone and shingles, this test method assesses the softening caused by the application of mild acid, which is intended to simulate exposure to acid rain.
- ASTM C666, *Standard Test Method For Resistance of Concrete to Rapid Freezing and Thawing*.[19] This standard was developed to evaluate concrete durability, but it is often specified for natural stone. Unfortunately, its applicability is limited; experience has shown that the method of evaluation is not appropriate for many natural stones and can mischaracterize potential in-service performance. Use of this test should be limited to comparison of possible stone selections.
- ASTM C1353, *Standard Test Method for Abrasion Resistance of Dimension Stone Subjected to Foot Traffic Using a Rotary Platform Abraser*.[20] Abrasion resistance based on laboratory testing is helpful in predicting the in-service behavior of natural stone in situations where it will be subject to abrasion from foot traffic or abrasion in general.
- ASTM C1721, *Standard Guide for the Petrographic Examination of Dimension Stone*.[21] This guide is used to evaluate the physical and chemical characteristics of the stone (mineralogy, texture, composition), and other features that may have a bearing on the in-service performance of the material. Petrographic examination uses microscopy and examination under various wavelengths of light to characterize a specimen. These methods are valuable to identify and classify stone, and they also can identify characteristics that can be deleterious to the installation. Typically, the supplier selects a small specimen, perhaps less than 1 ft^2 (0.1 m^2) in area and sends it to a petrographer for examination. However, it is best to provide a larger sample (as large as practical, such as a full wall cladding panel or paver) and allow the petrographer to perform a macroscopic examination and then select a specimen based on that assessment for more detailed petrographic examination. This approach takes full advantage of the petrographer's experience in identifying characteristics of potential concern to examine.
- ANSI A137.1, *Standard Specifications for Ceramic Tile*.[22]

Although these specifications are technically for ceramic tiles, the dynamic coefficient of friction (DCOF) portion of this standard is used to determine slip resistance of natural stone in paving and flooring applications and provides a recommended value for compliance. Currently, there is no mandatory DCOF requirement, but there are industry recommendations from the Occupational Safety and Health Administration,[23] and within the Americans with Disabilities Act .[24]

- Accelerated weathering protocol. Currently there is no formal stone industry-accepted standard for accelerated weathering to assess potential environmental effects on natural stone over time. Wiss, Janney, Elstner Associates Inc. has proposed a testing protocol to ASTM that involves cyclic temperature changes to simulate in-service temperatures and cycles of freezing and thawing, plus exposure to mildly acidic water spray to simulate acid rain. Physical property testing of the stone is performed before and after multiple temperature cycles to measure any losses that can be associated with durability, such as strength and absorption. This testing approach is commonly used for large-scale or high-profile projects to compare proposed stone selections, but it is not accepted by ASTM as a formal test standard.
- EN 12370, *Determination of Resistance to Salt Crystallization.*[25] This is a European standard adopted by the European Committee for Standardization (CEN), European Committee for Electrotechnical Standardization (CENELEC), and European Telecommunications Standards Institute (ETSI). It is often used to evaluate stone that may be exposed to elevated levels of chlorides for deicing purposes, or to determine suitability of a stone for placement at grade and in contact with soil. This test evaluates the impact of salts dissolved in water and absorbed into a stone specimen, which is then dried, leaving the salts to recrystallize with the stone.
- EN 16306, *Determination of Resistance of Marble to Thermal and Moisture Cycles.*[26] This is another EN standard that is used in the US market; it helps to determine susceptibility of the specimen to bowing and strength loss through hysteresis (deformation and/or strength loss resulting from to cyclic heating and cooling exacerbated by cyclic wetting and drying that results in the separation and dislocation of the mineral grain structure and permanent volume change), a condition associated primarily with several types of marble (both foreign and domestic) and some types of limestone.

New Work in Stone Testing Development

Stone material specification and testing standards are the responsibility of ASTM C18, Committee on Dimension Stone. In addition to maintaining and updating the existing ASTM standards, the committee considers new work items and develops new standards or guides related to the use of natural stone in building construction. Current and planned test standard work items include a stone-specific test protocol for resistance to freezing and thawing, salt crystallization resistance (similar to EN 12370), and possibly a procedure similar to EN 16306 to evaluate stone potential for strength loss and bowing.

WHY IS STONE TESTING IMPORTANT?

Stone is stone, right? Wrong. Stone is a natural material and extremely diverse in its origin, minerology, and physical properties.

There are several reasons why it is difficult, if not impossible, to determine the physical properties for many stone types from visual examination or by applying what is thought to be the relevant classification standard. Stone classifications are defined for construction purposes by ASTM International in the United States, and by other construction material standards organizations around the world. The classifications are generally based on common mineralogy and physical properties. However, stone properties can vary from classification to classification, within classifications, and even within the same quarry. Furthermore, the *consistency* of the physical properties of a stone can also vary. Another concern is that suppliers sometimes misclassify materials (for example, labeling marble as granite, or limestone as marble). These misclassifications can contribute to erroneous assumptions about whether a particular material is appropriate for a given application. Also, trade names for the same type of stone may vary depending on the quarry or supplier from which it originates. Quarries a few miles apart may provide essentially the same stone under differing names for marketing purposes.

For most building applications, the stone must support at least its own weight as well as some applied loads. Whether the loads are vertically or horizontally applied, stone must be engineered to support them. In conventional construction, the structural engineering of stone is typically delegated to a stone specialist who is more familiar with the variability of stone, appropriate safety factors, and the fabrication standards that will influence the design. The delegated stone design engineer can determine the demand with a high degree of certainty through application of material properties, anticipated dimensions, and relevant codes, However, they cannot estimate the capacity of the stone unless they have a resource for determining stone-specific physical properties.

The logical answer to the concerns raised herein is to improve designers' understanding of and reliance on natural stone testing to determine the physical properties necessary to implement successful designs. It is customary for a competent design professional to require physical property testing of concrete to ensure that its capacity will meet the required demand and that it will be durable in service. It would seem that a similar level of quality control should be implemented for stone when it is used in critical applications to ensure structural and serviceability expectations are met.

Stone Selection

Natural stone is selected for applications in building construction largely based on appearance, not performance. Aesthetics often drive design decisions and can lead to innovative uses of stone colors, characteristics, or textures that enhance our built environment. There is nothing wrong with this approach, provided that the physical properties of the chosen stone are understood so that its appropriateness for the application can be confirmed.

When stones from exotic classifications or unusual stone types within a classification are being considered for an atypical application, relevant physical property data may not be available or current. In the absence of adequate physical property data, one can consider using the industry-minimum properties for the particular stone classification, but that can be a problematic approach. Unfamiliar stones may be misclassified by the supplier, leading the design to erroneously make favorable assumptions that could mask a potential risk of failure. Conversely, a preferred stone selection could be eliminated from consideration because assumptions about strength or performance are overly conservative, pushing the designer to unnecessarily consider alternatives. Current stone test data can help the producer by fairly evaluating and representing their products, as well as the designer by providing reliable data about using the desired stone in the intended application.

The ASTM standard specifications provide the minimum requirements for a stone type to be categorized in one of the classifications described earlier. They are a lower-bound benchmark for preliminary stone engineering purposes. If the stone supplier certifies that the stone meets the ASTM standard, then they have the obligation to ensure through periodic testing that the stone supplied complies with the minimum physical properties for the entire period the stone is quarried, which can be decades. If the stone does not meet the standard requirements for compliance, the stone can still be considered for use; however, the designer should obtain reliable test data for a preliminary assessment to determine the material's appropriateness for the intended use.

Typical Stone Applications and the Physical Properties Needed for Design

The primary structural applications of stone in our built environment include exterior cladding, exterior paving, interior cladding, and interior flooring. Testing can be critical in such applications to determine the selected stone is appropriate for a particular use.

Of the stone applications, exterior cladding carries the greatest risk if it fails. A cladding failure can be costly and disruptive to building ownership and its tenants, and it can be a danger to the public. A stone panel falling from any height can have devastating consequences. Because exterior cladding carries such a clear structural risk, it is critical to obtain the most accurate data about the physical properties of materials selected for its design. Thin-stone-cladding design largely relies on flexural strength and anchor strength for structural adequacy. Cladding design must also consider findings from petrographic examination to determine a material's staining potential and identify stone defects that could compromise structural performance. In some environments, product data about moisture absorption and accelerated weathering are needed to determine whether strength loss or stone deterioration from environmental effects should be considered in the design.

Exterior paving is exposed to constant pedestrian traffic, precipitation, temperature extremes, and sometimes substantial vehicular loads (such as emergency vehicles). Therefore, the stones used in exterior paving applications must be very durable. To evaluate durability, petrographic examination is critical to identify deficiencies that can lead to premature deterioration or cracking. Absorption test findings are useful to assess stain resistance, and data about resistance to cycles of freezing and thawing are important since paving can remain saturated for long periods of time. Abrasion resistance data provide a measure of how quickly a stone will degrade under foot traffic. Slip resistance data can be used to assess whether additional treatments are necessary to reduce the risk of pedestrian injury. From a structural standpoint, data about the flexural strength of paving materials guides the determination of material thickness, whether the installation is supported on a setting bed, or the pavers span between supports points in a pedestal system.

The structural risks associated with interior cladding failure are similar to those associated with exterior cladding failure. However, the structural and environmental demands on interior cladding are lower than those placed on exterior cladding. Design of interior cladding relies primarily on data about flexural strength and anchor strength to resist interior pressure differentials. Compressive strength can also be a factor for some thinner stone-cladding installations that rely on stacking.

Interior flooring (in public spaces such as lobbies) can be deceptively challenging to design. Owners and designers may desire particular stone types and finishes desired for aesthetic reasons, but the materials must also stand up to constant foot traffic plus water, sand, and snowmelt chemicals tracked onto the flooring from the exterior. Interior flooring design largely relies on information about flexural strength, absorption (stain resistance), abrasion resistance, and slip resistance.

Table 2 summarizes general recommendations regarding the relevance of various direct-use and predictive

TABLE 2. Relevant stone testing methods by application and stone classification

Test methods	Applications			
	Exterior cladding	Exterior paving	Interior cladding	Interior flooring
Direct use*				
ASTM C97	M, G, L, Q, Sl, T, Se	M, G, L, Q, Sl, T, Se	M, G, L, Q, Sl, T, Se	M, G, L, Q, Sl, T, Se
ASTM C99	Q, Sl	Q, Sl	Q, Sl	Q, Sl
ASTM C120	Sl	Sl	Sl	Sl
ASTM C170	M, G, L, Q, Sl, T, Se	M, G, L, Q, Sl, T, Se	M, G, L, Q, Sl, T, Se	M, G, L, Q, Sl, T, Se
ASTM C880	M, G, T, Se	M, G, T, Se	M, G, T, Se	M, G, T, Se
ASTM C1354	M, G, L, Q, Sl, T, Se		M, G, L, Q, Sl, T, Se	
Predictive use†				
ASTM C97	M, G, L, Q, Sl, T, Se	M, G, L, Q, Sl, T, Se	M, G, L, Q, Sl, T, Se	M, G, L, Q, Sl, T, Se
ASTM C217	Sl	Sl		
ASTM C666‡	M, G, L, Q, Sl, T, Se	M, G, L, Q, Sl, T, Se		
ASTM C1353	M, G, L, Q, Sl, T, Se	M, G, L, Q, Sl, T, Se		M, G, L, Q, Sl, T, Se
ASTM C1721	M, G, L, Q, Sl, T, Se	M, G, L, Q, Sl, T, Se	M, G, L, Q, Sl, T, Se	M, G, L, Q, Sl, T, Se
ANSI A137.1		M, G, L, Q, Sl, T, Se		M, G, L, Q, Sl, T, Se
EN 12370	M, G, L, Q, Sl, T, Se	M, G, L, Q, Sl, T, Se		M, G, L, Q, Sl, T, Se
EN 16306	M, G, L, Q, Sl, T, Se	M, G, L, Q, Sl, T, Se		
Accelerated weathering	M, G, L, Q, Sl, T, Se	M, G, L, Q, Sl, T, Se		

Abbreviations: G = granite; L = limestone; M = marble; Q = quartz-based; Se= serpentine; Sl = slate; T= travertine.

*Uses directly related to engineering and design of stone systems.

†Uses related to predicting in-service behavior.

‡Testing should be limited to comparative testing and may require modifications to evaluation methods for some stones.

stone testing procedures to the four main structural applications for stone described in this section.

WHEN IS STONE TESTING MOST CRITICAL?

Obtaining accurate and current data about a product's physical properties for use in stone design is always good practice, and such data are often readily available from suppliers that understand the need for regular testing of their products. But when reliable physical property data are not available from the supplier, stone testing is critical in certain situations to ensure a safe and reliable installation. The importance or visibility of a project is an important factor when considering stone testing. Selection of stone for a prominent monument, museum, or institutional building with an expected service life of 100 years or more demands a comprehensive evaluation of proposed options. The decisions made regarding which stone to use can have an impact on repair and maintenance costs for generations.

Designers should also prioritize testing of stones that could be used for buildings in challenging environments. Environmental challenges can include extreme heat or cold, frequent cycles of freezing and thawing coupled with precipitation, high-wind events such as hurricanes or tornadoes, sandstorms, heavy pollution, and acid rain. Testing can provide valuable insights into long-term performance under these adverse conditions.

A stone supplier may be able to provide examples of similar installations in similar environments with the same stone being considered. Depending on the amount of time the stone has been in service, these exemplars can be one of the best ways to predict long-term performance of a particular stone. An exemplar does not eliminate the need for physical property data to complete a design, but it can reduce the amount of predictive testing warranted based on the similarities between the exemplar and the proposed application. Conversely, the absence of exemplars heightens the need for comprehensive physical property data from stone testing, as the lack of information can be an indication that the stone is not commonly used for the intended application.

Atypical or unusual stone applications—such as sloped or inverted cladding, applications incorporating a particularly aggressive stone finishing technique (potentially causing microfractures), or applications using stones as structural members to carry more load than self-weight—require special attention. The more unique the application is, the more unpredictable the performance and outcome can be. Highly unpredictable scenarios demand a high level of engineering conservatism. Accurate physical property test data can help designers mitigate risks associated with unusual applications.

Some stone types are known to have natural characteristics that can lead to adverse outcomes when in service. For example, pyrite inclusions can cause rust-colored staining, and some types of marble are prone to strength loss through hysteresis. Stone testing establishes a benchmark for use in design, but more importantly, predictive testing can inform choices about stone selection based on how the natural characteristics of materials will likely affect in-service performance.

One of the most distinctive and attractive features of natural stones are their variability in appearance—no two pieces of the same stone will ever look the same. But that variability in appearance can also mean that physical properties are inconsistent. Stone that is highly variable in appearance should be extensively tested in an effort to benchmark the range of physical properties resulting from compositional variations such as differences in the density and directionality of veining, the presence of various metals or other substances, and the presence of voids, fissures, and seams.

Because stone is a natural material, its physical properties are often associated with the location where it is quarried. Some quarries encompass large areas in which the geologic features can vary, leading to different physical properties from one part of the quarry to another. Designers should also be aware that the test data provided from a particular quarry may be for a stone that is several years old and may not accurately represent current production. (ASTM C1799[9] recommends stone test data that are less than 3 years old for this reason.) Designers should not rely on out-of-date test data, and the lack of current test data can serve as a warning that the stone has not been used in a recent application that requires engineering.

Some classifications of stone require more conservative safety factors than others. A higher safety factor is an indicator that the physical properties are less consistent historically or can vary from stone type to type within a classification. When larger safety factors are involved, accurate test data are important to obtain physical property values that are not overly conservative. Conservative values combined with large safety factors can lead to a design that is not cost effective, or simply less efficient and more expensive than necessary.

Some recent industry trends also increase the need for stone testing and accurate physical property data. For example, designers of applications such as rain screen systems in which stone is exposed to more severe environmental conditions require informative physical property data. Also, recent emphasis on sustainability has prompted scrutiny of the efficiency of all types of building products, including natural stone, which is energy intensive to produce and ship. The use of locally sourced stone materials may help meet sustainability goals and reduce costs on some projects, but designers must consider physical property test data before selecting these materials.

WHERE IS TESTING IN THE DESIGN AND CONSTRUCTION PROCESS?

Evaluation of stone testing has value at several stages of a project and can serve multiple objectives. Four major objectives to consider are feasibility, verification, material acceptance, and quality assurance.

Stone Product Feasibility

At the beginning of a project involving stone applications, designers may consider multiple stone types, with the initial evaluation of materials largely based on design intent and aesthetics. Once the options are established, physical property testing (including petrographic examination) should be solicited from the vendors. In some cases, the testing data made available are incomplete, not current, derived from non-ASTM test standards, or written in a foreign language. If the design team encounters any of these issues, a second request for information should be made, with specific instructions to contact the quarry and improve the quality of the test data provided. The quarry may have more current test data than the vendors that market the stone. In addition to test data, designers should request information about exemplars from both the quarries and the vendors (asking both for information is prudent because their project references will be different). Of particular interest are any local applications that the design team can visit with minimal effort. Note that this process of inquiry will likely result in some relevant test data for some of the stone options, but it probably will not provide a complete set of information for any of the options.

Based on the information provided, the stone classifications should be verified. As noted earlier, the quarry or the vendor might misclassify a stone for marketing reasons or out of ignorance. Verification is critical since the purpose is to benchmark the physical test data to the appropriate ASTM standard. Once the correct classification is established, the provided test data should be interpreted as well as possible, such as by comparing EN standards to ASTM standards or by obtaining translations of non-English-language documentation.

The data about each stone under consideration can be generally compared with the other options and the minimum ASTM standards. Depending on the stone application, attention should be focused on certain tests, such as moisture absorption for flooring and flexural strength for cladding. If the most critical test data for the application are not available, that lack of information suggests that the stone may not be appropriate for the intended use. The supplier may not be willing to perform any additional testing at this stage, but they should know that the stone may not be considered further unless reliable data are provided. The design team should note any major outliers in the data (that is, values that are abnormally low or abnormally high). The test results should also be compared with publicly available published data from other suppliers (if available) to look for any major discrepancies.

Once this evaluation process is complete, the design team can loosely rank the stone options, with those that have less desirable performance or insufficient test data at the lower end. At this stage, the team may add or eliminate options from consideration based on design intent, so the process remains fluid.

By the time stone types are being considered, the design team may have application formats and preliminary designs that indicate the parameters in which the stone will be used. Having this information as early in the process as possible helps ensure that the appropriate stone types are being considered to avoid a potential mismatch between physical properties of the stone and the demands of the application.

Verification of the Stones Selected for a Project

Once the stone types have been selected for specific applications, any gaps or concerns with the provided test data should be addressed to ensure that the selections are suitable for the applications. At this point, the quarry should be willing to supply comprehensive ASTM-specified test data that is representative of their current production, even if they must obtain additional testing. In the feasibility stage, the design team used conservative values based on the classification (either the ASTM minimums or the actual test values provided) to determine that the selected stone type can be suitable for the applications. The physical test data provided at this verification stage will be used for final stone engineering to make sure unit sizes and thicknesses will work based on the design loads anticipated.

Depending on the application and the project environment, predictive testing should be considered at this stage if relevant exemplars are unavailable. This is the last opportunity to evaluate the appropriateness of the selected stone before it is specified.

Material Acceptance

On some projects, a considerable period of time can pass between specifying a stone and the submittal process, and in that time, the stone production can change. Therefore, design teams may perform quarry visits during the material acceptance stage to verify that the selection of the stone meets the design requirements, and that quarry can achieve the production goals. Specific blocks of stone may be selected based on appearance. As part of the acceptance process, the quarry should be required to provide samples of the stone selected so that physical testing can be conducted by independent laboratory to make sure that the specimens meet the minimum design requirements and do not contain any undetected flaws or features that could compromise the installation. This process helps establish whether any culling of stone may be needed to provide only material that meets the project requirements.

Quality Assurance during Production

To ensure the material that is being delivered throughout the installation is consistent in quality and physical properties, testing should be performed periodically on material selected at random from the delivered shipments. The scope of testing can often be scaled back to only the most critical properties for the application, and the frequency of testing may be determined by considering the uniqueness of the stone, the quantity of stone being installed, and the variability in data obtained during prior testing. As long as the test results obtained are generally consistent and in line with expectations, the material delivered should be compliant with the project requirements.

CLOSING THOUGHTS

Many stone projects can be constructed and perform well without project-specific physical property testing. In particular, project-specific testing may not be needed when projects use stone products that have a long history of success and a reputation for consistent production, and there are historical test data to demonstrate that the selected products meet industry requirements for the classification. Also, not all the physical testing methods discussed in this paper are relevant to every application. It also must be acknowledged that stone testing has a cost. Therefore, it is up to the design team and the suppliers to make good decisions about what, why, when, and where stone testing will be a benefit to a project. Ultimately, the objective of stone testing is to ensure that design requirements will be met and to reduce risk of costly failures for all the parties involved.

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Roof-Mounted Solar:
ROI and Best Practices

ABSTRACT

What roof type is ideal for photovoltaic (PV) system mounting? What about "solar zone," roof orientation, environmental and collateral loads, system sizing, the building enclosure, and life-cycle cost analyses? All of these factors affect the sustainability and financial pro forma of the roof and PV system.

New technologies can be daunting. When it comes to PV design, small shifts in thinking can bring the things that matter into focus, producing huge savings and production efficiencies for improving the client's overall ROI.

This presentation will review and discuss the concepts of treating the roof and PV system as a single asset with supporting ROIs and IRR. Upon this review, participants will have a better understanding of the numbers regarding the ROI and IRR.

LEARNING OBJECTIVES

- Identify the real effects of solar orientation on system output.
- Compare the current tax and other incentives on return on investment (ROI) & internal rate of return (IRR).
- Evaluate initial and life-cycle costs with ROI comparison of photovoltaic (PV) on commercial roofs.
- Describe best practices for PV design and deployment.
- Summarize key takeaways for making decisions based on real facts and numbers regarding mounting rooftop solar.

SPEAKERS

Rob Haddock
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Rob Haddock is a metal roofing expert who has worked in the industry for five decades—first as a laborer, then contractor, forensic analyst, technical author, innovator, and founder of S-5! He is a member of NRCA, ASHRAE, the American Society of Civil Engineers (ASCE), the Construction Specifiers Institute (CSI), IIBEC and ASTM. He is also a lifetime honorary member of the Metal Building Contractors and Erectors Association and Metal Construction Association. Haddock innovated the concept of seam clamps for standing seam roof profiles. He has served as faculty for the Roofing Industry Educational Institute, RCI, and the University of Wisconsin. He is a recipient of numerous awards including the RCI Richard M. Horowitz Award and was a charter inductee to the Metal Construction Hall of Fame.

Mark Gies
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Mark Gies is director of product management at S-5! He has nearly 15 years of solar experience and over 30 years of engineering and management experience. Prior to S-5!, he held management positions at a mounting system company and with a solar project developer. His solar expertise includes product development, operations, installation, codes and standards, and sales and business development. Gies is vice-chair of the Mounting Systems Manufacturers Committee at the Solar Energy Industry Association, a member of the Structural Engineers Association of California PV Committee, and a founding member of UL2703's Standards Technical Panel.

AUTHOR:
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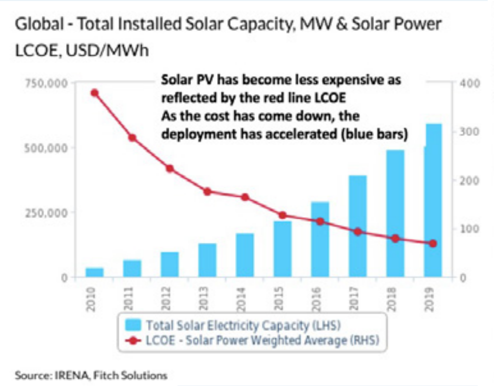
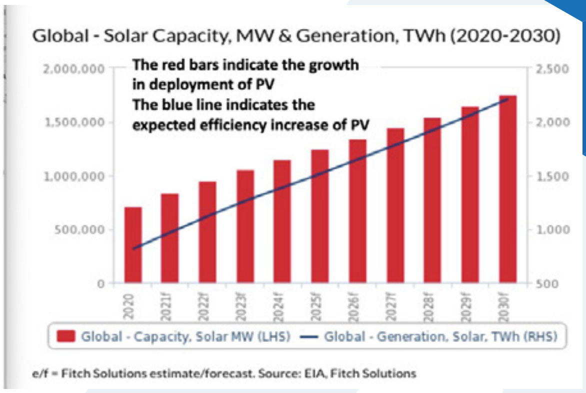




The use of solar in building design is sharply on the rise. When considering adding rooftop solar, knowing what information is needed up front, planning the solar PV system design for optimal power production, and utilizing quality materials to secure the system for its lifetime are essential. But what information is needed to make an informed decision?

First, it's important to understand why mounting solar to a metal roof rather than alternative roof types can make the most sense.

Today's trends lean toward evaluating the long-term costs of owning and maintaining a roof. For owners and designers, environmental aspects of the industry—pre- and postconstruction—have become the primary focus in the life cycle of a roof's materials. Additionally, concerns over landfills becoming overburdened with former building components discarded due to shortsighted, budget-conscious building objectives are driving the focus on more sustainable roofing materials and their "cradle-to-grave" carbon footprint.

Metal roofing is known for its durability, environmental sustainability, variant styles, and versatility. The life-cycle costs and environmental appeal of metal offer several advantages over current life-cycle trends. As a result, metal is experiencing a surge in popularity for both commercial and residential applications because the maintenance requirements and life-cycle ownership costs are substantially lower than those of the alternatives.

SERVICE LIFE

In the commercial/industrial market sector, a field/lab study published by the Metal Construction Association indicates that the service life of (standing seam) coated steel is in the range of 70 years. Based upon empirical data, several domestic producers of 55% AlZn steel have recently raised no-cost warranted material performance up to 60 years, equaling the assumed building service life as described in LEED version 4. Additionally, because of the negligible maintenance afforded by properly installed metal roofs, owners are not faced with costly roof upkeep, patching, and repair.

With few exceptions, nonmetal commercial roofing systems generally expire after 15 to 20 years. They not only have more intense maintenance requirements but also costs of repair year over year, and eventual tear-off, and replacement, offering no life-cycle cost advantage over standing seam metal roofing, which is documented to a service life approaching 70 years.

SUSTAINABILITY

The growing demand for durable and environmentally friendly construction materials with reduced maintenance and longer service lives often can lead commercial designers and owners to metal roofing. It is attractive, highly reflective, long-lasting, weather-resistant, and easy to maintain.

Metal roofing is a sustainable material because of its extended service life, low production

Powerful Percentages

How does domestically produced hot-rolled structural steel stack up sustainability-wise?

- 93% recycled content
- 98% recycling rate
- 95% of U.S. production is represented by facility-specific environmental product declarations (EPD)
- 75% is produced via electric arc furnace (scrap-based)

Modern Steel Construction (*EAF statistics*), May 2023 consumption of natural resources, zero-petroleum byproducts, and recyclable economic prudence.

At nearly an 98% recycling rate, steel is one of the most-recycled construction materials available, second only to copper. This is important to building owners and designers conscious of both environmental and economic efficacies. Old metal roofs rarely end up in landfills, thus preserving landfill space and helping to protect the environment.

Metal roofing is also resistant to fire, weather, and climate conditions due to its sturdy and inert composition. It is noncombustible, adds no fuel, and will not ignite during a wildfire or lightning strike, which may help save on insurance premiums.

Metal is impervious to ultraviolet degradation. Premium factory finishes of polyvinylidene fluoride paint films offer up to 40-year warranties against excessive fade, chalk, and film integrity. Further, because metal panels have structural characteristics, they can be designed to resist virtually any wind speed, including a Category 5 hurricane.

THE METAL ROOF, A PERFECT PLATFORM FOR SOLAR PV

Today, building owners are adding grid-tied solar photovoltaic (PV) sources to augment the power required to run their facilities. The financial prospect of PV makes sense, turning cash positive in three to seven years and providing power for decades thereafter.

This 28-year old roof is estimated to have remaining service life of 35+ years. It is about to be retrofitted with a PV array.

With over 150,000 points of attachment, Apple HQ's Aluminum roof has an expected service life of 100 years with no penetration, no ballast and no warranty violation from the 7-MW PV array.

With the increasing use of solar on commercial buildings, metal roofing has become a driver for roof type selection in many cases.

The service life of solar PV is between 28 and 37 years, with an average of 32.5 years, according to Wiser, Bolinger, and Seel. Most alternative roofing systems expire long before the life of the PV system. This leads to costly disassembly of the PV array, reroofing, and reassembly. A standing seam metal roof provides an ideal platform and is the only commercial roof type featuring a service life that exceeds the solar PV system.

It is also easier and less expensive to mount solar to a metal roof than any other roof type. In most cases, these cost savings are even sufficient to offset the premium initial cost of a standing seam roof. Solar PV can be mounted to the standing seams of the roof penetration-free, ballast-free, and with tested and engineered mechanical attachment methods.

With the cost of solar decreasing over the last decade, federal and local incentives, as well as public policy mandates driving the popularity of solar, the numbers improve every year. When solar PV is incorporated into building design, the standing seam roof makes sense from both a financial and ecological perspective.

LIFETIME ROI

Once the decision is made to utilize solar, metal roofing is a driver for roof type selection because not only is a solar-and-metal roof system less expensive up front than other roof system combinations, but it also improves the real lifetime return on investment (ROI) of the system.

When computing ROI within the solar pro forma, inverter replacement is usually factored in at about year 15—but what about the cost of roof replacement? The solar array must be totally dismantled and then reinstalled on the replacement roof. Often, even the initial cost of the solar-and-metal roof is less than that of solar and other roof type alternatives. Factor in roof replacement, and the cost advantages become grossly magnified. Hence, the PV array and the roof should be regarded as a single asset.

A number of exorbitant expenses associated with completing a PV system/ reroof include removing the solar modules, removing the mounting and racking system, decommissioning the system during the reroof, reroofing, reinstalling the PV system, recommissioning the system, the potential for damaged components during this process, and some new wiring and loss of power production during the project.

With metal, roof replacement is avoided. The roof will perform long after the service life of the solar array has expired. When considering new construction, the standing seam metal roof actually lasts the lifetime of the first solar array as well as the second. In the case of solar retrofit, 30-year-old standing seam roofs that are properly designed, installed and maintained are still viable candidates for consideration.

For these and other reasons, metal has become a preferred roof type for the solar roof. The solar-and-metal roof can achieve significant improvements in the lifetime ROI and provides lower up-front costs than alternative roof system combinations. It is not only rational but vital to consider the roof and PV as a solitary asset, as the two are mutually dependent.

INVESTMENT TAX CREDITS AND OTHER INCENTIVES ON ROI

Since the introduction of the Inflation Reduction Act (IRA), the U.S. solar market is now poised to reach the goal of 30% of U.S. electricity generation by 2030. The legislation includes a 10-year extension of the solar Investment Tax Credits (ITC), new additional incentives also known as adders, significant incentives to boost domestic manufacturing throughout the solar production supply chain, tax credits for energy storage, workforce development provisions, and additional policies that promote a clean energy economy. These new policies are expected to accelerate growth, triggering an avalanche of solar development throughout the United States.

WHY IS THIS IMPORTANT TO NEW SOLAR INSTALLATIONS?

Solar projects built through 2033 are eligible for the 30% ITC and can increase their tax credits significantly by qualifying for “adders.” These include domestic content, energy communities, and low-income communities.

For the domestic content adder, if at least 40% of the products are made in the U.S., a project qualifies for 10% additional tax credits. For energy communities, installing solar in eligible areas, such as brownfields or closed coal mines, qualifies for another 10% tax credit. Installations in low-income areas receive an additional 10–20% tax credit.

In addition to ITCs, there is other federal money available, including the USDA’s Rural Energy for America Program for designated rural areas. Some states, municipalities, and utilities are also offering loans, grants, and other incentives.

An important piece of the IRA is to grow U.S. businesses, especially manufacturers, and the combination of the supply-side incentives and the ITC adder provides that opportunity to the solar industry in the U.S. Besides economic reasons, this is important because in the wake of the pandemic, U.S. companies quickly realized the need to limit their reliance on foreign goods and services and increase domestic manufacturing to meet the demand. Ongoing supply chain issues also underscore the importance of domestic production.

An increase in domestic production of solar components should offset potential price increases, reduce shipping and import costs, and likely increase the level of support for solar PV and other renewables in the U.S.

HOW DO NATIONAL AND/OR LOCAL ENERGY POLICIES AND BUILDING/ ELECTRICAL CODES PLAY INTO THE USE OF SOLAR?

The role of codes and regulations is a double-edged sword. Some are very positive for solar, such as the residential solar mandates required for all new construction enacted in California a few years ago, while others may increase hurdles, making it more complex and difficult to install solar. As the use of solar increases, so do the number and revisions of codes, standards, and policies. This is inevitable and the right thing to do but may inadvertently increase the hurdles to deploying solar. Some energy conservation policies are focused on energy efficiency first, which may reduce the demand for solar.

That said, various municipalities and even entire states have enacted regulations, building codes, and public policy mandating the installation of solar PV or solar-ready design on new building construction. This is a major shift from the past, when there was no consideration for accommodating solar with new construction design, and solar was retroactively fitted to the roof in the best way possible. New mandates will result in the accelerated growth of rooftop solar, with the intent also to reduce costs and maximize the energy output of solar installations—leading to higher ROIs with fewer hurdles in deploying solar PV.

The key to complying with these mandates is in the up-front planning and design of new buildings with respect to factors not traditionally considered—factors focused on the anticipation of a solar installation on a new building.

For example, according to the solar-ready regulation St. Louis, Missouri, passed in December 2019, the area of a new commercial building’s roof that is functional for solar must be at least 40% of the total roof area, often referred to as the “solar-ready zone.” For new residential homes, the solar-ready zone must be at least 600 square feet and oriented between 110 and 270 degrees from true north to the southernmost point as possible—to produce more energy.

As more buildings are constructed with solar installed or solar-ready, the demand for better solutions will foster greater innovation of products and technology to allow a building, its roof, and its solar PV to work as a single system. This could be new products performing multiple functions, such as building-integrated PV, which has been around the industry for years but has also been relatively unsuccessful due to economic and technical difficulties.

DESIGNING A SOLAR-READY ROOF AND THE EFFECTS OF ORIENTATION ON THE SYSTEM’S OUTPUT

Whether mandated or not, it is a good idea to plan for a solar-ready roof during the design stages, as up-front planning can minimize cost and increase feasibility. Planning for a solar installation in the future ensures informed decision-making with regard to the timing of the installation and ensures optimal power production.

Mounting rooftop PV should always be consistent with the design principles of the host roof and vary according to the specific roof type. Further, a PV array on a rooftop is exposed to the environmental forces of wind, snow, rain, hail, and even earthquakes. These forces can be complex, making secure attachments of PV crucial. PV arrays improperly designed and installed can become airborne during a wind event and pose a serious threat of personal injury or property damage. Therefore, skilled design, engineering, and production of these components are required. All these criteria point directly to metal. So, a working knowledge of metallurgy, sealant chemistries, metal roof types, and other variables is also critical to a long-lasting solar-and-metal-roof combined asset.

When planning the location of the rooftop solar array, the orientation of the building should be considered to maximize the solar gain (increase in solar absorption of the area due to the natural direct exposure to the sun) and power production of the system. When a steep-slope roof (a slope approaching latitude) is involved, a south-facing roof surface is the optimal location for the array. Southwest and southeast orientation can also be good options affecting power production minimally. As the module orientation moves away from a south-facing orientation, the solar gain and total energy produced on any given day are reduced. Orientation is not as critical for low-slope roofs (roofs 5% or lower).

Today, solar modules are normally installed planar to the roof surface on steep roofs and planar or very slightly tilted on low-slope applications. Aggressive tilting of modules is seldom done primarily due to economic considerations (adversely affecting the ROI payback period) but also due to adverse wind effects on roof systems and structures.

Tilted systems are still sometimes used in very northern geographies or on roofs that are not oriented to the south. It is a delicate balance between increased cost and increased power production.

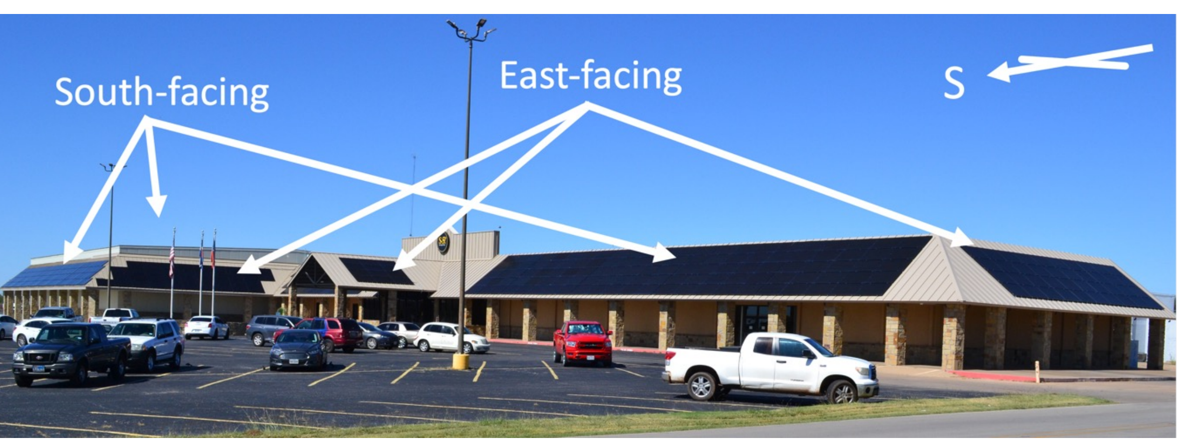
When designing a project, structural analysis should always include the potential added collateral load, as solar modules add approximately 2½ pounds per square foot. A rail-mounted system adds 3 pounds or more per square foot. A rail-less system is lighter weight because it eliminates the need for 85% of the collateral load of rails.

Another design consideration is an unobstructed roof area(s), free of shading issues. Building components, such as plumbing stacks, skylights, chimneys, and adjacent walls and roofs, can create shadows on the solar system; therefore, the system should be designed to avoid obstacles and eliminate shadows. Consideration should also be given to any future buildings or trees planted near the building that could cast a shadow on the system.

After the building design is finalized, there should be a specific area called out as the solar zone for the PV system. This is the predetermined maximum roof area usable and best suited for solar mounting considering roof orientation, free space availability, and the building's consumption. Other issues that affect the size of the solar zone include building and fire codes, roof access paths for maintenance, the balance of system components, and the size of the array.

TYPES OF SOLAR MOUNTING SYSTEMS ON METAL ROOFS AND BEST PRACTICES

Solar modules are secured to metal roofs by several methods, generally falling into two categories: either flush mounted to achieve maximum module density or tilted to achieve optimal sun angle. Both methods result in different energy outputs from a given module or number of modules. These options may have differing roof inter-row spacing, structural engineering factors, and serious cost implications, so initial cost and ROI should be analyzed individually when considering and comparing the two options.



In years past, when PV modules were at their highest cost per watt and lower efficiencies, tilted systems were the norm to achieve optimal sun angle and were also demonstrably financially prudent. Solar array design was driven primarily by the high cost

FIGURE 1. Flush Rail Mounting; Use of rails on the metal roof is redundant, and adds unnecessary collateral load.

of the PV module, hence achieving optimal sun angle using tilted mounting systems was worth the added costs. Within the last decade, PV costs per watt have fallen from dollars-to-dimes/Watt, so the gain in power production from optimal sun angle seldom offsets the added costs of tilting. Trends now favor lower-cost, flush-mounted systems that facilitate higher power density (watts per square foot) with less-severe wind effects and other structural considerations.

The next consideration concerns further details of the actual flush-mounting method.

RAIL MOUNTED

As demonstrated in **fig. 1**, a typical rail-mounted system utilizes aluminum or light-gauge coated steel rails mounted above the seams or ribs of a metal roof.

This method normally orients the rails traversing the seams or ribs of the south-facing metal roof. Most module producers specify the “grabs” (hold-down clamps) for the module to engage the module along the long dimension, resulting in modules with “portrait” orientation to the roof slope. In high-wind areas, additional rails are sometimes necessary to provide another module attachment point (**fig. 2**).

Continuous rail allows neighboring modules to be within an inch or less of each other, which may maximize power density.

The offset above the base roof surface (usually 7 to 9 inches) allows easy access during installation and extra space for microinverters, optimizers, and rapid-shutdown equipment.

In climates prone to snow accumulation, the forces acting on the surface of the module create an eccentric loading (or moment arm) at the rails’ attachment points, increasing the forces applied to the attachment components. This effect is increased by higher offset dimensions (height above the roof), snow load, and roof slope. These variables must be considered in the design of the system. The disadvantages of this configuration include structural design complications, the resulting additional material and labor costs (over rail-less mounting), higher collateral loads, and the (perceived or real) negative aesthetics of a system raised above the roof.

Another version of a flush-rail PV mounting system is a flush “short-rail” (aka mini-rail or micro-rail), where short sections of rail are mounted on metal roof ribs as needed, to mount solar modules. These short-rails are installed parallel or perpendicular to ribs, depending on module orientation, and are sheet-only attachments when used on face-fastened roofs. While a short rail may save material costs and lessen collateral loads compared with continuous rails, the method of attachment should be carefully scrutinized.

Many products simply use one or two sheet metal screws on the top of the roof panels’ ribs. This method puts the fastening in direct withdrawal and yields very low pull-out values in light-gauge sheet metal. In contrast, fastening to the side of the rib wall puts the fastening in shear rather than direct withdrawal and is generally preferred (**fig. 3**).

RAIL-LESS MOUNTED (DIRECT-ATTACHED)

Solar modules may also mount directly to the seams of a standing

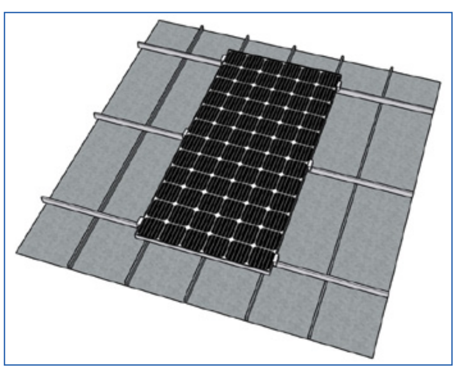


FIGURE 2. Flush Rail Mounted Portrait with 3 attachment points per side.

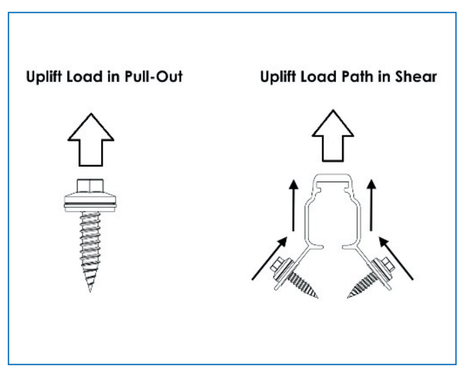


FIGURE 3. Wind Uplift Load Reactions with fastener in pull-out and shear.

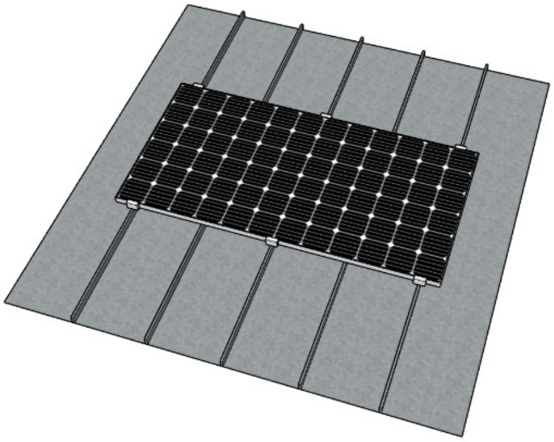


FIGURE 4. Flush Rail-less Mounted Landscape with 3 attachment points per side side.

seam metal roof or to the ribs of a face-fastened metal roof, eliminating the rail and related components entirely. Instead, the seams or ribs inherent to the metal roof serve as the mounting rails. The modules are installed in landscape orientation (**figs. 4,5**), still enabling recommended anchorage at the long side.

This method is like the flush-rail mounted system; however, it is lower in profile (usually 4 to 5¾ inches above the plane of the roof). This mounting method provides a more uniform load distribution to the roof and/or roof structure with as little as 15% of the weight (collateral load) of rails. Cost savings can be dramatic, especially in regions experiencing high-wind exposure, as in such cases the third rail is also obviated.

Another advantage of this method is that the roof is replete with ribs or seams, so there is increased module placement flexibility. Any loss (if it occurs) of power and energy density should be balanced against the rail material and labor cost savings in the financial analysis.

CONCLUSION

With increasing popularity, the metal roof is the ideal host for mounting solar PV due to its extended service life. Alternative roofing types will likely expire years before the life of the PV system, leading to erosion of the aforementioned ROI model.

Designers and owners should know about roofing alternatives and their service lives to bring added value to their customers. When it comes to attaching solar modules to metal rooftops, using conventional rails has been the traditional method. Yet, familiar concepts don't necessarily deliver the best outcomes. By installing solar on metal roofs with lower material, labor, and shipping costs, the rail-less attachment solution is proving to be a green innovation in both the solar and roofing industries. Solar Engineering Procurement Construction companies are often underinformed on all these subjects.

Recyclable metal roofs have a demonstrated service life several times that of any other roof type and are never destined for a landfill. Therefore, solar metal roof attachments enable installation on most aged roofs without a roof replacement. Production of rail-less systems saves an estimated 90% of the energy used to produce rail mountings and 85% of carbon emissions in transportation, hence a much lower carbon footprint.

Because of significant cost savings, time savings, ease of installation and flexibility of module layouts, simplified and low-cost logistics, and a greater return on investment, rail-less mounting on metal roofs is gaining traction—fast. As more industry professionals experience these benefits firsthand, these innovations will continue to be a go-to solution for metal rooftop solar mounting.

FIGURE 5. Flush Rail-less Mount.

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Mass Timber Moisture Protection

ABSTRACT

As interest in mass timber building design grows, there are new protection strategies that must be employed for a successful installation to ensure occupant long-term health and safety. This presentation will explain moisture protection strategies by providing in-depth test results on mass timber wetting and drying studies, methods to protect during each construction phase, and the vapor-permeable protection technology available to address wood's unique moisture characteristics. All to create a sustainable, stable structure and preserve the beauty of the mass timber building.

LEARNING OBJECTIVES

- Review the history of mass timber, its fast-growing use in today's construction markets and its popular use as a panel product in building construction.
- Examine mass timber's unique attributes related to moisture, ability as a hygric buffer, and susceptibility to damage from elevated levels of moisture.
- Appraise and discuss findings from field studies related to moisture levels in mass timber components during and post-construction.
- Discuss analyses from laboratory evaluations related to mass timber moisture exposure and drying using water vapor permeable and nonpermeable protection strategies.
- Understand which areas of mass timber construction are necessary to mitigate moisture intrusion and its effects on occupant health and safety.
- Discuss the importance of risk management best practices for designing and installing mass timber.

SPEAKER

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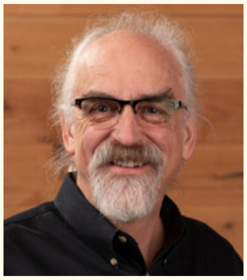

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Mass timber is now commonly referencing glued laminated timber (glulam and cross-laminated timber (CLT), the two most common types of current mass timber construction. CLT and glulam both consist of a series of layers of dimensional lumber—orientated perpendicularly in CLT or parallel in glulam—glued and pressed together to form large panels or beams. Prolonged and/or intermittent wetting of wood may cause staining, mold growth, and excessive dimensional change, which can result in decay and loss of strength. Throughout manufacturing, construction, and the building's expected service life, moisture is an important consideration when building with wood, including engineered mass timber products.

The introduction of CLT and glulam mass timber buildings has created opportunities for low-carbon and sustainable buildings. Due to these systems' fairly recent introduction, there has been a learning curve for the industry's understanding of their strengths and weaknesses. One such area where knowledge has been uncovered is in how moisture can compromise the material's durability. This paper will introduce mass timber CLT and glulam systems and raise awareness for the importance of protecting mass timber from the impacts of moisture during construction through building occupancy.

MASS TIMBER

Mass timber post and beam construction has been around since 2000 B.C. Glued laminated beams were introduced in Europe in the early 1890s and patented in 1901.

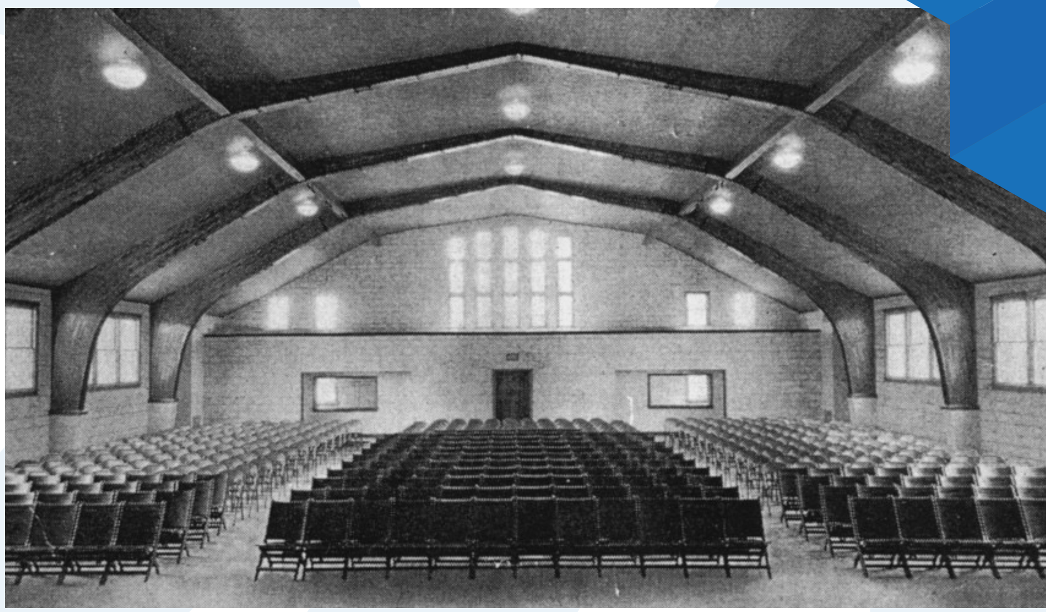

FIGURE 1. The first building in the U.S. to use glulam was a school gymnasium built in 1934 in Peshtigo, Wisconsin. Image from the Forest History Society.

The first structure to use glulam in the U.S. was a gym in Peshtigo, Wisconsin, built in 1934 (**Fig. 1**). Since its introduction, the use of glulam has become widely accepted. In 2022 the glulam market size was valued at around $3.8 billion.

Following the introduction of glulam, mass timber manufacturers have developed numerous types of panel systems, with the CLT being the most common for large panels. **Figure 2** shows various types of laminated wood panels. CLT panels were

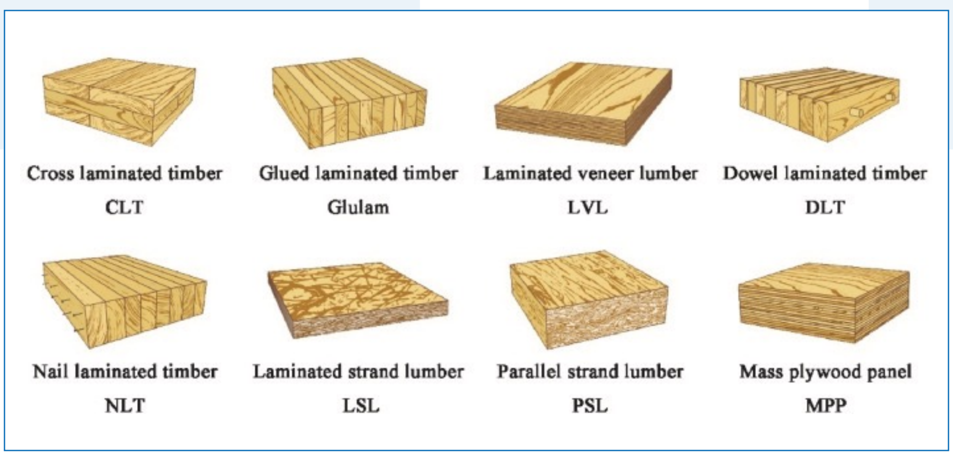

FIGURE 2. Different types of mass timber panels.

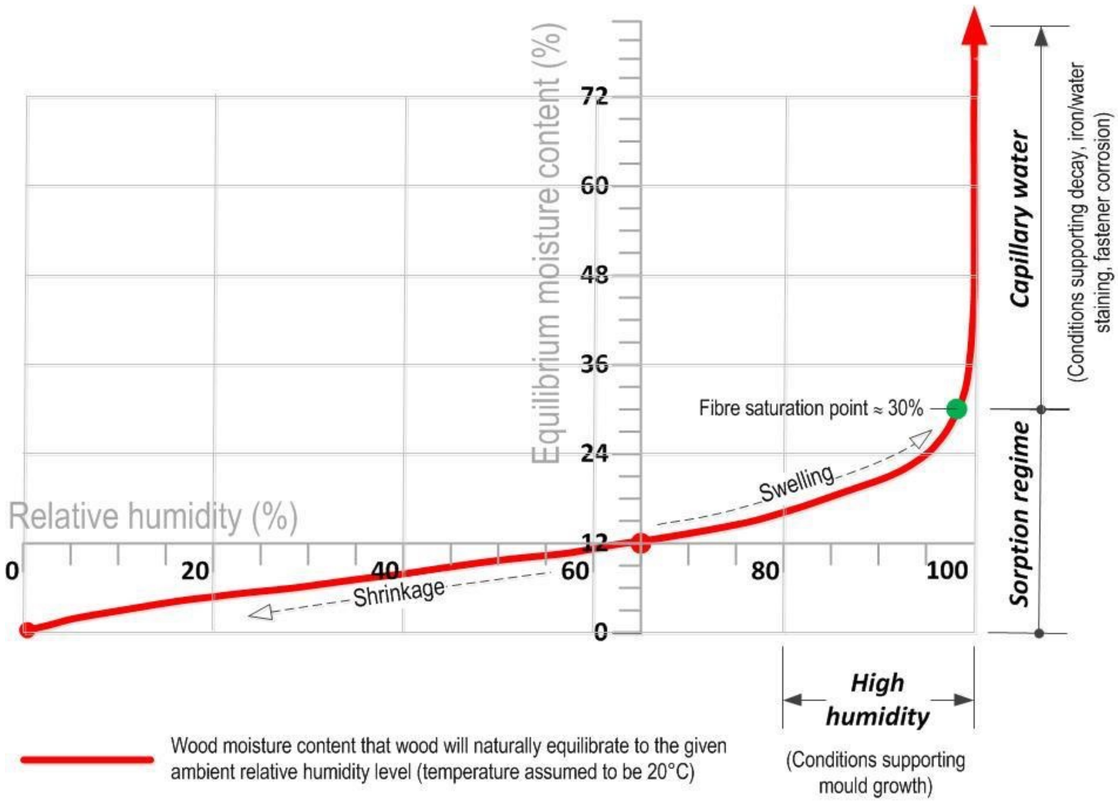

FIGURE 3. Sorption isotherm showing moisture levels of wood in relation to relative humidity. As relative humidity reaches 80% the moisture content levels of the wood are at 16% or greater which support mold growth and its degradation.[6]

first used in construction in Germany in the 1990s. Two decades later they were used in the United States for commercial buildings. Close to 2000 mass timber projects have been built in the United States, with heights reaching 25 stories. Due to mass timber's use of low-grade and smaller-diameter trees as raw material and its reduction in carbon emissions from non-wood building materials, it is becoming a popular choice for designers and owners. Global annual CLT production in 2020 was estimated at close to 100 million ft^3, with almost 43 million ft^3 within the U.S.[1]

The interest in mass timber as a construction material can be attributed to several advantages; One is low environmental impact, which includes carbon footprint, high strength-to-weight ratio, ease of installation, and aesthetic features. Regarding sustainability, mass timber stores carbon during its service life. Studies have shown that mass timber used in buildings has less than half the embodied CO^2 of conventional reinforced concrete buildings[2] and operating mass timber buildings is not highly energy-intensive.[3,4] A CLT panel or glulam beam can be reused or recycled, which can further reduce a building's carbon footprint. It is estimated that CLT panels and glulam beams can reduce construction time up to 30%, which lowers labor costs.[5]

DURABILITY

Durability of construction materials and components is particularly important for longevity as sustainability becomes ever-important. The benefit of timber- and wood-based products is their lifespan can be almost indefinite if they remain in a relatively dry condition. Timber is at risk of fungal decay and excessive dimensional change if its moisture content exceeds 20% for an extended period of time. In a well-designed and well-constructed timber frame building or pitched roof, the moisture content in service will be between 10% and 14%—well below the fungal decay threshold. While CLT follows the same durability principles as lighter structures constructed with dimensional lumber, its thickness and the mass of timber used present additional considerations when it is exposed to moisture. Dimensional studs, joists, and rafters have a relatively large surface area–to–volume ratio and will typically dry rapidly when conditions allow. On the other hand, CLT has a much smaller surface area–to–volume ratio, so drying rates can be substantially slower, which can greatly affect durability.

Wood is hygroscopic and moisture-content changes can affect a variety of properties. Studies show that moisture content increases as relative humidity increases. At a high level of relative humidity, the moisture content of wood reaches levels that support mold growth and degradation (**Fig. 3**).

Moisture ingress into CLT panels can lead to reductions in structural integrity due to physical changes that affect glue bond integrity as well as creep and dimensional stability. High moisture content will allow growth of organisms that degrade timber (**Fig. 4**).

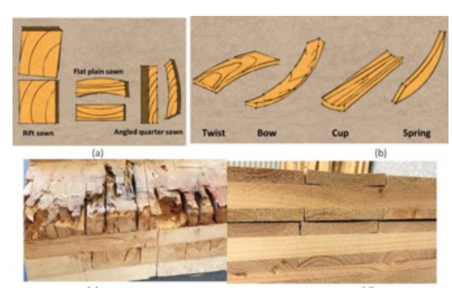

FIGURE 4. Effects of moisture on wood.[7]

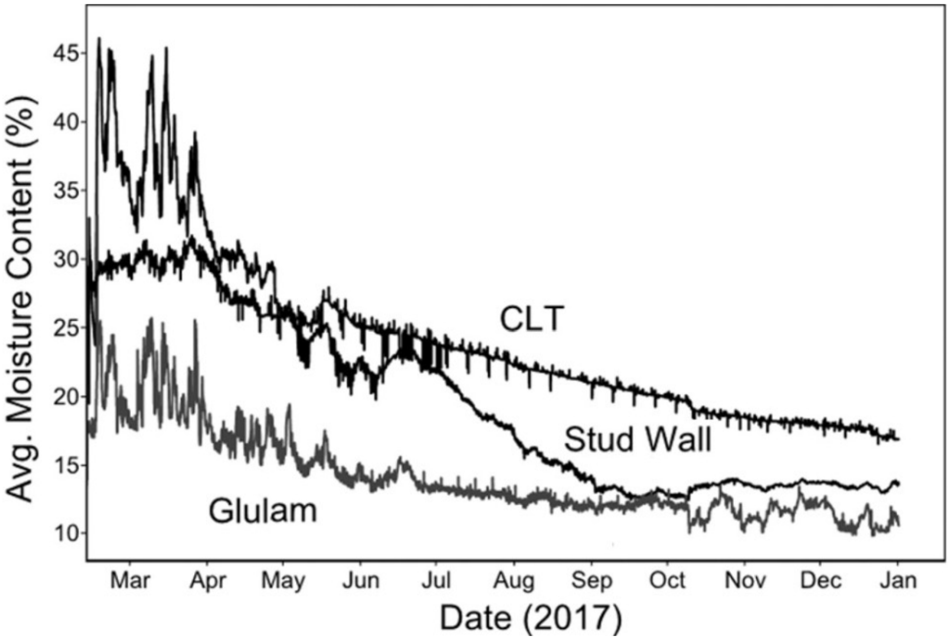

FIGURE 5. Monitored moisture content of the glulam, CLT and stud walls for one year, showing high average moisture content in the CLT panels from construction to the end of the study throughout the Portland study.

MONITORING MOISTURE LEVELS IN THE FIELD

Field studies of mass timber building projects in various climates show that when properly protected, moisture content and the damage associated with excessive moisture can be controlled. A 2019 study of an eight-story mass timber building constructed in Portland, Oregon, was monitored for one year from transportation, through the building process of January–April 2017, until December 2017.[8] Its construction used glulam columns and beams with CLT panel slabs. A steel framing system was used as additional support for seismic and wind loads. Light-framed stud walls were installed for exterior walls and interior partition walls.

Moisture sensors were installed to monitor the moisture levels of the mass timber systems. Moisture content was stable until the panels were unwrapped on site for installation and exposed to the weather. The unprotected CLT panels showed wetting during the many rain events of the Pacific Northwest throughout the construction. Applying a vapor barrier on the roof in April reduced the rain exposure as well as inhibited outward drying, slowing the drying process. Moisture content values of the glulam beams did not indicate any potential wetting problems as they were protected from excessive moisture by the CLT panels above.

Monitoring of the moisture conditions of the glulam and CLT panels shows that from manufacturing through shipping, the protective wrap kept moisture levels stable at approximately 10% moisture content. However, during construction, the unprotected CLT experienced high moisture content. The drying of the CLT panels was slowed due to the presence of vapor barrier installation, which was to protect from additional moisture exposure. The results indicate that exposed mass timber products should be protected from moisture throughout the construction, but still allow drying by incorporating vapor-permeable water-protection membranes (**Fig. 5**).

A field study monitoring a mass timber building in a humid southern climate was performed during the summer of 2019.[9] The mass timber structure Adohi Hall in Fayetteville, Arkansas, a three-story complex of interconnected buildings, was the largest glulam, CLT building at the time of construction.

Similar to the Portland project discussed earlier, moisture levels remained low during transportation, increasing during construction prior to waterproofing (**Fig. 6**). The authors of this study recommend protecting all mass timber material throughout the build process. Though moisture protection was eventually provided, it used a vapor barrier, which limited vapor-diffusive drying of the wet mass timber materials. This vapor barrier, as expected, inhibited further

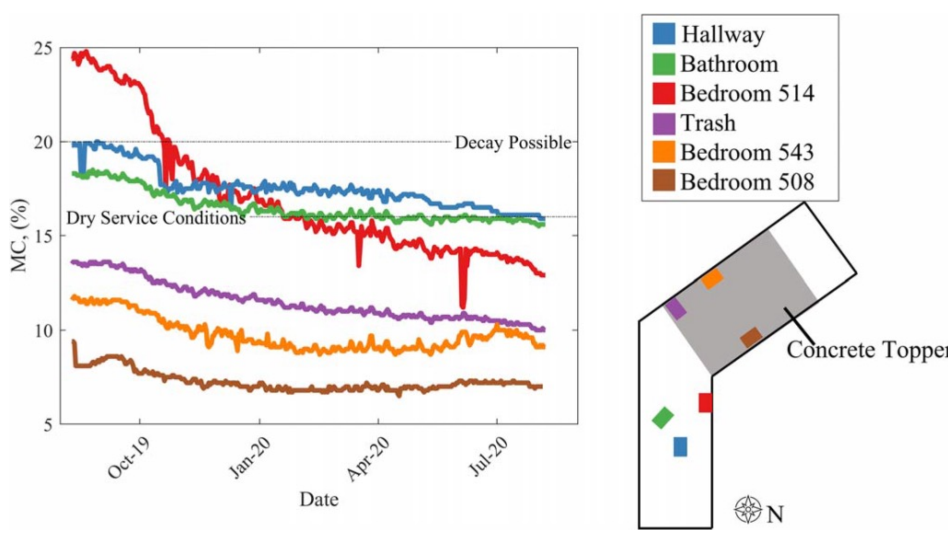

FIGURE 6. Monitored moisture content of the CLT for one year, showing high average moisture content due to unprotected panels during construction for the University of Arkansas Adohi Hall study.

FIGURE 7. Figure from the 2019 study by Schmidt et al.10 i) Edge B before weathering; ii) Edge B after two cycles of weathering.

wetting though slowed drying of the wet materials.

DRYING STUDIES EVALUATING WEATHER PROTECTION IN THE LABORATORY

A 2019 study by Schmidt et al.10 clearly shows the dimensional effects of moisture exposure to the CLT panel when moisture content levels exceed 16% (**Fig. 7**). Mass timber protection from moisture exposure is clearly important to prevent the damage moisture causes (**Fig. 8**). Both of these field studies described previously used a vapor-barrier for water-resistive protection, which provided protection from further water entry but limited drying through vapor diffusion.

In 2023 RDH Building Science Laboratories performed an evaluation for water holdout and the drying differences of a CLT panel using an unprotected panel, and panels protected with either a vapor-impermeable or vapor-permeable self-adhered membranes.[11] Following a 50-day surface wetting period of the CLT panel, the membranes were placed onto the panel surface. Moisture content was measured either gravimetrically (weight loss) or using moisture sensors. The results shown in **Figure 9** indicate fast drying for both the exposed (no membrane covering) and vapor-permeable self-adhered covered CLT panels. The vapor-impermeable self-adhered membrane-covered CLT shows much slower drying.

At 14 days, the moisture content of both the exposed CLT and vapor-permeable-membrane-covered CLT dropped below 20%, whereas the vapor-impermeable membrane showed very little drying. At 60 days, both the exposed CLT and vapor-permeable membrane showed a stable moisture content below 16%. These results show that a vapor-permeable self-adhered membrane has the advantages of both moisture protection and providing the opportunity for drying by vapor diffusion,

FIGURE 8. Damage due to moisture exposure from the 2023 RDH Building Science Laboratories evaluation.[11]

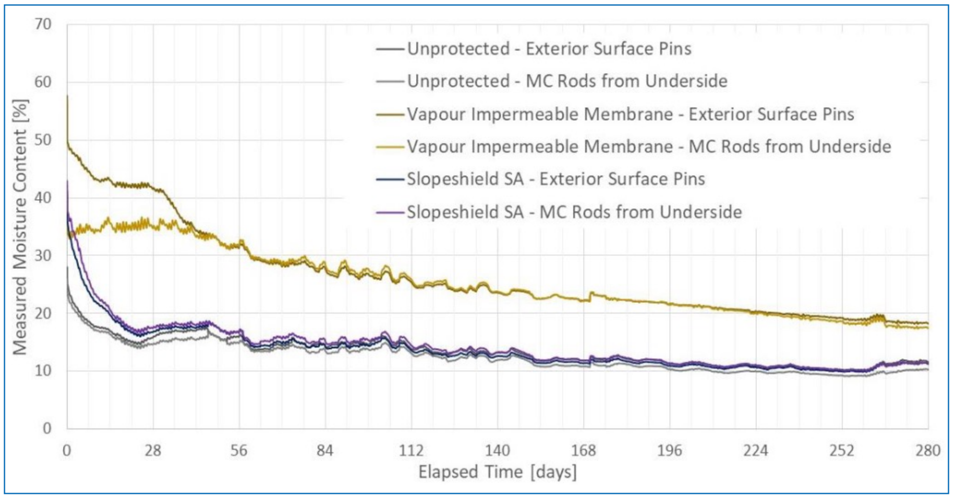

FIGURE 9. Moisture content sensor data during drying.

should moisture be present during the membrane's application. Faster drying will also occur if damage to the vapor-permeable membrane allows moisture ingress.

MOISTURE PROTECTION FROM MANUFACTURING THROUGH OCCUPANCY

It is clear from observing numerous mass timber buildings, references, research projects, and field testing, that the material must be kept dry. Without protective coverings, drying has been incorporated in some projects using heat, fans, and dehumidification to reduce the moisture content to a recommended level of below 16%. Because of CLT's smaller surface area–to–volume ratio, if long-term wetting occurs, drying the core rates can be substantially slower than traditional dimensional wood framing.

As described previously, mass timber damage will result in long-term exposure to moisture. This includes expansion severely moving the panels out of plane and out of dimensional tolerances, requiring expensive efforts to correct. Significant checking or cracking in the surfaces of the glulam or CLT panel faces also can occur. Drying efforts are possible, though the core will take additional time to dry especially when vapor impermeable moisture protection is used.

Due to the beauty of mass timber, it is typically left exposed for visibility. If mass timber systems are left exposed to weather, water that drains around and between the glulam and CLT panels will stain the exposed faces, requiring extensive, time-consuming, and costly remediation before the project is finished. For all these reasons it is necessary to limit mass timber materials' exposure to moisture.

Moisture protection should include cover during shipping, transportation, and storage. This typically includes wrapping the mass timber. It may also include installation of a vapor-permeable, water-resistive, self-adhered membrane at manufacturing. This can provide continuous moisture protection from manufacturing through the construction process. Because end grain is particularly sensitive to moisture, a water-repellent application covering the exposed edges with tape or sealants is sometimes used.

During construction some projects rely on moisture protection of the roof, leaving the floors exposed during construction from above and wall openings. Roof protection provides minimal moisture protection leaving the floors exposed and vulnerable to elevated moisture caused by weather conditions such as rain or snow events. There are alternative methods that are used to protect the movement of moisture through the CLT panel joints. One such method is taping over the joints or splines, leaving the face of the panel exposed. This option fails to stop surface water penetrations, resulting in staining or damage to the CLT panel on the underside exposed panel face.

The best approach includes a protective, vapor-permeable, water-resistive, self-adhered membrane immediately over the surface (**Fig. 10**). This prevents moisture that

FIGURE 10. Moisture protection applied to the CLT floors as a vapor permeable self-adhered membrane and glulam columns using a vapor permeable membrane wrap.

may enter the floor before the next level or roof is installed and hold out water coming from unfinished walls or rough openings that have not had the fenestration components installed. Should moisture enter the protective, vapor-permeable, water-resistive, self-adhered membrane through holes, the adhered membrane will inhibit lateral moisture movement and the vapor open membrane will provide additional drying through the membrane. As with all moisture-protection strategies, consistent removal of any standing moisture is important to reduce the risk of absorption.

Once the superstructure has been constructed, the cladding design should include a ventilated rainscreen to support outward drying of the CLT panels. This is only true if a vapor-permeable water-resistive barrier system is used. The ventilated rainscreen design provides drainage and drying when the cladding leaks, as well as supports vapor-diffusive drying into the vented cavity of the rainscreen.

CONCLUSION

Mass timber building has progressed over thousands of years from large timber framed construction to more recent technologies, such as the glulam and CLT panel systems discussed in the paper. CLT and glulam's introduction into building construction has provided many benefits: it shortens build time, sequesters carbon, and improves aesthetics. Being a fairly new technology, the recognition of mass timber building systems is gaining acceptance. Careful planning for design, manufacture, and installation is critical. Because wood is degraded by elevated moisture conditions, it must be protected. Moisture-protection strategies should include integrating weather protection from shipping to occupancy. The plan described in this paper incorporates water-resistant barriers that provide water ingress restriction while supporting vapor-diffusive drying should the mass timber become moist. In addition, for protection throughout construction, a ventilated rainscreen design can help extend the effective service life of the building.

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Restoration of Historic Temple Emanu-El

ABSTRACT

Temple Emanu-El is a historic synagogue built in 1927 and located in Providence, Rhode Island. Over many years and through various repair campaigns, the Temple's distinctive cast stone facades exhibited significant damage from cycles of freezing and thawing, blistered, and peeling coatings, and spalled concrete. Starting in 2015,the project team collaborated with the congregation to develop, design, and execute a restoration of the sanctuary facades, including replacement of original cast stone units with new cast stone units, a new glass-fiber-reinforced polymer shell to replace the cornice, repainting of the dome, and window and door restorations. This paper offers an insiders' view of the investigation, design, and challenges with recladding a historic composite mass masonry facade.

LEARNING OBJECTIVES

- Identify the components of a composite mass masonry wall.
- List three failure mechanisms for coatings on concrete
- Explain the importance of minimizing alkali-silica reaction in new concrete.
- Describe various challenges with restoration of a historic building facade for a religious congregation with limited funding opportunities.
- Identify observed deteriorated cast stone conditions.

SPEAKER

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Tara Ikenouye, AIA, CPHC, is an architect with master's degrees in architecture and historic preservation. She is a senior associate with Wiss, Janney, Elstner Associates Inc. at the Boston office. She has performed condition assessments, designed repairs, restoration, and renovations for many historic buildings from the 18th, 19th, and 20th-centuries. In addition to a practice in historic preservation, Ikenouye provides enclosure consulting services for new and existing building projects with technical expertise in brick and stone masonry, concrete, windows, and roofing. She can often be found asking questions at the front of a historic house tour.

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Temple Emanu-El is a synagogue that is a prominent landmark in the East Side neighborhood of Providence, Rhode Island. The Temple complex consists of the original domed sanctuary built in 1927 designed by the then Boston-based firm Krokyn & Brown, an education building built in 1953, and a meeting house built in 1959 (**Fig. 1** and **2**). Wiss, Janney, Elstner Inc. (WJE) started working with the congregation at Temple Emanu-El in 2015 to investigate coating and repair failures at the cast stone facades of the sanctuary. In 2019, WJE was contacted again by the Executive Director and President of the Temple in 2019. Frustrated with the ongoing deterioration of the cast stone facades that clad the section of the sanctuary that greeted neighbors walking by and welcomed congregants inside, Temple administrators enlisted WJE to design a full facade restoration of the sanctuary. This project would require significant effort to remove existing cast stone units from the building facades and replace them with more than 400 new cast stone units. WJE, Temple administrators, congregation members, and Joseph P. Gnazzo Company (Gnazzo), an experienced historic masonry contractor, collaborated to successfully resolve the many challenges encountered during construction, and the restoration was completed three years later.

FIGURE 1. Temple Emanu-El. This photo was taken some time between 1930 and the 1950s. *Source: Temple Emanu-El Archives.*

In the era when Temple Emanu-El was designed and built, architects were experimenting with ways to use manufactured materials such as concrete and terra-cotta to mimic natural stone. At that time, cast stone cladding was a more economical material than natural stone and could be cast to mimic the visual appearance of traditional masonry materials. The Temple sanctuary is designed in the stripped classical (modern classical) style that was developing in Europe and the United States in the early 20th-century. This is a streamlined architectural style that retains foundational elements of classical architecture, such as porticos, colonnades, and domed roofs, but eliminates more decorative aspects of traditional classical styles. Many public and institutional buildings in the United States and Europe were designed in this style during this time as a physical manifestation of classical government ideals. The Temple sanctuary consists of a central square mass with a domed roof, and a longer

FIGURE 2. Temple Emanu-El site plan from Sanborn Insurance Map. *Source: City of Providence Archives.*

FIGURE 3. Cast stone units at the parapet with freeze-thaw damage and coating failure. *Source: Wiss, Janney, Elstner Associates Inc.*

and narrower rectangular mass oriented diagonally along the northeast to southwest axis. There are three sets of hand-carved wood double-doors, a four-column cast stone colonnade forming a shallow portico, and a cast stone cornice above the columns with an entablature carved and gilded with the inscription "Seek Ye The Lord And Live."

The main entrance and return facades of the sanctuary are clad with 4- and 8-in.-thick (102 and 203-mm-thick) cast stone units placed in a running bond pattern with multi-wythe structural clay tile backup walls. The typical cast stone unit at these facades is approximately 24 in. (610 mm) tall and 36 in. (914 mm) wide. Each unit weighs between 300 and 600 lb (136 and 272 kg), depending on the depth of the unit. The other facades of the sanctuary building are primarily constructed of multi-wythe brick masonry with cast stone coping units along the parapet, a cast stone belt-course that wraps around the building at the top of the facade, and other decorative cast stone elements such as plaques with gilded inscriptions or designs, and two cast stone units depicting the Ten Commandments with gilded lettering at the center of the parapet above the main entrance.

Historical photographs from the time of original construction show that the cast stone elements of the sanctuary were not coated. However, by 2015 when WJE was first engaged by the Temple, coatings that had been applied on the cast stone starting in the early 1990s exhibited pinholes, splits, and blistering, and were delaminating at many locations. Where the coating was distressed or damaged, the underlying cast stone also exhibited craze cracking, uneven surface texture, pockets of efflorescence, and incipient spalls. Multiple cast stone units at sanctuary facades had damage from cycles of freezing and thawing (**Fig. 3** and **4**). As part of the initial condition assessment, core samples from three cast stone units were removed for petrographic analysis. Samples of the various coatings were also removed to study the many layers and types of coatings applied to the cast stone.

The petrographic analysis was used to microscopically assess failure mechanisms, mixture proportions, and air entrainment in the concrete. It demonstrated that the sampled cast stone was a wet cast mixture versus dry tamp cast mixture, which are the two methods to manufacture cast stone units. The mixture was not air entrained and exhibited properties consistent with a mixture that had a high water-to-cement ratio. The non-air-entrained concrete made the cast stone units more susceptible to freeze thaw damage, which was consistent with findings from the petrographic study. The parallel microcracks present at the outer end (the exterior face of the cast stone unit) and inner end (the face of the unit next to backup masonry) of two sample cores were a result of cyclic freeze-thaw deterioration (**Fig. 5**). Without air voids to accommodate expansion within the units from the pressure of ice formation during freezing-and-thawing cycles, the concrete cracked. The finding that the inner end of the core samples showed deterioration from freezing and thawing indicated that the unit embedded within the mass-masonry wall was experiencing saturated conditions. This finding aligned with overall conditions of the sanctuary facades.

FIGURE 4. Cast stone units at the belt course with blistered and peeling coatings and efflorescence. The top and bottom photos are from 2015 and 2019, respectively. *Source: Wiss, Janney, Elstner Associates Inc.*

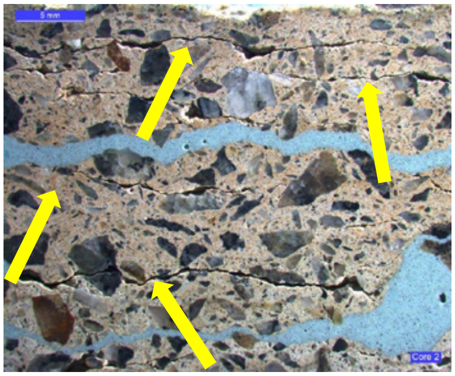

FIGURE 5. This is a cross-section sample from one of the cast stone core samples. Parallel microcracks in a cast stone sample are indicative of damage from cycles of freeze-thaw damage. *Source: Wiss, Janney, Elstner Associates Inc.*

FIGURE 6. The removal of cast stone units from the sanctuary facade exposed structural clay tile back-up masonry. Note the void where 8-in.-deep (203-mm-deep) units were removed (arrow). *Source: T. Ikenouye, Wiss, Janney, Elstner Associates Inc.*

Water had a pathway into to the cast stone facades from troublesome conditions present at the sanctuary. Sealant installed at mortar joints had blocked water from migrating out of the wall through these joints. The layers of coatings that were intended to protect the cast stone from moisture actually trapped water within the concrete when moisture bypassed the coating through splits, voids, and peeling coatings. Through-wall flashings with short drip edges were also sealed without weeps. As composite mass-masonry walls, the facades of the sanctuary were designed to manage water from rain and snow with a cycle of absorption and release through the cast stone and brick masonry. However, the many added layers of coatings effectively became a vapor barrier, and with the sealed mortar joints, this moisture management system was disrupted. These modifications were causing significant damage to the facades.

After the investigation and laboratory analysis, WJE presented Temple administrators and congregants with three options to address the conditions at the cast stone facades. These included baseline repairs to address aesthetic concerns and repair conditions at the facades to prevent further water intrusion and protect the concrete; facade overcladding; or facade recladding with new cast stone units. The baseline repairs would include repointing, new flashings, removing the existing coatings, completing crack and concrete repairs, replacing some cast stone units, and installation of a new elastomeric coating. This scope of work would become the first of many cycles of repairs to maintain and continue to repair the original cast stone units where damage from prolonged saturation and freeze-thaw cycles could not be undone but only managed.

The overcladding option envisioned a new mechanically fastened cladding anchored to the backup masonry, bypassing the existing cast stone units but leaving them in place. A thorough structural analysis of the existing backup walls would be required for this option. The overcladding option also meant a major alteration to the appearance of the historic building.

The third option, which was ultimately selected by the Temple, was to reclad the cast stone facades with new cast stone units. This option offered a pathway to address the deterioration of the facades, reduce future maintenance requirements, and restore the sanctuary to retain its historic appearance. In addition to removing existing cast stone units and replacing with new cast stone units, this option involved full restoration of other facade elements, including new flashings, complete repointing of the brick masonry facades of the sanctuary, sealant replacement at building joints, restoration of historic stained glass wood windows, re-gilding decorative elements, and painting the dome. This was the scope of the project that Temple Emanu-El, WJE, and Gnazzo started in the spring of 2020, as the world was grappling with the initial effects of the COVID-19 pandemic.

The restoration project designed by WJE was based on findings from the investigation in 2015, and additional investigation in 2019. Without historical drawings, information about the as-built construction of the sanctuary had to be collected through fieldwork and inspection openings. From the inspection openings, the project team learned that the cast stone units alternated between 4 and 8 in. (102 and 203 mm) deep. The team decided to design new cast stone units to be 3½ in. (89 mm) deep to allow for a ½ in. (13 mm) joint for new adhesive anchors and grout. The expectation was that the 8-in.-deep units would remain embedded in the backup masonry with the outer 4 in. cleaved off. However, once the masonry contractor started removing cast stone units, they proposed fully removing the 8-in.-deep units and infilling with brick masonry (**Fig. 6**).

FIGURE 7. Historic door pull handle found in storage room. A mold based on this handle was used to cast new bronze pull handles for the restored front doors. *Source: Wiss, Janney, Elstner Associates Inc.*

This approach was easier for the masons and maintained the load path of the back-up masonry wall.

The concrete mixture for the new cast stone units reflected what the construction industry has learned about extending the service life and long-term performance of concrete since the first units at the sanctuary were cast nearly 100 years prior. The new units were wet cast with a concrete mixture that had 4% to 6% air entrainment in accordance with ASTM C185, *Standard Test Method for Air Content of Hydraulic Cement Mortar*,[1] and a maximum water-to-cement ratio of 0.35. That maximum ratio, which took into account water added to the mixture as well as moisture content from the fine and coarse aggregates, had previously demonstrated successful resistance to freeze-thaw damage. WJE required the cast stone manufacturer to test the fine and coarse aggregates, in accordance with ASTM C1260-14, *Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar Bar Method)*,[2] to demonstrate that the aggregates would not adversely react to the cement alkalis in the concrete mixture. This reactivity, which is referred to as alkali-silica reaction (ASR), results in a silica gel formed around the aggregate and is associated with expansion that leads to cracking of concrete.[3] The process of the cast stone manufacturer sourcing and testing aggregates and cement for ASR took several months before a combination tested within acceptable alkali-silica reactivity limits.

Some of the concrete elements of the sanctuary facade would not be replaced but would receive concrete repairs and be recoated with an elastomeric coating. Therefore, the new cast stone units were cast with a pigmented concrete mixture to closely match the color of the new coating. The light-beige color selected for both the concrete and the coating so closely resembled the color of the coating of the old facades that most passersby would not have known that the extent of the restoration at the sanctuary involved more than new gilding and updating of the gold-painted dome.

The cast stone units that comprised the cornice were large and deeply embedded in the exterior wall, and the original plan for restoration and repair at the cornice above the portico was primarily localized concrete repair. However, when demolition was underway, it became apparent that freeze-thaw damage was widespread in the projecting sections of the cornice and would require extensive concrete repair. The Temple, WJE, and Gnazzo agreed that retaining the embedded sections of the cornice, removing the deteriorated concrete, and replacing the cornice with a new glass-fiber-reinforced polymer (GFRP) shell was an appropriate option. Aesthetically, the GFRP was a smart choice because the shell could match the profile of the existing cornice as well as the color of the new cast stone units and new coating. The GFRP shell also replaced concrete, which would have continued to deteriorate and require regular repair.

While the ongoing deterioration of the cast stone at the sanctuary was the main reason for the restoration project, many other elements of the facades were in as much need of repair. The project budget allowed for restoration of some of the smaller stained and colored glass windows that were set in the cast stone sections of the facade. The frames of these windows had to be modified because of the placement of the new cast stone units. Additionally, restoration of these windows involved wood repair, repainting, reglazing, and installation of new exterior storm windows.

The large, double-height-stained glass windows that provide light into the main sanctuary space already had protective exterior storm windows. These were repaired and repainted as part of this project. The Temple planned to apply for historic preservation grant funding so that these stained glass windows could be restored at a future time.

In addition to wood window restoration, the three front entrance doors with hand-carved surfaces were removed and carefully restored off site. During construction, the property manager for the Temple found one of the historic bronze door handles in a storage room. The contractor located a nearby foundry to mold and cast new handles for all three doors (**Fig. 7**).

Elements of a facade that can be touched, such as the Temple's door handles, or that can be seen from afar, like the gilded carved designs and lettering, and the glistening gold-painted dome, are what most people notice when it comes to the building restoration. That is why it was important for this restoration to address those features. For the depiction of the Ten Commandments tablets at the parapet above the main entrance, new cast stones were cast and gilded. The three cast stone plaques above the front doors, the cast stone plaques at each corner of the building, and the entablature below the new GFRP cornice did not have the same extent of concrete deterioration as

FIGURE 8. The restored Temple Emanu-El with new cast stone units, a glass-fiber-reinforced polymer cornice, and gilding completed.

other areas. Therefore, the team only had to remove the coatings on these elements and recoat the concrete before applying new gold-leaf gilding to the carved designs and lettering.

The dome atop the sanctuary is constructed of steel, metal lathe, and stucco and is clad with flat-seam copper roofing. Many coatings and paint had been applied to the copper over the years. The project budget did not allow for reroofing the dome with new copper, but the Temple did not want to leave the dome as-is so the team decided to repaint it. The contractor designed and erected a creative system of rope access so that painters were able to remove many of the layers of paint on the dome down to an asphaltic coating. This coating was well-adhered to the copper and could not be fully removed. Repainting the dome required a specialized paint formulated for applications on exposed architectural metal surfaces that had to be supplied from the Midwest. WJE performed field-adhesion testing on several primer and paint mock-ups before a combination capable of adhering to the substrate was determined.

Work on the dome, which was the last major part of this project to be completed, was finished in the fall of 2022. At this point, WJE had been working with the Temple for seven years starting with the first investigation in 2015. When design for recladding with new cast stone units and restoration of the sanctuary facades was completed in early 2020, the construction team planned to start work in the spring of 2020 and initially established a 12-month to-completion schedule. Then, the COVID-19 pandemic disrupted the project timeline.

With construction work stopped by local government shutdown restrictions, supply chain delays, and a lack of skilled labor, the project had many pauses and schedule resets. However, the project was successfully completed because of the crucial combination of an engaged client, a pragmatic design team, and a skilled and resourceful historic masonry contractor. Temple Emanu-El is a place of personal importance to many in the congregation and community (**Fig. 8**). Individual donors, who contributed to funding for this project; volunteers, including a member of the Temple (also an architect), who lent their time each week for project team meetings and site visits; members of Temple operations committees, and Temple staff, who had with many other responsibilities besides this project were at the heart of this successful project.

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Cold-Weather Condensation Problems in Fully Insulated Low-Slope Roof Systems to Meet NFPA 13 Requirements

ABSTRACT

Many low-slope roof systems installed over insulated framing spaces develop condensation problems. Unlike similar steep-slope roof systems that use convection- and wind-driven ventilation to dissipate moisture, effective venting is difficult to achieve in low-slope applications. The risk of condensation problems is especially of concern in framing spaces that are fully insulated to avoid the use of sprinklers in accordance with NFPA 13 requirements, which is the focus of this paper. Interior air can flow into these insulated framing spaces through ceiling penetrations, interior walls, pressurized ductwork, and other sources. Solutions often involve using unvented roof systems that consider insulation and air barrier placement. Recent code changes have reduced (although not eliminated) the risk for condensation in unvented insulated roof framing systems. This paper reviews the causes of condensation in these systems and methods for preventing them.

LEARNING OBJECTIVES

- Discuss the common causes of condensation problems in low-sloped insulated framed roof systems and why these systems operate differently than similar vented steep-sloped insulated systems.
- Analyze how the use of pressurized ductwork within roof framing and how rooftop vents and exhaust fans increase the risk of condensation.
- Explain how recent building code changes that added requirements for unvented roof systems have reduced (although have not eliminated) the risk for condensation problems in these systems.
- Develop design and repair approaches for reducing the risk of condensation problems in these systems.

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FIGURE 1. Sheathing and truss failure in insulated roof framing system (insulation removed to show distress).

INTRODUCTION

The authors have investigated numerous failures in low-slope roof systems installed over insulated framing spaces. In many cases, these failures are severe, involving decay and structural failure of the roof sheathing and top chords of wood roof trusses (**Figure 1**), even in climate zones with relatively moderate winter temperatures. A recent increase in the number of requests to investigate failures of these systems indicates to the authors that the issues causing these failures are not well understood by the building community. A significant percentage of these failures involve multistory, multifamily buildings where the roof framing spaces are filled with noncombustible, air-permeable insulation to avoid the use of sprinklers within concealed spaces in buildings governed by NFPA 13.[1]

In 2021, we investigated a failure of this type in the Midwest (Climate Zone 5). The four-story wood-framed apartment building, completed in 2017, has wood floor and roof trusses spanning the 60 ft width of the building. The top chord of the roof trusses sloped from 36 in. to 20 in., creating a roof slope of ¼ in. per ft (**Figure 2**).

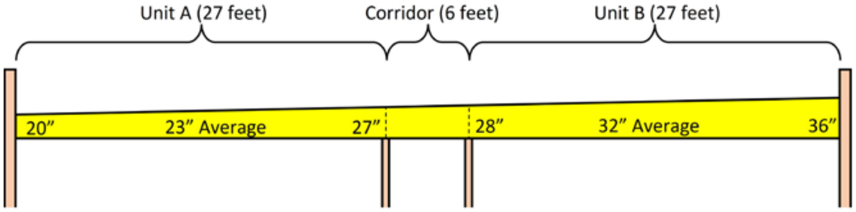

FIGURE 2. Diagram of truss.

FIGURE 3. Ductwork within insulation.

FIGURE 4. Zip tie connection of flexible duct to ceiling diffuser.

The building height exceeds 60 ft, triggering NFPA 13[1] sprinkler requirements. To omit sprinklers from the roof framing space, the roof framing space was filled with noncombustible insulation. Although the fiberglass batt insulation was specified to be slightly compressed by the roof sheathing, the actual construction typically has a small gap between the insulation and the sheathing. No vapor retarder was required or provided above the ceiling below the insulation. However, installing a vapor retarder in this location in an unvented assembly can increase the potential for moisture issues by trapping any moisture that is introduced into the truss space between two vapor retarders (the roof membrane at the top side and the vapor retarder at the bottom side). Each apartment unit includes a 1.5- or 2-ton heat pump unit with ductwork (both flexible and rigid) located in the roof framing space (**Figure 3**).

As is common, the flexible ductwork was connected to the main rectangular ducts and ceiling diffusers with plastic zip ties (**Figure 4**).

We will review the causes of this type of failure and how it can be avoided. Our analysis focuses on multistory, multifamily residential buildings conforming to NFPA 13.[1]

BACKGROUND

Code Changes that Increase Condensation Risk

Increases in Required Thermal Performance

Low-slope wood-framed roof assemblies are common in multistory, multifamily buildings due to their familiarity, simplicity, and cost effectiveness. Historically, these assemblies were often insulated with a relatively thin layer of rigid insulation on the top side of the sheathing or a small amount of insulation above the ceiling. Even with insulation in the framing space, the potential for condensation was low since the temperature differential across the minimal thickness of insulation was relatively small. As prescriptive requirements for thermal performance increased, placing all the insulation within the framing space became a practical and economical method for achieving code-required roof thermal performance. However, this approach can increase the potential for condensation since the large temperature differential across the insulation thickness causes the sheathing temperature to approach the exterior temperature during winter months. Any interior air that enters the framing increases the moisture content of the air in that space. This moisture will condense on surfaces that are below the dew point temperature of this air, such as the sheathing. Prolonged exposure to condensation can contribute to conditions such as apparent water leakage to the interior (from condensation dripping to the space below), biological growth, corrosion of metal components and fasteners, and, in severe cases, wood decay.[2] Researchers have estimated that as many as 20% of assemblies insulated with only air-permeable insulation within the framing space fail within the first 10 years,[3] particularly in cooler northern climates.[4,5]

NFPA 13

Another important code issue that is increasing the frequency of condensation problems in low-slope roof systems relates to sprinkler requirements. In the past, codes often did not require sprinklers. However, sprinklers are currently required in most parts of the United States, governed by the requirements of either NFPA 13[1] or NFPA 13R.[6] While the more stringent NFPA 13 is intended to provide property protection in addition to life safety, NFPA 13R is limited to providing life safety.[7] NFPA 13R is only permitted for residential occupancy buildings with four stories or fewer that do not exceed 60 ft above grade.[6] The 2021 IBC also includes provisions to allow taller multifamily residential buildings with podium construction and sprinklers per NFPA 13.[8]

NFPA 13 incentivizes designers to fill the wood-framed roof spaces with noncombustible insulation to avoid the need for costly sprinkler protection.[4] Since air-impermeable insulations such as polyurethane and polystyrene foams are combustible, air-permeable noncombustible insulations, such as fiberglass batt, loose fiberglass fill, and cellulose fill, are typically used. As the amount of insulation added to fill the framing space is often far greater than that required by energy code, the surface temperature of the roof deck and portions of the framing will approach exterior temperatures during winter weather, increasing the potential for condensation.

Reflective Roof Surfaces

The potential for condensation problems in these systems during cold weather is further increased by code-required reflective roof membranes. Roof membranes with high reflectivity result in cooler roof decks and consequently higher moisture contents, since the roof, by design, will absorb less solar radiation.

Code Changes that Reduce Condensation Risk

Until recently, the design and construction of low-slope, insulated framed roof assemblies was not clearly addressed in the building codes. Whereas some designers and code officials have applied the ventilation requirements for steep-slope roofs to these low-slope roofs, these ventilation requirements are generally not appropriate in this application, often making condensation problems worse by drawing interior air into the framing space. A viable approach was not provided in the building codes until the 2015 IBC, which added guidance in Section 1203.3 (1202.3 in subsequent editions).[9]

The code revisions to address condensation in low-slope and unvented roof assemblies primarily consider: (1) airflow and air leakage via air barrier placement and detailing,[10] (2) the appropriate ratio and placement of air-impermeable versus air-permeable insulation,[11] and (3) exterior design temperatures which provide an appropriate balance between practicality and conservatism.[12] Based on field studies and analyses by the authors, the options for insulation selection and placement can significantly reduce the potential for condensation. However, pressurized ductwork located within the roof framing, which can be a significant source of air leakage, is notably absent from the code provisions.[8]

CONDENSATION FORMATION

Moisture within the air of the roof structure (and thus, condensation risk) increases due to airflow from the interior in combination with ineffective ventilation of the framing space with exterior air.

Sources of Interior Air

Assuming that the roof membrane and adjacent wall interfaces are watertight, moisture typically enters the roof framing space via interior air leakage driven by positive pressurization of the occupied space relative to the framing space. Although vapor diffusion can also contribute to moisture in these roof framing spaces, it is generally only a small fraction of the moisture delivered by air flow.[12,13] In typical construction, there are numerous potential airflow paths between the interior and the unconditioned framing space. These include partition walls interrupting the plane of the ceiling, MEP penetrations (including exhaust fans for spaces with high moisture generation such as bathrooms and kitchens), sprinklers, and recessed light fixtures. Vapor barriers beneath the framing spaces, when provided, are rarely airtight. Such incomplete barriers allow interior air to flow into the framing space. As noted previously, vapor retarders placed both above and below the framing space increase the potential for damage.

Although interior air flowing into the framing space adds moisture, perhaps the most significant source of air and moisture is the presence of pressurized HVAC ductwork above the ceiling. The air within the ductwork will either have approximately the same moisture content as the room air, or greater if humidification is supplied by the HVAC system. Therefore, the amount of moisture within the ductwork that may be added to the framing space via duct leakage can be significant. For sound transmission, space savings, and maintenance accessibility, ductwork for each dwelling unit is typically placed in the ceiling of the unit served, rather than within the ceiling of the unit below. As in the example discussed earlier, the ductwork at the top floor occurs within the roof structural system. Even reasonably well-sealed ductwork is not airtight, with unsealed crimped seams and connections commonly formed with zip ties. Based on infrared thermography and other studies by the authors, most duct leakage occurs at connections with ceiling diffusers and at joints and connections with sheet metal ducts. Since the air is under pressure, even small voids and joints can allow significant leakage. Based on research by others, "low leakage" can be characterized as less than 5% of duct inlet flow.[14] This characterization is supported by measurements of 11 residential sites in California, Nevada, and Texas constructed circa 2000[15] and 19 residential sites in Wisconsin constructed circa 2008.[16]

Ineffective Ventilation

Steep-slope framed roof systems are typically vented to dissipate moisture via natural convection and wind. This is accomplished by providing lower (soffit) and upper (ridge) vents, as required in the IBC. Although attic ventilation is often attributed primarily to natural convection (warm air rising out of upper vents is replaced by cool air entering lower vents), studies have shown that ventilation by convection is typically an order of magnitude less than that provided by wind.[17,18] To be effective, wind must enter on the windward side and leave on the leeward side. This type of cross-ventilation is typically not practical in low-slope roof systems. This is especially difficult to achieve in framing spaces with draft stopping per the

FIGURE 5. Turbine-style roof vent.

IBC and NFPA 13R, or those filled with insulation per NFPA 13, to avoid sprinklers in the framing space. When roof vents are placed on the top surface of the roof to ventilate the system, wind blowing across the roof creates negative pressure that will draw air out of these vents. Natural convection can also provide a small additional contribution to the negative pressure, with solar radiation heating the roof surface and causing the adjacent air to flow out the topside vents.

The air drawn from the topside roof vents is replaced with interior air, increasing the potential for condensation within the framing space. This risk is further increased with turbine roof vents (**Figure 5**), whose spinning action moves more air.

Most insulation products applied within the wood framing space (e.g., fiberglass or cellulose) are not airtight, regardless of how densely packed the assembly may be.[3] Whereas heat from leakage sources such as ducts, pull-down attic access ladders, or recessed light fixtures will not uniformly heat surfaces throughout the roof assembly because of the insulation, air and moisture from these sources will flow throughout the assembly. This can contribute to unique distributions of condensation, with the most severe damage counterintuitively located at surfaces away from the leakage source which are not effectively warmed above the dew point temperature.

ANALYSIS OF UNVENTED ROOF ASSEMBLY OPTIONS PER IBC

Options for Insulation Placement per 2021 IBC

For the purposes of this study, the 2021 IBC[8] was considered. (For Climate Zones 5, 6, 7, and 8, Section 1202.3—formerly 1203.3 in 2015—is essentially unchanged since its first adoption in 2015.) This section outlines requirements for unvented roof assemblies, including four basic options for insulation placement: (1) 1202.3.5.1.1 – only air-impermeable insulation, in direct contact with the underside of the sheathing, (2) 1202.3.5.1.2 – air-permeable insulation in direct contact with the underside of the sheathing, with a prescribed *R*-value of rigid insulation above the roof deck for condensation control, (3) 1202.3.5.1.3 – a prescribed *R*-value of air-impermeable insulation in direct contact with the underside of the sheathing and air-permeable insulation directly beneath (no insulation above the deck), and (4) 1202.3.5.1.4 – air-permeable insulation beneath the sheathing, with rigid insulation above the roof deck in sufficient thickness to maintain the monthly average surface temperature of the underside of the sheathing above 45°F (7°C), given an interior temperature of 68°F (20°C) and an exterior temperature equal to the monthly average air temperature for the coldest three months of the year.8 Each of these options has subsequent impacts on fire protection, assembly thickness and detailing, and other project requirements, which must be considered.

Options #2 and #4

Only Option #2 and Option #4 above comply with the NFPA 13 exception to avoid the need for sprinklers in the framing space (provided insulation fills the space), since the materials that are typically used for air-impermeable insulation included in Option #1 and Option #3 are combustible. Option #2 and Option #4 describe the same basic type of construction, but with different criteria for determining the amount of insulation above the deck. Option #2 prescribes a minimum insulation thickness above the deck based on climate zone,[11] while Option #4 employs a practice for selecting an exterior design temperature and corresponding insulation thickness.[12] Overall assembly thickness must also be considered, as adding insulation above the roof deck increases the thickness (and cost) of the assembly and may require modifications to drainage and flashings.

Filling the framing space with air-permeable insulation to meet NFPA 13 requirements increases the potential for condensation in Option #2 for deep roof framing by placing a large percentage of the total insulation below the sheathing, decreasing the sheathing temperature. The authors have encountered buildings where wood trusses exceeding 40 in. (101.6 cm), needed for structural support and to accommodate ductwork and equipment, were filled with noncombustible insulation to meet the requirements of NFPA 13. In such cases, the thickness of insulation above the sheathing is not increased in Option #2; however, significant additional insulation must be added in Option #4 to maintain the sheathing temperature above 45°F (7°C). Therefore, projects that use Option #2 and omit sprinklers may be vulnerable to condensation problems depending on the insulation thickness above the deck.

Note that NFPA 13 allows a maximum 2 in. air gap between the insulation and sheathing. Therefore, the insulation may not be in “direct contact” with the sheathing, as

TABLE 1. Minimum *R*-values and design temperatures for each climate zone.

Climate Zone	Minimum *R*-Value of Air-Impermeable Insulation[(a)]	Corresponding Thickness of Rigid Insulation, in.[(b)]	Monthly Average Outside Air Temperature for Three Coldest Months, °F[(c)]
6A	*R*-25	4.25	20
5A	*R*-20	3.5	24
4A	*R*-15	2.5	33
3A	*R*-5	1	41

(a) Source: 2021 IBC, Table 1202.3.8
(b) Source: Calculated based on R-value of 6 per in.
(c) Source: Calculated from the climate data file from the WUFI database using the representative location for each climate zone.

required in Option #2. However, since the insulation is air permeable, this small gap is unlikely to significantly alter the behavior related to condensation formation. As noted above, Option #2 and Option #4 do not include consideration of pressurized ductwork within the framing space. Leakage from ductwork moves interior air into the insulation filled roof framing, increasing the risk of condensation formation.

Other Considerations for Options #1 and #3

Both Option #1 and Option #3 require costly sprinkler systems in the roof framing space to meet NFPA 13 since the concealed spaces are not filled with noncombustible insulation. By not requiring additional rigid insulation above the roof deck, Option #3 reduces the overall thickness of the assembly and simplifies detailing for drainage and flashings. However, for both options, installation of ductwork and other components within the framing space may be impeded by the impermeable insulation beneath the roof deck. Further, in the event of potential future roof leakage, the impermeable insulation applied directly to the underside of the deck can hold moisture against the sheathing, concealing leakage and associated damage until the problem becomes advanced.

Hygrothermal Analyses of Code-Prescribed Options

For this study, the researchers focused on Options #2 and #4, which meet NFPA 13 requirements, as discussed above. The roof assembly described in the introduction with 32 in. (91.44 cm) deep trusses was modeled, with a 2 in. air space between the insulation and sheathing (reducing the insulation thickness to 30 in. [76.2 cm]), per NFPA 13 allowances. Assessments were made for four different major cities in the United States, corresponding to northern and mixed climate zones:[19] Minneapolis (Zone 6A), Chicago (Zone 5A), Baltimore (Zone 4A), and Atlanta (Zone 3A). A series of WUFI simulations were performed to evaluate the hygrothermal performance of the assembly and assess the impact of air leakage from pressurized ductwork within the framing space. The simulation results were evaluated according to commonly accepted criteria regarding the potential for biological growth and water content of the wood roof deck.

Comparison of Option #2 and Option #4

Tables 1 and **2** below compare Option #2 and Option #4, with insulation above the sheathing as determined in each of these options. Table 1 below shows the minimum *R*-value for each climate zone as specified in Section 1202.3.5.1.2, along with the corresponding thickness of rigid insulation. **Table 1** also includes the average temperature for the three coldest months of the year for each location, per Section 1202.3.5.1.4.[8]

To calculate the temperature of the underside of the structural roof sheathing in accordance with Section 1202.3.5.1.4, a temperature factor calculation was applied in accordance with ISO 13788.[20] This methodology was used for the modeled assembly in all four climate zones, with the calculation carried out for various *R*-values of rigid insulation above the deck. In this way, the rigid insulation requirements from Sections 1202.3.5.1.2 and 1202.3.5.1.4 could be compared, as shown in **Table 2**.

Table 2 reveals two issues with the current code. First, the cases which satisfy Option #2 (minimum prescriptive *R*-value) but do not satisfy Option #4 (maintaining the underside of the deck above 45°F) indicate that the prescribed insulation options do not provide equivalent levels of protection against moisture problems, although their offering as alternatives suggests otherwise. Second, the magnitude of insulation required above the deck to achieve 45°F sheathing when deep framing spaces are filled with insulation is impractical, suggesting this may not have been considered by the code authors.

Note, further calculations revealed that 7.1 in. (18.03 cm) of air-permeable insulation, without a 2 in. air layer, is the thickness for which all values satisfy both Option #2 and Option #4, suggesting that the authors of the code likely did not consider more than 7.1 in. (18.03 cm) of loose fill or batt insulation in these assemblies. See **Table 3**.

TABLE 2. Temperature at underside of structural roof sheathing (°F) for various locations with code-prescribed rigid insulation thicknesses above the sheathing and 30 in. (76.2 cm) deep roof framing space filled with batt insulation.

R-Value of Rigid Insulation	Climate Zone			
	6A, Minneapolis	5A, Chicago	4A, Baltimore	3A, Atlanta
R-4	21.8	26.1	34.4	41.7
R-5	22.3	26.5	34.7	42.0
R-10	24.5	28.6	36.3	43.3
R-15	26.6	30.4	37.8	44.4
R-20	28.4	32.1	39.2	45.5
R-25	30.1	33.6	40.4	46.5
R-30	31.7	35.1	41.6	47.3
R-35	33.1	36.4	42.6	48.2
R-40	34.4	37.6	43.6	48.9
R-45	35.7	38.7	44.5	49.6
R-50	36.8	39.7	45.3	50.3
R-55	37.9	40.7	46.1	50.9
R-60	38.9	41.6	46.8	51.4
R-65	39.8	42.4	47.5	52.0
R-70	40.7	43.2	48.1	52.5
R-75	41.5	44.0	48.7	52.9
R-80	42.3	44.7	49.3	53.4
R-85	43.0	45.3	49.8	53.8
R-90	43.7	46.0	50.3	54.2
R-95	44.3	46.5	50.8	54.5
R-100	44.97	47.1	51.2	54.9
R-105	45.6	47.6	51.7	55.2

☐ Cases that satisfy neither 1202.3.5.1.2 nor 1202.3.5.1.4.

☐ Cases that satisfy 1202.3.5.1.2 but not 1202.3.5.1.4.

☐ Cases that satisfy both 1202.3.5.1.2 and 1202.3.5.1.4.

Hygrothermal Simulation: Modeling Assumptions

To assess the impact of air leakage from pressurized ductwork in the framing space, a series of WUFI simulations were performed and evaluated according to commonly accepted criteria regarding the potential for biological growth and water content of the wood sheathing. The studied roof assembly consisted of (from exterior to interior): white EPDM roof membrane, air-impermeable insulation (thickness selected per Option #2 by climate zone, see Table 1), ⅝ in. (1.6 cm) plywood sheathing, 32 in. (81.3 cm) roof framing space with 30 in. (76.2 cm) fiberglass insulation, optional vapor retarder, and ½ in. (1.3 cm) interior gypsum board coated with latex paint (7 perm). Material properties were obtained from the WUFI database.

Simulations were performed for each of the four selected climate zones, with and without pressurized ductwork in the framing space, with and without a Class II (1 perm) vapor retarder (which also functions as an air barrier), and with two variations on roof membrane color and solar reflectivity: white membrane (70% reflectivity) and black membrane (10% reflectivity), resulting in a total of 32 simulation cases. Nighttime overcooling effects were considered using the built-in long-wave radiation exchange model with the surrounding sky, using a long-wave emissivity of 90%, which represents opaque materials.[21]

The outdoor climate conditions for each simulation were obtained from the WUFI database for the selected locations. Indoor climate conditions have been assumed to be 72°F (22°C), with indoor relative humidity modeled as an annual sine curve.[22] See **Figure 6**.

Simulating Moisture Load from Air Duct Leakage

For the presented example, the airflow from the 2-ton heat pump unit is 800 cfm in a 1,200 ft^2 dwelling. With a 32 in. framing space, 95% air within the batt insulation, and presuming a "low" duct leakage level of 5%, this amounts to one air change every 45 minutes. However, since modifying the software to simulate one air change every 45 minutes was considered neither practical nor reliable, a different approach was selected.

The moisture impact of air leakage from the pressurized ducts has been modeled such that whenever the HVAC system is running, the moisture associated with air at the indoor absolute humidity level is available at the interior surface of the plywood to be absorbed during winter weather conditions. For the analysis, 5% of the excess moisture (the difference between the vapor pressure of the interior air and that of the air within the sheathing) is assumed to be available for this moisture transfer, with the other 95% assumed to dissipate via convective flow. Similarly, moisture in the plywood can be dried by the simulated air leakage during summer weather conditions. This approach was selected since

TABLE 3. Temperature at underside of structural roof sheathing (°F) for various locations with code-prescribed rigid insulation thicknesses above the sheathing and with 7.1 in. (18.0 cm) deep roof framing space filled with batt insulation

R-Value of Rigid Insulation	Climate Zone			
	6A, Minneapolis	5A, Chicago	4A, Baltimore	3A, Atlanta
R-4	27.5	31.3	38.5	44.96
R-5	29.0	32.6	39.6	45.8
R-10	35.0	38.0	43.9	49.2
R-15	39.4	42.0	47.2	51.7
R-20	42.7	45.1	49.6	53.6
R-25	45.4	47.5	51.5	55.1

☐ Cases that satisfy neither 1202.3.5.1.2 nor 1202.3.5.1.4.

☐ Cases that satisfy 1202.3.5.1.2 but not 1202.3.5.1.4.

☐ Cases that satisfy both 1202.3.5.1.2 and 1202.3.5.1.4.

it produced results that closely matched observations by the authors in building failure investigations. For these calculations, a moisture transfer coefficient was assumed from previous research.[23]

The HVAC system is assumed to operate in heating mode when the exterior temperature falls below 65°F (18°C) and in cooling mode when the exterior temperature is above 70°F (21°C). The stated set points include indoor thermal gains which result in a 5°F shift of the indoor temperature according to ASHRAE 160,[24] resulting in actual thermostat set points of 70°F (21°C) and 75°F (24°C) for heating and cooling, respectively.

The percentage of heating time in an hour is assumed to be at 100% at the coldest hour of the year, two minutes at times where the exterior temperature falls minimally below the set point of 65°F (18°C), and linearly interpolated for all points between. An analog procedure was used to determine the percentage of cooling time during summer conditions.

Evaluation Criteria

The hygrothermal simulations were evaluated based upon the mold growth index (MGI), per ASHRAE 160,[24] as measured at the interior surface of the sheathing. The MGI, whose calculation depends on the sensitivity class of the substrate, relative humidity, temperature, and time shall stay below 3.0, per ASHRAE 160 (see **Table 4**). The simulations were also evaluated based upon the simulated water content of the sheathing, which must remain below 20% by weight to prevent decay.[2]

Simulation Results

Each simulation case and its corresponding final MGI value and maximum sheathing water content in the last year of the calculation are listed in **Table 5**. Note that MGI and water content values indicative of biological growth or decay are shaded.

The results above show that even with significant insulation below the sheathing, the minimum insulation provided by code is sufficient to minimize the risk of condensation, if ductwork is not present and the flow of interior air into the roof framing space is low. This also suggests that Option #4 in the building code may be more conservative than necessary to avoid condensation-related moisture problems, provided significant flow of interior air into the roof framing space can be avoided. However, the results show elevated values for MGI and plywood water content for cases which include the effect of air leakage from pressurized ductwork in the framing space. As such, biological growth and/or wood decay may be expected to occur in these cases.

The influence of the roof membrane color is significant, with a black membrane leading to increased solar gain, drying the roof assembly better than a white surface. This effect has been studied many times.[26,27,28,29] However, the impact of the black membrane alone is not sufficient to

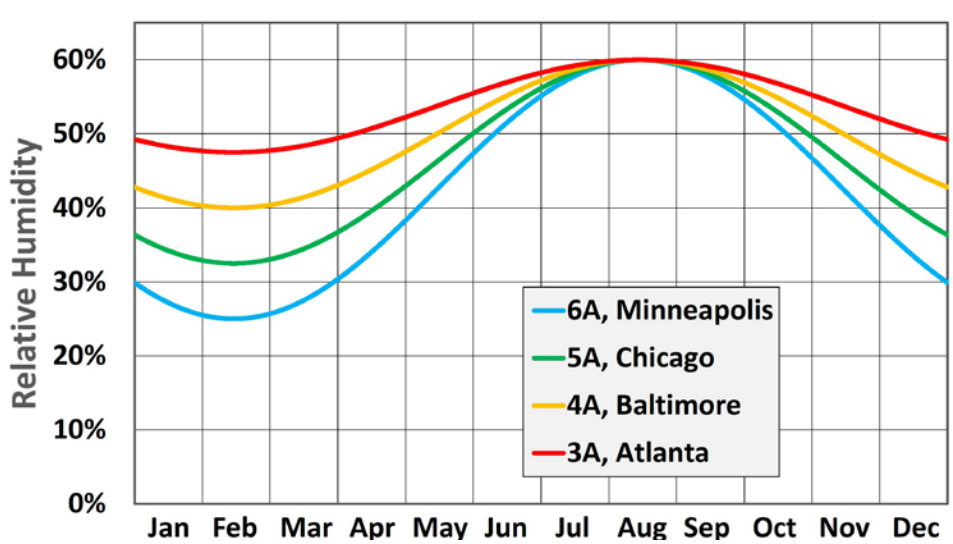

FIGURE 6. Seasonally assumed indoor relative humidity used within the simulations.

TABLE 4. Mold growth index (MGI) for experiments and modeling[25]

MGI	Description of Growth
0	No Growth
1	Small amounts of mold on surface (microscope), initial stages of local growth
2	Several local mold growth colonies on surface (microscope)
3	Visual findings of mold on surface, <10% coverage, or <50% coverage of mold (microscope)
4	Visual findings of mold on surface, 10%–50% coverage, or >50% coverage of mold (microscope)
5	Plenty of growth on surface, >50% coverage (visual)
6	Heavy and tight growth, coverage about 100%

result in a moisture-safe design.

The influence of the vapor retarder is minor for cases with ductwork in the framing space because wetting and drying occurs primarily through the leaking air from the ducts, bypassing the vapor retarder. For cases without ductwork, a Class II vapor retarder provides slightly improved performance.

The influence of climate zone is minor, since colder climate zones are also associated with lower winter indoor relative humidity values, as shown in **Figure 6**. However, this effect will be negated with the use of humidifiers to raise the indoor relative humidity above levels assumed in this study, especially in northern climates.

CONCLUSIONS

The recent revisions to the IBC greatly reduce the potential for condensation in roof framing systems, provided that these spaces do not include ductwork or other significant sources of airflow from the interior. This is true even when considering a high percentage of air-permeable insulation below the sheathing to meet NFPA 13 requirements. The approach listed in Option #4 is significantly more conservative than the approach listed in Option #2 for air-permeable insulation thicknesses greater than 7.1 in. If ductwork is placed in the framing space, the potential for condensation greatly increases. The amount of risk is dependent on the amount of duct system air leakage and the ratio of air-permeable insulation to total insulation. Although the roof membrane color is significant, use of a dark membrane by itself is not sufficient to reduce the condensation risk. The influence of a vapor retarder is minor for cases with ductwork in the framing space but can offer modest protection for assemblies without ductwork.

RECOMMENDATIONS

Additional study is needed to develop computer simulation procedures to reliably predict these failures. The authors plan to construct roof systems with controlled values for simulated ductwork leakage to calibrate computer models. However, until such refined models are available, we suggest the following approaches for low-slope systems with insulation in the framing space complying with NFPA 13:

A. Do not place pressurized ductwork in the insulated framing space.

B. If ductwork is located in the framing space, place ductwork below the air permeable insulation and use Option #1, Option #3, or Option #4, with sprinklers in the roof framing space per NFPA 13.

C. To include ductwork and omit sprinklers, use Option #2 in conjunction with extremely low-leakage high-speed ductwork (e.g., PVC piping or metallic tubing with airtight joints) with sealed connections (e.g., at diffusers).

In all cases, hygrothermal analysis is recommended if the air permeable insulation thickness or interior relative humidity will exceed those included in this study.

TABLE 5. Summarized WUFI simulation results

Case No.	Climate Zone	Ducts in Trusses	Roof Color	Vapor Retarder	Final MGI, Plywood Sheathing	Max. Water Content, Plywood Sheathing, by Weight
1	6A	No	White	None	0	15%
2				Class II	0	16%
3			Black	None	0	12%
4				Class II	0	11%
5		Yes	White	None	3.9	39%
6				Class II	3.9	40%
7			Black	None	0.6	27%
8				Class II	0.3	27%
9	5A	No	White	No	0	15%
10				Class II	0.1	16%
11			Black	None	0	12%
12				Class II	0	11%
13		Yes	White	Yes	4.3	39%
14				Class II	4.2	40%
15			Black	None	2.9	31%
16				Class II	2.4	30%
17	4A	No	White	None	0.1	15%
18				Class II	0.3	16%
19			Black	None	0	11%
20				Class II	0	11%
21		Yes	White	None	4.5	46%
22				Class II	4.5	47%
23			Black	None	3.1	34%
24				Class II	2.6	33%
25	3A	No	White	No	0	15%
26				Class II	0	15%
27			Black	None	0	11%
28				Class II	0	9%
29		Yes	White	Yes	4.3	40%
30				Class II	4.3	39%
31			Black	None	1.0	25%
32				Class II	0.5	24%

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Condo Chronicles:
Navigating Condominium Fenestration Replacement and Restoration Projects

ABSTRACT

Condominium fenestration replacement and restoration projects are complex endeavors and require careful planning and execution. Whether a condominium association opts for fenestration replacement or restoration depends on several factors, including logistical challenges, financial implications, ownership responsibility, code considerations, performance requirements, and impact on residents. We review these factors from the design professional's perspective, discussing the complex dynamic between the property manager, condominium association, unit owners, and design professional throughout the project.

LEARNING OBJECTIVES

- Identify when a condominium board should take on a fenestration project based on age and performance of the systems, maintenance, and impact on tenants.
- Compare the benefits and drawbacks of both fenestration replacement and existing fenestration restoration, including code implications and performance requirements.
- Describe the common financial challenges and logistical impacts of pursuing a fenestration project at a condominium.
- Explain common tensions between a condominium board, property manager, and individual unit owners.
- Discuss the design professional's role in advising/consulting on the project and risks faced by the design professional.

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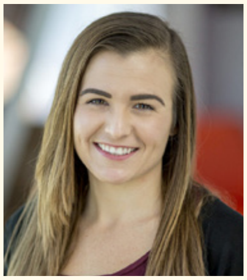

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In the ever-evolving world of architectural design and construction, condominium fenestration replacement and restoration projects are complex endeavors that require strategic planning, expert execution, and an understanding of the intricate dynamics at play within a condominium complex. Challenges arise from the blend of shared ownership, communal living, and diverse stakeholder interests characteristic of condominium communities. The challenges and considerations presented in this article apply most directly to large tower or midrise condominium complexes; however, many points are also relevant for low-rise, multifamily residences and smaller condominium complexes.

Fenestration, which encompasses windows, doors, and their related components, plays a critical role in any building's performance, energy efficiency, functionality, and aesthetic appeal. Fenestrations are a distinctive part of the building enclosure, but, unlike the rest of the building enclosure, they may be owned by individual unit owners rather than being common property owned by the condominium association. For this reason, wholesale, property-wide replacement or restoration of fenestration is unusual in condominium complexes compared to single-owner residential buildings. Fenestration ownership structures may vary between condominium associations, and it is important for designers to understand who carries financial responsibility.

Condominium associations or individual unit owners may find that fenestration replacement or restoration is necessary to resolve water leakage, air leakage, thermal discomfort, operability issues, and/or structural issues. In our experience, wholesale fenestration replacement is only mandated across an entire building or complex when the issues with the existing fenestrations are so severe that they are causing deterioration of adjacent building components or pose a safety concern, such as damage to the exterior framed structural framing components. Smaller, voluntary replacement or restoration projects that are executed by individual owners opting into the project are more common.

In this article, we delve into the complexities of fenestration replacement and restoration in condominiums from the perspective of design professionals who collaborate with condominium clients and property managers. We focus primarily on describing the common challenges associated with these types of projects, including logistical hurdles, financial implications, ownership responsibilities, adherence to building codes, performance requirements, and the potential impact of the projects on residents' daily lives. We aim to provide the various condominium complex stakeholders with a catalog of considerations for executing condominium fenestration projects, ensuring that they are well equipped to navigate the multifaceted challenges and opportunities presented by these intricate endeavors, and provide other design professionals with guidelines for their fenestration projects.

COMMON RELATIONSHIPS AND RESPONSIBILITIES

In a condominium complex, several parties play crucial roles in making decisions and executing fenestration replacement or restoration projects. Understanding the relationships among these parties is essential for design professionals and contractors involved in such projects. The following is a summary of the stakeholders and their roles and responsibilities as they relate to the fenestration systems.

Condominium Association

A condominium association is a legal entity that is governed by a board of trustees or directors (elected unit owners), which acts on behalf of all unit owners and is responsible for managing and maintaining the common/shared elements of the condominium complex. The responsibilities of a condominium association can vary depending on the specific bylaws and regulations of the condominium, as well as the state or local laws that govern condominiums.

The association is responsible for ensuring that any fenestration work executed at the property complies with the bylaws and regulations of the condominium. The association can require a unit owner to replace or make repairs to the unit's fenestration systems if those systems are affecting common area elements or the building structure. The association can also approve a defined procedure mandating certain requirements or products/assemblies for work executed by individual unit owners.

Unit Owners

Individual unit owners hold a stake in the condominium and contribute financially to the condominium association through monthly dues and other assessments. They have a vested interest in the maintenance and improvement of common elements, as these affect the value and livability of their units.

Unit owners may have differing opinions on the timing and scope of fenestration projects, which can lead to discussions or conflicts within the community. Unit owners commonly confuse what are considered common elements (owned by the association) and unit owner elements (owned by the individual unit owners). Even when unit owners are financially responsible for their unit's fenestration (as is the case in most condominiums), they are required to comply with any regulations approved by the association.

Property Manager

In professionally managed condominiums, the property manager is typically hired by the association to oversee day-to-day operations, including maintenance and repair projects, and act as a liaison between the association, unit owners, and external contractors and professionals. The responsibilities of a property manager can vary depending on the condominium association. In some cases, a condominium may not have a property manager, and the association may perform the role of property manager.

Property managers often directly engage with and coordinate the work of design professionals, such as architects and engineers, on behalf of the condominium association to assess, plan, and execute fenestration projects. Property managers may act as the association representative during fenestration projects and assist with coordinating the project work with the individual unit owners.

Design Professionals

Design professionals (engineers and architects) are responsible for assessing the existing fenestration systems, determining the scope of work required, providing design recommendations, and specifying systems. They are engaged by and collaborate closely with the property manager and condominium association to ensure that the project aligns with the condominium's requirements, goals, and budget.

Design professionals are responsible for selecting or designing fenestration systems that comply with the technical project requirements, including aesthetic design, structural integrity, safety and performance requirements, and compliance with building codes. Design professionals must carefully assess the existing conditions, propose appropriate solutions, and oversee the project to minimize risks and potential liabilities for all involved stakeholders.

Contractors

Contractors are responsible for managing the construction process, which includes schedules, budgets, permits and city approvals, site management, safety, and managing work. They are responsible for ensuring that all work, material, and installation meets or exceeds the quality standards and specifications outlined in the contract and complies with building codes and industry standards. Contractors provide guarantees that cover defects in materials and workmanship for a specified duration.

Contractors are responsible for coordinating the various trades as required to execute a fenestration replacement or repair project, including demolition, waterproofing, cladding, glazing, and interior finish subcontractors. Contractors need to work closely with the property managers and unit owners to execute the work to their satisfaction.

Fenestration Product Manufacturers

Fenestration product manufacturers are responsible for fabricating and providing products that meet or exceed industry standards and project-specific requirements. Manufacturers need to obtain and maintain relevant certifications and documentation to demonstrate compliance with industry standards, building codes, and regulations. They offer product warranties that cover defects in materials or workmanship for a specified duration.

Fenestration manufacturers are responsible for fabricating fenestration systems that meet or exceed industry standards and the project specification requirements dictated by the project's design professionals. The manufacturers often offer technical support and assistance to design professionals and contractors during the fenestration design and installation process.

RESTORATION VERSUS REPLACEMENT

The first step in executing a fenestration project is for the design professional to evaluate existing conditions and help the property manager, unit owners, and condominium association determine the scope of work. The decision of whether to restore or replace existing fenestration can be difficult because several factors must be considered. The opportunities to improve air, water, structural, or operability performance of existing fenestrations may be too limited to provide the benefits sought by the owners, and the overall project cost of restoring fenestration can be similar to the cost of replacement. It can be difficult to justify the cost of restoring existing fenestration if restoration will achieve only marginal performance improvement. However, restoration may be dictated by historic-preservation requirements or be a jurisdictional requirement for another reason. Restoration may also be appropriate if the condominium intends to perform an opt-in project, where the condominium association oversees a fenestration project that multiple unit owners opt-in to as opposed to mandating a complex-wide project, and does not want changes to select fenestration to alter the aesthetics of the building.

FIGURE 1. Figure 1. Storm windows installed at localized fenestration of a condominium building. Yellow arrow indicates a location with a storm window, red arrow indicates a location without a storm window.

Design professionals should carefully review the relative feasibility, costs, and benefits of replacement and restoration projects and discuss the options with the project stakeholders before a condominium decides whether to proceed with a fenestration restoration or replacement project. Note that the issues discussed in the Design- and Construction-Phase Considerations section of this article apply to both restoration and replacement projects.

RESTORATION-SPECIFIC CONSIDERATIONS

Performance

Restoration is typically constrained by the design of the existing fenestration and therefore it offers limited opportunities to improve air, water, and thermal performance of existing fenestration assemblies. The existing frames may be able to accommodate insulated glass units (IGUs). However, the increase in overall thermal performance will be minimal if the existing framing members are not thermally broken. In some cases, the configuration of existing frames that use monolithic glass cannot readily accept IGUs and need to be modified. When fenestration is operable, new gaskets and hardware can be installed around the operable sashes to achieve improved air infiltration resistance and operability. However, the gaskets will often need to be adhered and will remain maintenance items. Storm windows can be installed outboard or inboard of the existing windows to provide some improvement to the thermal performance and air infiltration, thus improving occupant comfort (**Fig. 1**). However, storm windows can have a negative impact on the ease of operation, ventilation, and aesthetics.

Concealed Structural Deterioration

Existing interior and exterior finishes can conceal significant structural deterioration, and the true condition of existing steel or wood window frames will not be known until the finishes, glazing, and/or coatings are removed (**Figs. 2a** and **2b**). This is primarily an issue with older wood and steel fenestrations.

Because it is difficult to estimate the extent of deterioration until the windows are disassembled and the existing finishes are removed, the design professional will be challenged to forecast project costs and advise clients about whether to pursue fenestration repairs or replacement. If there is severe deterioration in isolated locations, isolated framing members may need to be removed and replaced or reinforced, but if there is widespread deterioration, the scope (and cost) of the repair/replacement project will be much more extensive.

Contractor Interest/Availability

Window restoration is specialized construction that requires artisan contractors with skilled craftsmen to perform the repairs. Successful execution of a fenestration restoration project is dependent on the availability of skilled contractors willing

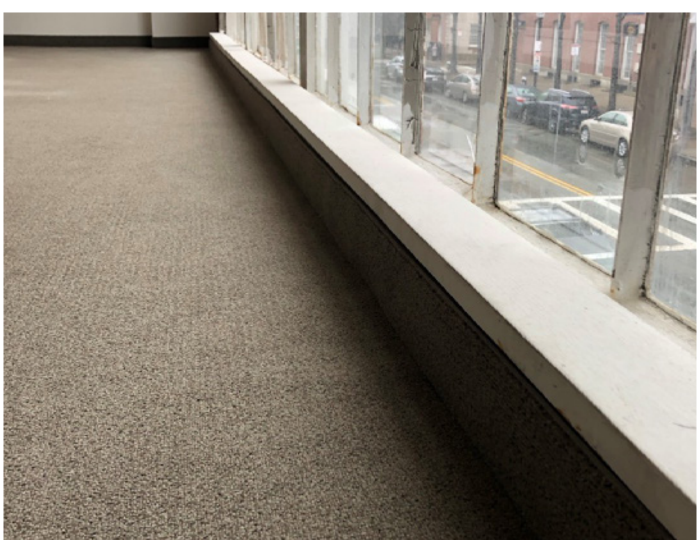

FIGURE 2A. Coating and glazing putty conceal corrosion of steel mullions.

FIGURE 2B. Coating removal reveals extensive corrosion of steel mullions.

to reglaze, reconfigure, and restore existing fenestration systems. Design professionals should assist the association in vetting qualified contractors while compiling a bid list. On past projects, we have found that few glazing contractors are qualified to do this type of restoration work, and even fewer are willing to undertake repair of existing fenestration and to provide warranties, especially for one-off work. This work may have more perceived risk than replacement with a fully integrated system, and it may result in higher construction costs than a replacement project. It is critical that the Design Professional educate the Condominium Association about these considerations and implications prior to the Association determining whether to perform a restoration or replacement project.

Cost

Unit owners and condominium associations may assume that restoring existing fenestration is less costly than replacement. However, the cost of restoration can depend heavily on the extent of the restoration and the expertise of the contractors performing the work. Depending on these factors, the overall cost of restoration may be less than, comparable to, or even more than the cost of replacing existing fenestrations with new. The comparative cost of restoration vs. replacement is often dependent on the type of replacement window that is being proposed. If the overall project cost to restore windows is less than or comparable to replacement, restoration may still be less cost effective over the long term, as the service life of restored fenestration is usually not as long as that of new fenestration. To assist the Condominium Association with determining how to proceed, the Design Professional should provide approximate cost per square foot estimates and estimated services life for both restoration and several replacement options for consideration.

Expectations

It is difficult to predict the performance of restored fenestrations, as they will not be rated assemblies that meet rigorous water penetration and air infiltration field-testing standards. We generally recommend using mock-ups to assess the proposed restoration procedures, testing the mock-ups for performance in general accordance with *ASTM E1105 (Standard Test Method for Field Determination of Water Penetration of Installed Exterior Windows, Skylights, Doors and Curtain Walls, by Uniform or Cyclic Static Aire Pressure Difference)* and *ASTM E783 (Standard Test Method for Field Measurement of Air Leakage Through Installation Exterior Windows and Doors)*, and comparing the testing results to the expected performance of new fenestrations. However, this phase is often not performed at condominiums because it adds to the project cost, can be disruptive for owners, and extends the overall project schedule. It is critical that all owners who participate in a restoration project understand the limitations of restoration and that the project may not fully restore functionality, alleviate occupant discomfort, improve energy efficiency, or address water leakage issues over the long term. Additionally, owners should understand that restored fenestrations may require more frequent maintenance than new fenestration assemblies, depending on the extent of surface preparation performed and quality of new coatings on existing windows that require recoating.

REPLACEMENT-SPECIFIC CONSIDERATIONS

Existing Profiles and Sightlines

Some existing types of fenestration, especially older, non-thermally-broken steel or wood-framed units, have narrow profiles that can only be achieved by replacing the units with similar products that match the original profile. Replacement with more-affordable standard fenestration products, such as aluminum- or composite-framed systems can result in increased sightlines. In many cases, installing alternate fenestration products to improve performance can also affect building aesthetics. Following an opt-in replacement

FIGURE 3. Sightlines at the replacement fenestration (indicated with the arrow) are thicker than existing fenestration profile next to it.

project, the sightlines would vary between the new and existing fenestrations (**Fig. 3**). Therefore, if most owners in a condominium do not support a proposed fenestration replacement project where sightlines would be increased, the condominium may choose to perform an opt-in restoration project in lieu of an opt-in fenestration replacement project to avoid varied fenestration sightlines around the building.

Code Requirements

Fenestration replacement projects are typically considered by code officials as Level 1 Alterations under the *International Existing Building Code*1 and must meet current *International Energy Conservation Code (IECC)*[2] prescriptive requirements. In several states, including Massachusetts, the 2021 version of the IECC has been adopted with additional state-specific amendments that include more stringent U-value requirements.

These new U-value requirements can be difficult to meet with standard thermally broken aluminum-framed fenestration. Many of the aluminum-framed assemblies that we would typically specify for larger mid- to high-rise condominium fenestration replacement projects cannot meet the new U value requirements, even with triple glazing and multiple e-coatings. The inability to meet code requirements is more pronounced if the building has smaller fenestration units, as it is difficult for smaller units (which have low glazing-to-frame ratios) to meet U-Value requirements. Adding triple glazing may be cost prohibitive for owners and may have structural implications due to the increased weight of glazing, leading the condominium to instead choose vinyl or aluminum-clad wood replacement fenestration products, which have better thermal performance than aluminum-framed products. Filing for an energy code variance through the authority having jurisdiction is possible; however, the feasibility of this option depends on the jurisdiction, and our experience is that most local jurisdictions will not consider higher cost to unit owners as a reason to waive energy code requirements.

Interior Finish Impacts

During fenestration replacement projects, interior finishes may be affected if the new frames are deeper than the existing frames or interior finishes need to be removed to install a continuous interior air seal between the new frame and the rough opening. Removing and replacing interior finishes in condominium units can be challenging, as the existing conditions can vary by unit, and unit owners have differing expectations of modifications inside their homes. If owners have added decorative trim, wood stools, wainscoting, shades, or other intricate interior finishes, removal and replacement is not as simple as cutting and patching drywall. It can be difficult for contractors to price this work, and it is time consuming to document and catalog all existing conditions for contractor pricing. To avoid misaligned expectations, it is critical that both the contractor and the owners acknowledge who is responsible for performing and paying for interior finish replacement and painting. In our experience, it is best practice to limit the impact of a fenestration project on interior finishes as much as possible. If the new frames are wider than the existing frames, we recommend maintaining the interior plane of the existing fenestration and accommodating the added depth on the exterior side of the opening. However, that option is not always possible, depending on the construction of the exterior wall assembly and the alignment between the new frame and existing cladding.

DESIGN- AND CONSTRUCTION-PHASE CONSIDERATIONS

Once the scope of work is defined, the next steps of the project are design and construction. Successful fenestration projects in a condominium complex require effective communication and collaboration among the design professionals, property managers, condominium association, and fenestration suppliers to ensure that the project meets quality, safety, and budgetary goals while addressing the needs and concerns of unit owners and the condominium association. The considerations identified in the following sections should be reviewed and discussed by the project team throughout the design and construction phases.

Failure Mechanism

A fenestration project is commonly precipitated by performance failure of the fenestration units. Types of performance failure include water penetration or air leakage to the interior, condensation within IGUs, operability issues, or occupant discomfort. It is critical that the failure mechanisms are identified and the contributing factors are thoroughly diagnosed so that they can be addressed by the fenestration project. If adjacent construction or interior conditions contribute to the failure, a fenestration replacement or restoration project will need to address these contributing factors; otherwise, the performance failures may continue once the project is complete.

One common example is water leakage through perimeter conditions (see **Fig. 4** and **5**). Owners may observe active water leakage or deteriorated interior finishes around an existing fenestration and assume that replacing the fenestration will address water-intrusion issues. However, the fenestration perimeter flashings may not be properly integrated with the adjacent exterior

FIGURE 4. Water leakage at interior appears at window head; however, the leakage path is through exterior masonry wall above.

FIGURE 5. Interior finish damage beneath fenestration was caused by water accumulating between the storm window and the original fenestration unit.

wall assemblies. If the fenestration is restored or replaced but the perimeter flashings are not modified to properly integrate with the adjacent exterior wall assemblies, it is likely that water leakage will continue after the replacement window is installed.

Execution Method and Cost Implications

It is important to determine how the project will be executed early in the design phase. Once the design professional has been engaged and has determined the required scope of work, the project team must determine how to execute the project. The three most common ways to execute fenestration replacement or restoration are wholesale building/complex project, a multiunit opt-in project, and single unit/one-off project. In the following sections, we discuss considerations for each execution method.

Wholesale Building/ Complex Project

Over the long term, the most economical option for conducting a fenestration restoration project is to restore or replace all fenestration for the building/complex at once. This approach takes advantage of economy of scale, and the total cost per fenestration (including material, labor, and access costs) is generally lower than other execution options. Many manufacturers will reduce the price per fenestration if the total quantity of units ordered is above a certain threshold specific to the manufacturer. Contractor overhead costs, front-end costs, and design professional fees are also spread among owners from the entire condominium complex. Performing replacement or restoration for the entire complex also ensures that the fenestration life cycles of all units are aligned, which makes future maintenance and replacement easier to track.

However, performing a wholesale project can be politically and legally challenging, especially when unit owners own the fenestration within their units, as it is unlikely that all owners will want to proceed with a fenestration project simultaneously. Executing a mandatory fenestration project could require changing condominium documents so that the association assumes ownership of the fenestration, passing a required quorum vote, or pressuring unit owners to pay for work which they may not be willing to or able to pay for.

In a wholesale project, the design professional is engaged to develop construction documents for the entire building or complex, with the assumption that the work will be completed at once. Furthermore, when a project is large and costs are shared among the unit owners, it may be cost-effective to engage the design professional to perform construction administration during the construction phase. The design professional can provide responses to contractors' requests for information and perform quality assurance reviews, which generally improve the overall quality of the final installation and limit risk to the condominium association. Additionally, compared with a small project, a large, wholesale project will generally be more likely to attract experienced contractors, increasing the odds for success on complex projects.

Multiunit Opt-In Projects

Multiunit opt-in fenestration projects are hybrids between wholesale and one-off projects. A multiunit execution strategy provides some of the economy of scale and cost-sharing benefits provided by a wholesale project without the complication of forcing all unit owners to participate in the project. In many cases, the design professional's fees are covered by the condominium association, as the design documents can also serve as a basis for future one-off fenestration projects. Because the costs are shared among multiple owners, it may be affordable to engage the design professional to perform limited construction administration and quality assurance reviews during the construction phase.

Single-Unit/One-Off Projects

Performing a fenestration replacement or restoration project at a single unit will be the most financially burdensome option for that unit's owner and will likely have less design professional involvement and oversight than a wholesale or multiunit project. If a single unit owner decides to replace or restore the fenestration within their unit independently, they will likely engage a contractor directly. Unless the association has a predetermined process in place that provides owners direction on how to replace or restore fenestration, the unit owner in this scenario will rely on the contractor that they hire to act as the design professional. The quality of the final installation will thus be highly dependent on the skill and knowledge of the contractor. In our experience, a one-off fenestration project will attract a residential contractor, who may have limited experience performing fenestration restoration or replacement under the direction of a design professional. If a unit owner opts to perform a fenestration project on their own, there is a risk that the project will not address the underlying cause of performance failure. For example, a single-unit fenestration replacement will likely not involve exterior access or removal of exterior wall components. The perimeter conditions would likely be limited to interior-installed sealant which may not provide a continuous seal to the water-resistive barrier within the exterior wall assembly, depending on the type of exterior wall assembly (**Fig. 6**).If water leakage was occurring through the tie-in between the existing fenestration and exterior wall, replacing the fenestration with a new fenestration without providing an improved tie-in to the exterior wall will not address the underlying cause of the leakage, and it is likely that leakage will recur.

The best method for executing one-off fenestration projects is to engage a design professional to develop construction documents for the entire complex with the assumption that fenestration will be replaced on a one-off or as-needed basis. Such documents include standard replacement or restoration details and a specification package listing recommended materials and manufacturers. Research regarding product availability is required, as many manufacturers will not provide products in very limited quantities. A challenge with this execution method is that it is difficult to ensure that the work is completed per the design documents without design professional involvement during construction. One-off replacements significantly increase liability risk for design professionals, as they have less control over the final installation.

Access

Fenestration projects typically require exterior access to the building. Condominium associations may request that the project be completed with interior-only access, but that approach may limit the contractor's ability to provide adequate tie-ins to adjacent wall construction and dictate how much of the fenestration can be assembled in a factory instead of on site. While field-fabricating portions of fenestration offers flexibility, fabricating in the field increases the risk of workmanship issues; can increase overall cost because it requires increased field labor; increases the risk of weather-related delays; and can extend overall construction schedules. Fenestration systems that are factory built offer greater quality control, improved consistency between products, ideal environmental conditions for sensitive material installation, and warranties.

Interior-only access can also pose safety risks when fenestration is removed or replaced. Exterior access can significantly increase project costs, as work will require either an aerial lift rental and associated street permits, pipe staging or scaffolding, or swing staging. Exterior access is typically more affordable for larger projects because the access costs are spread among more units.

Occupant Disruption

Any fenestration project will affect the unit occupants while work is being completed within their living spaces. The area surrounding the fenestration will likely be isolated from the remainder of the unit during the duration of the project, altering the amount of natural light and living space within the unit. If scaffolding or pipe staging is required to perform the work, views from units will be obscured, and occupants will be near the work zone. While increasing the number of fenestration units included in the project scope offers cost efficiencies, it may increase the duration of tenant disruption and discomfort. Once a construction schedule is determined, it is vital to communicate with the condominium association, unit owners, and tenants to ensure that the expectations regarding timelines and disruptions are clear.

CONCLUSION

When fenestrations require replacement or restoration, the execution of the project will require careful consideration and planning.

Successful fenestration projects in a condominium building/complex require effective communication and collaboration among all stakeholders. Design professionals, contractors, property managers, and fenestration suppliers must work together to ensure that the project meets quality, safety, and budgetary goals while addressing the needs and concerns of unit owners and the condominium association. Careful planning, documentation, and risk management are essential to minimize potential liabilities and disputes.

Considering the intricate nature of executing fenestration work within condominium buildings/complexes, condominium associations should be proactively equipped to address fenestration failures and provide guidance to unit owners who wish to replace or restore their fenestration on a one-off basis. The best strategy is to proactively provide association-approved contract documents for fenestration replacement or restoration, and establish a well-defined procedure that delineates for individual unit owners the criteria governing fenestration replacement and restoration. This strategy is critical, as in the absence of clear guidelines, unit owners could install fenestration products that may not align with the preferences of various stakeholders or use installation procedures that adversely affect other parts of the building enclosure. Even if there is no immediate need for wholesale or large-scale fenestration replacement or restoration, it is prudent for condominium associations to forecast potential future projects and factor that forecast into their financial planning.

FIGURE 6. One-off fenestration replacement where the perimeter air/water barrier is limited to sealant.

REFERENCES

1 International Code Council (ICC). *2021. 2021 International Existing Building Code*. Washington, DC: ICC.

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