Low-Rise Foam Adhesive Research Project

By Randy Adams and Richard S. Koziol

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This article describes a testing and research project to determine how the bond capacity of low-rise foam adhesive between insulation panels at varying adhesive ribbon spacings was affected when the adhesive was applied to both fiberglass- and organic-faced polyisocyanurate insulation boards. The project scope included design and fabrication of custom 4 × 4 ft aluminum frames; testing of eighteen 4-ft square specimens in direct tension until failure; testing six companion, small-scale (12 × 12 in.) specimens in direct tension until failure; evaluation of test results; and development of key observations from the test program.

The research and testing program outlined in this article was developed based on a request for proposal (RFP) titled "Low Rise Foam Research Project," which was issued by the Midwest Roofing Contractors Association (MRCA) Technical Research Committee in May 2019. It has been recognized in the industry that the handheld wand and cartridge application technique for field installation of low-rise foam adhesives is unlikely to produce consistent ribbon spacing. Thus, the problem statement presented in the MRCA RFP states, "What impact does variation in foam ribbon spacing have on ultimate roof uplift capacity?"

The problem defined in the MRCA RFP states that typical manufacturer installation instructions provide for low-rise foam adhesive ribbons to be applied at 6 and 12 in. spacings. Accordingly, the program was ultimately refined to include testing of insulation adhesion at these spacings, as well as ribbons spaced at 18 in. on full-size, 4 × 4 ft square specimens. In addition, investigators performed supplemental testing of adhesion on 1 × 1 ft square companion specimens, as well as tensile testing of adhesive-only samples.

OBJECTIVE

The objective of this research project was to determine the effect on bond capacity of low-rise foam adhesive between insulation panels at varying adhesive ribbon spacings, with the adhesive applied to both glass fiber- and organic-faced polyisocyanurate insulation boards. The project scope included:

- Development of a testing plan and protocol in collaboration with the MRCA Technical and Research Committee.
- Design and fabrication of custom aluminum loading frames to apply uniform forces to the 4 × 4 ft square test specimens.
- Preparation of 18 specimens, each composed of two 4 × 4 ft square, 2-in.-thick polyisocyanurate insulation boards adhered together with low-rise foam adhesive ribbons. Three sets of six panels were prepared with ribbons applied at spacings of 6, 12, and 18 in. centers. Within each set of six specimens, three specimens featured glass fiber-faced insulation boards and three featured cellulosic-felt-faced insulation boards. The insulation boards were attached to nominal ¾-in.-thick plywood base layers fitted with special tee-lock connectors to accommodate anchorage of the specimens to the test frames.
- Testing of the 18 specimens in direct tension until failure, while simultaneously monitoring loads, measuring specimen elongation, and recording relative displacements at edges of specimens.
- Testing of six companion, small-scale (12 × 12 in.) insulation specimens in direct tension until failure. These specimens—three each for glass fiber-faced and organic-faced insulation—were fabricated with a single foam adhesive ribbon.
- Testing two companion, small-scale (12 × 12 in.) insulation specimens fabricated with full-coverage foam adhesive between insulation boards—one each for glass fiber-faced and organic-faced insulation.
- Direct tension testing of the low-rise foam adhesive. Tests were conducted of cured foam specimens that were either approximately ⅛-in. thick or approximately ⅓₂-in. thick.
- Evaluation of test results and development of key observations from the test program.

MATERIALS

The polyisocyanurate insulation boards and foam adhesive cartridges used for the testing were supplied to Wiss, Janney, Elstner Associates Inc. (WJE) by an MRCA member roofing contractor. Four pallets of insulation with factory-protective wrapping were received approximately 30 days before testing and stored in a warehouse building with the wrapping removed. Two types of insulation were used for the 18 full-size tests: nine of the specimens used ASTM C1289[1] Type II, Class 1, Grade 2 polyisocyanurate boards (glass-fiber-reinforced cellulosic felt facers and 20 psi compressive strength), and nine specimens used ASTM C1289 Type II, Class 2, Grade 2 boards (coated polymer-bonded glass fiber mat facers and 20 psi compressive strength). The dimensions of the insulation boards for all full-size specimens were nominally 48 × 48 in. with a thickness of 2 in. The insulation boards were

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Figure 1. ***Lines were drawn on the insulation boards (with spacings centered on boards) to guide the application of the low-rise foam adhesive ribbons. The lines were centered so that application of the adhesive would be symmetrical. The photo shows the line layout for a 12 in. ribbon spacing.***

Figure 2. ***Grid of low-rise foam adhesive being applied to plywood panels to achieve an approximate 6 in. grid onto which one of the insulation boards would be placed.***

delivered to our lab with these dimensions; no larger boards were cut to size. For this test program, polymer-coated glass fiber- and cellulosic felt-faced insulation specimens were designated Type A and Type B, respectively.

A two-component, low-rise polyurethane foam adhesive was used to adhere the insulation boards. The adhesive was provided in dual-chambered cartridges with attached mixing tips that combined the two components. The adhesive was applied with an electrically powered applicator in beads spaced as required by each test series. To create a base layer for specimens, the same two-component low-rise adhesive was used to attach insulation boards to ¾-in.-thick, 48 × 48 in. sanded BC plywood panels.

FABRICATION OF SPECIMENS

Full-Size Specimens

Low-rise foam adhesive was applied by a skilled roofing tradesperson to all plywood panels and insulation boards using a power-actuated applicator inside the conditioned testing facility. Each of the plywood base-layer panels was drilled with 29/64-in.-diameter holes at 26 locations to match the locations of the attachment points on the top and bottom of the custom-fabricated aluminum stiffening frames. Into each of these holes, a nominal ⅜-in.-diameter twist-resistant tee nut with a 1-in.-diameter flange was inserted and embedded into the plywood.

Polyisocyanurate insulation specimens were sorted to separate the Class 1 boards from the Class 2 boards and put into six groups of three. The boards were inspected for labeling that read "This Side Up" or "This Side Down" and were placed appropriately. A permanent marker was used to highlight the applicable insulation board facer surfaces with line markings at the test spacings of 6, 12, or 18 in. (**Fig. 1**). The "knit line" orientation on the insulation boards was

Figure 3. ***Typical low-rise foam adhesive bead width being applied to two separate insulation boards with 18 in. ribbon spacing lines.***

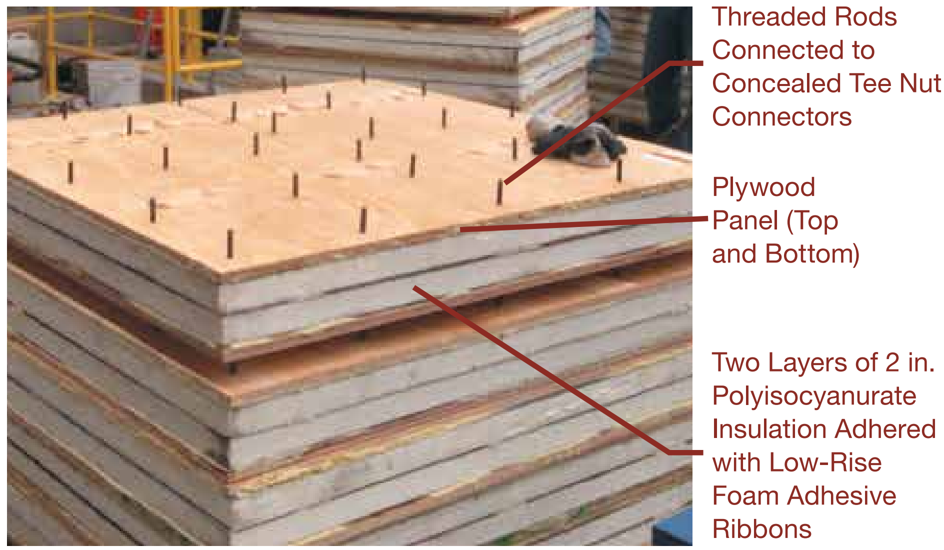

Figure 5. ***A cross section of an insulation and plywood specimen.***

Figure 4. ***Typical weights used as ballast until the foam adhesive set up, typically for 10 to 15 minutes per specimen.***

identified and placed in positions so that the knit lines of the top insulation board were oriented in perpendicular position relative to the bottom insulation board for each pair of boards comprising a test specimen.

The two-part polyurethane foam adhesive was initially installed onto the plywood board surfaces in ribbons approximately 6 to 9 in. on center in each direction (**Fig. 2**). Immediately after placement of the adhesive, insulation boards were installed on the prepared plywood boards. Five weighted buckets, approximately 26 lb each, were placed on the insulation boards, one at each corner and one in the center. The buckets remained in place for approximately 10 to 15 minutes while the adhesive cured. The adhered plywood and insulation halves for each of the specimens were allowed to set up and cure between 12 to 24 hours before final assembly.

After setup and curing, the two-part polyurethane adhesive was applied in ribbons onto half of the specimen along the highlighted markings at designated ribbon spacing. The foam adhesive ribbons were applied at an initial application width of approximately ¾ in. (**Fig. 3**). The foam ribbons were installed in straight, parallel lines from one end of the insulation board to the other, in lieu of a serpentine pattern. Effort was made to keep the bead width as uniform as possible; however, some variation in adhesive bead width did occur. In addition, in some instances, a small amount of adhesive accumulated at the ends of the boards because of the nature of the applicator tool and the handheld process used.

Immediately after placement of the adhesive ribbons, the top insulation board was positioned on top of the ribbons, and weighted buckets (approximately 26 lb each) were placed on the plywood panels at the corners and in the center (**Fig. 4**). The buckets remained in place for approximately 10 to 15 minutes while the adhesive cured. **Figure 5** presents a cross-sectional view of a typical completed specimen assembly.

Companion Specimens

Companion tests were performed on two small-scale specimen configurations to provide supplemental information of bond strength of the adhesive between the polyisocyanurate insulation layers as well as the tensile strength of the two-part polyurethane foam adhesive.

1 × 1 ft Specimens

Eight 1 × 1 ft square companion specimens were made with the same plywood and insulation materials as the full-sized specimens (**Fig. 6**). Six test specimens were made by adhering insulation with a centrally posi-

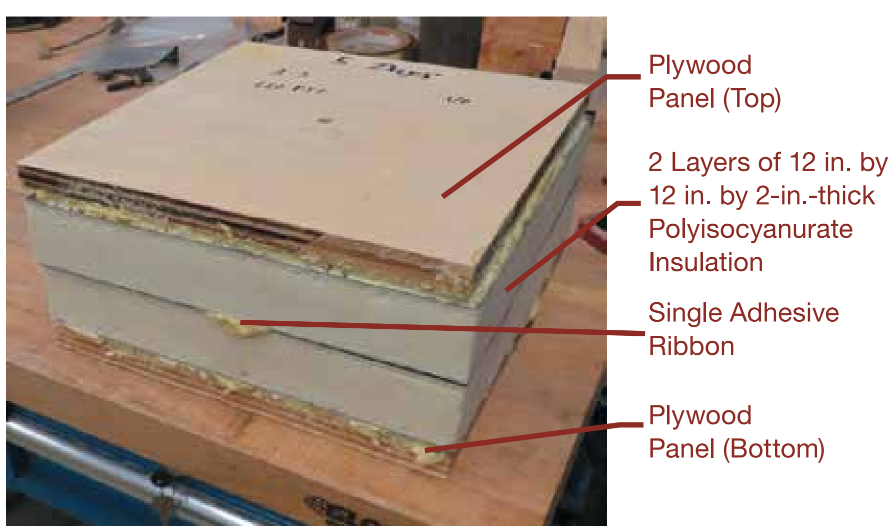

Figure 6. ***A 12 × 12 in. insulation board specimen with a single ribbon of adhesive.***

Figure 7. ***Two pucks with a ⅛-in.-gap space filled with foam adhesive.***

Figure 8. ***Example of the alphanumeric system and label used to identify the insulation specimens. B-18-3 indicates a cellulosic felt facer (B) with 18 in. ribbon spacing, and specimen number 3.***

tioned single 12-in.-long ribbon of foam adhesive. Three of the six specimens were made with coated glass fiber facers (Type A) and three with cellulosic felt facers (Type B). The remaining two specimens, one made with Type A insulation and the other made with Type B, were fabricated with a continuous film of foam adhesive to effectively provide full coverage over the 1 ft^2 surface area.

Adhesive-Only Specimens

To assess the tensile strength of only polyurethane foam adhesive, we used a controlled, thin-layering methodology in which the material was placed and adhered between two aluminum pucks (**Fig. 7**). The pucks have a machined surface on one side and a threaded hole on the other side to receive a threaded rod used to apply tensile test loads. Six specimens were prepared by initially cleaning and abrading the flat face of the aluminum puck. A layer of the project's two-part polyurethane foam was then applied to the face and inserted into a fabrication jig that holds and secures both pucks while maintaining a ⅛ in. gap between their planar surfaces. Subsequent expansion of the foam produces a controlled ⅛ in. separation of the pucks, ensuring appropriate resistance and simulating the effects of restraining ballast for actual installations. These specimens were intended to determine tensile strength of the foam adhesive at a thickness judged to be representative of typical use.

Three additional specimens were fabricated in a similar configuration as the first series, except that the pucks were adhered with a minimal space between the two puck surfaces (1/32 to 1/16 in. thickness). This specimen was intended to evaluate tensile strength of the foam adhesive in a thin-film configuration, possibly representing a condition of maximum confinement and restraint.

DESIGNATION AND IDENTIFICATION OF SPECIMENS

Full-Size Specimens

To provide unique identification of the 18 full-size test specimens, investigators developed an alphanumeric system consisting of letters to represent the facer type—polymer-coated glass fiber (A) and cellulosic felt (B)—followed by the ribbon spacing measurement, and the specimen test number (**Fig. 8**). For example, specimen number B-18-3 indicates a cellulosic felt-faced insulation board with 18-in. adhesive ribbon spacing, and specimen no. 3. **Table 1** summarizes the test matrix for all 18 specimens.

Companion Specimens

Of the six 1 × 1 ft square companion specimens fabricated with a single ribbon of adhesive, three were made with polymer-coated glass fiber

Facer type	Ribbon spacing (in.)	No. of specimens
Type A Polymer-coated glass fiber	6	3
	12	3
	18	3
Type B Cellulosic felt (organic)	6	3
	12	3
	18	3

Table 1. Test matrix for the full-size specimens

facers (A) and three with cellulosic felt facers (B). The three specimens with polymer-coated glass fiber facers were numbered A-1, A-2, and A-3, and the three with cellulosic felt facers were numbered B-1, B-2, and B-3.

The two additional 1 × 1 ft square companion specimens with full-coverage foam adhesive (FCA/FCB) applied between insulation boards were numbered FCA-1 and FCB-1.

Adhesive Specimens

The six puck specimens fabricated for tensile strength testing of the foam adhesive were identified as specimens TBS-1 through TBS-6. All six specimens were fabricated in a manner that allowed for a ⅛ in. gap between the pucks. Specimens TBS-1, TBS-2, and TBS-3 were allowed to cure for two days, and specimens TBS-4, TBS-5, and TBS-6 were allowed to cure for five days before testing.

Three additional pucks fabricated with the thin-film configuration were identified as ABS-1 through ABS-3.

AGE AND CONDITIONING OF SPECIMENS

The insulation boards and polyurethane foam adhesive were delivered to the laboratory on September 17, 2019, by an MRCA member contractor. The materials were delivered in unopened packaging, and after they were relocated into a warehouse building, the coverings were initially cut to allow for air movement. The materials remained in this location until assembled into the test specimens (approximately 30 days).

The environmental conditions in the warehouse during the time that the 4 × 4 ft square specimens were adhered with low-rise foam adhesive were 55°F to 67°F with relative humidity (RH) varying between 42% and 50%. The adhered specimens were kept in the warehouse building for two days; then they were moved to the conditioned laboratory space and allowed to acclimate to space environment of 70°F temperature and 30% RH for three additional days (five days total), prior to the start of testing on October 22, 2019.

The six 1 × 1 ft square insulation specimens, A1 through A3 and B1 through B3, and six pucks, TBS-1 through TBS-6, were fabricated in the warehouse building under similar conditions as full-size specimens. A single cartridge of low-rise foam adhesive was used to adhere the insulation boards to the plywood panels, and a separate cartridge was used to adhere the insulation boards together into adhered layered specimens for testing. This same cartridge was also used to adhere pucks TBS-1 through TBS-6. After setup, these samples were then relocated to the laboratory building and allowed to cure for five days. Pucks TBS-4 through TBS-6 were fabricated in a similar fashion but were allowed a cure time of two days before testing.

TEST APPARATUS AND INSTRUMENTATION

It was the intent of the program to subject the full-size adhered insulation specimens to direct axial tension force to effectively determine ultimate bond strength without inadvertent introduction of eccentric loading, prying, or peeling actions. This was accomplished by fabricating a custom test frame that secured the test specimen to an upper and lower aluminum plate system. These aluminum frames served as stiffening elements to the insulation specimens and ensured near-uniform axial loading to the adhered, layered specimen during testing.

The frames consisted of an upper and lower grillage of orthogonally oriented 6-in.-deep aluminum plates welded to a 4 × 4 ft square, ⅜-in.-thick aluminum base plate. Refer to **Fig. 9** for an overall schematic of the test frame. The lower frame was anchored to and supported by four steel tube legs on 3 ft spacings, while the upper aluminum frame was fitted with a steel yoke that served to transfer a single vertical force to the center of the 4 × 4 ft square grillage. Attachment of the assembled insulation test specimen to the frames was accomplished by a series of 26 anchor bolts each at the top and bottom sections of the specimen. The ⅜ inch studs were threaded into the tee nuts installed in the upper and lower plywood backers and passed through mating holes within the aluminum base plates and secured uniformly with wing nuts. Refer to **Fig. 10** for an overall view the upper test frame with an attached insulation specimen.

The aluminum test assemblies were positioned in an existing load reaction frame within the laboratory. The load reaction frame is a steel assembly used to support and apply loads and consists of steel columns and overhead steel back-to-back wide-flange beams secured to the laboratory's reinforced concrete reaction floor system. A 20,000-lb-capacity hydraulic actua-

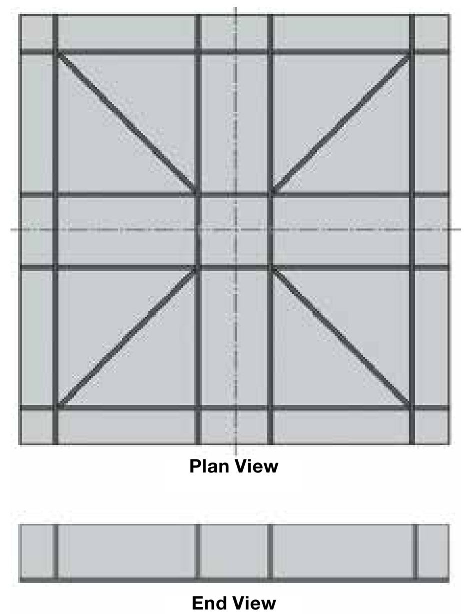

Figure 9. ***Schematic of stiffened upper aluminum test frame. All plates are ⅜ in. thick.***

Figure 10. ***A stiffened aluminum test frame and secured insulation board test specimen.***

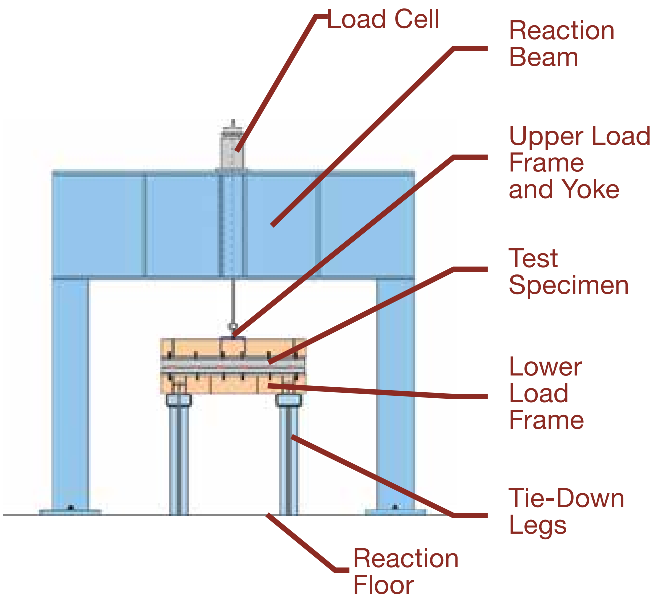

Figure 11. ***Schematic of existing steel reaction frame for application of load to specimen.***

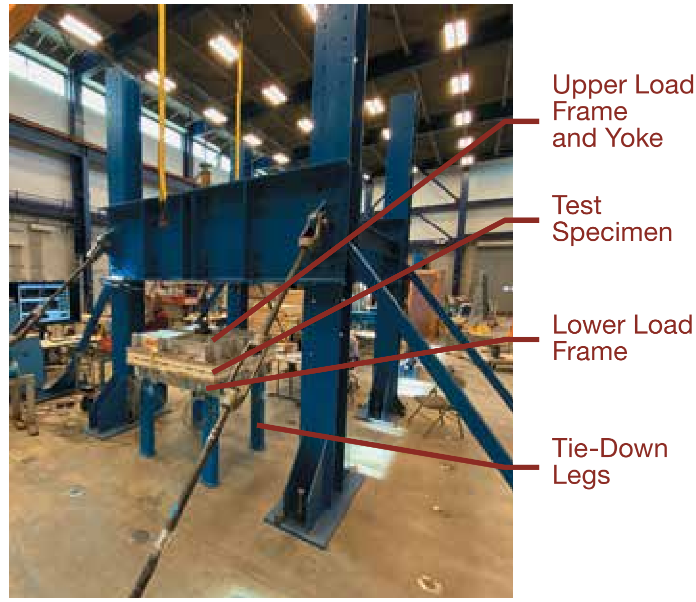

Figure 12. ***Existing steel reaction frame for application of load to specimen.***

tor was positioned on top of the reaction frame and connected to the captured test specimen via a high-strength coil rod with end swivels. For schematic and overall views of the existing reaction frame with aluminum test frame setup, see **Fig. 11** and **12**.

A key performance parameter to evaluate relative behavior of the full-size test specimens is the load-deformation relationship. Accordingly, displacement of the specimens during tension loading was measured by four discrete displacement transducers (string potentiometers) positioned at the midpoint of each of the four edges of the specimens to measure movement between the upper and lower aluminum test frames (**Fig. 13**). The displacement transducers measured the combined effects of axial strain (stretching) of the two 2-in.-thick insulation layers, as well as separation and elongation of the low-rise foam adhesive during loading. The displacement transducers at each edge location had a total stroke of 2 in. and an accuracy of 0.001 in. For overall test fixture monitoring and measurement of any flexural deformation of the upper aluminum load frame, displacements near the center of the frame were additionally measured relative to the reaction frame at two locations.

Applied load provided by the hydraulic ram was monitored by a 20,000-lb-capacity electronic load cell. Output from all six displacement transducers and the load cell were captured by a computer-controlled data acquisition system that scanned sensors at approximately 1-second intervals. Displacements and loads were visually displayed on a large light-emitting diode screen to facilitate monitoring during testing.

Figure 13. ***Displacement transducer positioned at the edge of a test specimen to measure separation and elongation of insulation during testing.***

TESTING PROCEDURES

Full-Size Specimens

Procedures for subjecting each of the 18 full-size specimens to uniform axial load were based on applicable provisions of ANSI/SPRI IA-1, *Standard Field Test Procedure for Determining the Uplift Resistance of Insulation and Insulation Adhesive Combinations over Various Substrates.*[2] Procedure IA-1 is commonly used to determine the uplift resistance of an installed roofing/insulation system in the field, and it provides for a loading protocol of incremental pressure increases and a dwell, or holding period, at each load stage. Investigators believed that this regimen would appropriately provide for a combination of incremental and sustained loading to effectively determine stiffness response and any short-term, nonlinear deformation tendencies. It is recognized that this modest loading rate may produce slightly lower ultimate load capacities compared with a more rapid application of load (such as a load application simulating wind gusts).

The general testing sequence of each full-size specimen consisted of the following:

1. Placing the adhered insulation specimen onto the lower aluminum test frame
2. Lowering the upper aluminum test frame onto the specimen
3. Securing the specimen to the upper and lower load frames by hand-tightening the wing nuts
4. Attaching the loading pin and pull-rod assembly to the loading yoke of upper frame
5. Attaching the north, south, east, and west edge displacement transducers
6. Attaching the two center-frame displacement transducers
7. Zeroing the displacement transducers and load cell and initiating data logging
8. Applying the preload/starting load of 30 lb/ft^2 plus tare weight
9. Maintaining the load for 1 minute
10. Incrementally increasing the load by 15 lb/ft^2 (240 lb)
11. Maintaining the load for 1 minute
12. Repeating incrementally increased loading until failure

Figures 14, **15**, and **16** present overall representative views of test setups and in-progress testing.

Companion Specimens

Companion tests were performed on two different small-scale insulation board specimen configurations to provide supplemental information about bond strength of polyisocyanurate insulation layers as well as the tensile strength of the low-rise foam adhesive.

1 × 1 ft Insulation Board Specimens

Nominal ⅜ in. threaded pull rods were anchored to each plywood back to facilitate load application. Specimens were installed in a hydraulic test machine, which provided application of a direct tensile load (**Fig. 17**). Load was applied in a similar manner as was employed for the full-size specimens: a preload of 30 lb/ft^2 was held for 1 minute, followed by incremental loading of 15 lb/ft^2 with 1-minute hold periods. The load was incrementally increased until failure occurred.

Puck Specimens

The nine aluminum puck specimens were tested in tension in the hydraulic test machine (**Fig. 18**). Load was applied in a similar manner as for other tests: a preload of 30 lb/ft^2 was held for 1 minute, followed by incremental loading of 15 lb/ft^2 with 1-minute hold periods. The load was incrementally increased until failure occurred.

Figure 14. ***Positioning the upper aluminum load frame onto a test specimen.***

Figure 15. ***Securing the upper load frame to a test specimen with a plate and wing nuts onto threaded rods.***

Figure 16. ***Application of axial load to a test specimen.***

Figure 18. *A 2-in.-diameter aluminum puck specimen with ⅛-in.-thick low-rise foam adhesive being tested in the hydraulic test machine.*

Figure 17. *Testing of a 1 ft² insulation board specimen with a single ribbon of adhesive in the hydraulic test machine.*

TEST RESULTS

Full-Size Specimens

Direct tension testing of the 18 full-size specimens was performed at our structural laboratories from October 22 to October 24, 2019. Portions of the testing were witnessed by Mark Langer, representing MRCA. Specimens were tested at an age ranging from four to six days from assembly. Each specimen was loaded in 15 lb/ft² (240 lb) increments followed by 1-minute hold periods until separation failure occurred, in accordance with the previously described test protocol. Total test time per specimen ranged from approximately 27 to 67 minutes, depending on the magnitude of the failure mode. Continuous readings of applied load, the four displacement transducers at the specimen edges, and two at the center were recorded for the duration of each test.

Direct tension strengths for each specimen were computed by subtracting the tare weight of the upper load assembly (consisting of the pull rod, shackles, the aluminum load frame, and a single layer of foam/plywood) from the maximum measured test load and dividing the result by the nominal cross-sectional area of the specimen (16 ft²).

Average test strengths for Type A (polymer-coated glass fiber) specimens for ribbon spacings of 6, 12, and 18 in. were 674, 497, and 342 lb/ft², respectively. Average test strengths for Type B (cellulosic felt) specimens for ribbon spacings of 6, 12, and 18 in. were 614, 379, and 307 lb/ft², respectively. **Tables 2** and **3** summarize the testing results. The relationship between measured failure loads

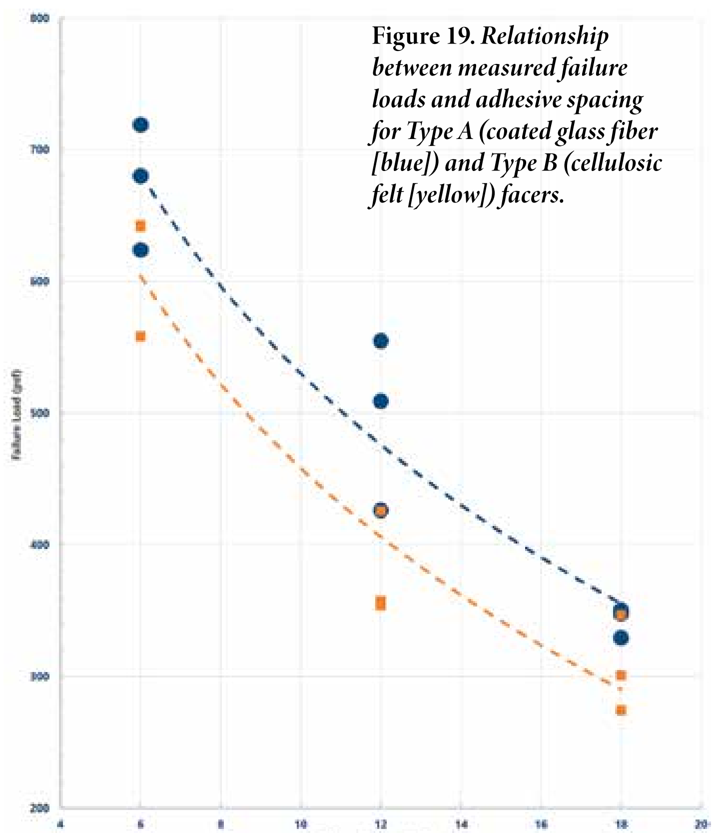

Figure 19. *Relationship between measured failure loads and adhesive spacing for Type A (coated glass fiber [blue]) and Type B (cellulosic felt [yellow]) facers.*

Ribbon spacing (in.)	Specimen ID	Test age (days)	Test strength (lb/ft^2)	Average test strength (lb/ft^2)	Coefficient of variation
6	A-6-1	4	719	674	7.1%
	A-6-2	5	680		
	A-6-3	6	624		
12	A-12-1	5	426	497	13.1%
	A-12-2	5	555		
	A-12-3	4	509		
18	A-18-1	4	348	342	3.4%
	A-18-2	5	329		
	A-18-3	5	351		

Table 2. ***Summary of test results for specimens with Type A (polymer-coated glass fiber) facers***

Ribbon spacing (in.)	Specimen ID	Test age (days)	Ribbon spacing (in.)	Test strength (lb/ft^2)	Average test strength (lb/ft^2)	Coefficient of variation
6	B-6-1	5	6	558	614	7.9%
	B-6-2	6	6	643		
	B-6-3	6	6	642		
12	B-12-1	5	12	354	379	10.7%
	B-12-2	4	12	426		
	B-12-3	5	12	357		
18	B-18-1	4	18	274	307	11.9%
	B-18-2	5	18	301		
	B-18-3	5	18	347		

Table 3. ***Summary of test results for specimens with Type B (cellulosic felt) facers***

and adhesive spacing for Type A and B facers is depicted in **Fig. 19**.

Separation Displacements

Displacements between the upper and lower aluminum load frames were measured during each test and represented the combined effects of axial strain (stretching) of the two 2-in.-thick insulation layers as well as separation and elongation of the polyurethane foam adhesive during loading. **Figure 20** shows the plot of applied load versus average edge displacement (P-∂ plot) for specimen A-12-3. The curve is fairly linear up to failure load, at which time displacements rapidly increase due to large separation of the insulation layers.

The P-∂ relationships provide two distinct performance indicators for the tested tensile specimens: (a) maximum displacement/separation at failure and (b) stiffness. The data reveal that the average edge displacements at failure for specimens made with adhesive ribbon spacings of 6, 12, and 18 in. were 0.16, 0.19, and 0.23 in., respectively. As expected, greater displacements were achieved at higher ultimate loads; no significant difference in maximum displacements was noted between specimens with coated glass

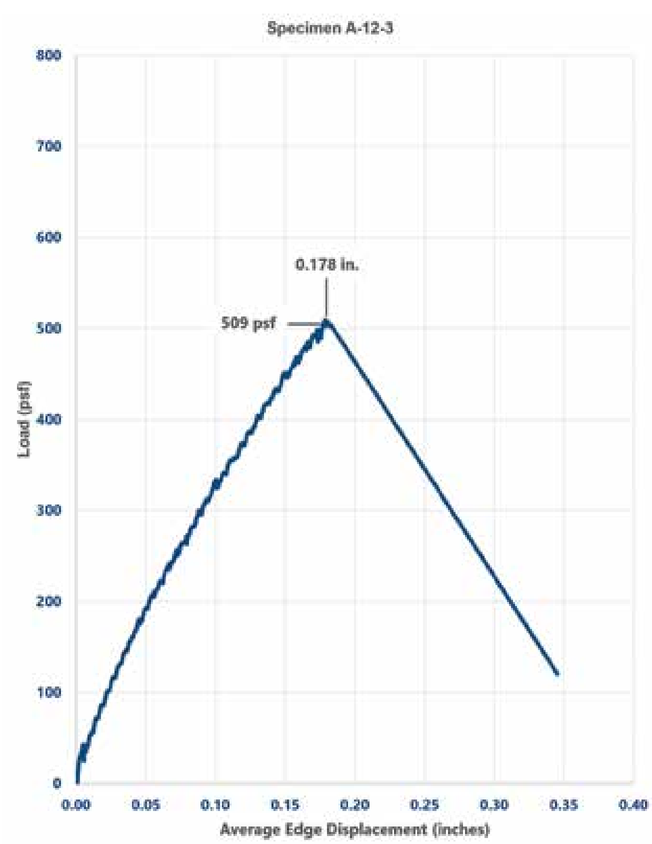

Figure 20. ***Load displacement plot measured for specimen A-12-3.***

Facer type	Ribbon spacing (in.)	Maximum average edge displacement at failure load (in.)
A	6	0.21
	12	0.20
	18	0.17
B	6	0.15
	12	0.18
	18	0.24

Table 4. ***Maximum average edge displacements at failure load***

fiber or organic facers. **Table 4** summarizes the measured maximum average displacements for the test specimens.

Stiffness

The structural stiffness of a component is a strong indicator of the overall performance of an element. Stiffness is defined as the resistance of a body to deflection or deformation from an applied force—that is, elements with greater stiffness will deflect or deform less than those with lower fundamental stiffness properties. For the adhered insulation test specimens, axial stiffness was calculated for each specimen as the ratio of applied tensile load to average separation displacement between stages corresponding to 10% and 50% of ultimate loads, as shown schematically in Fig. 20.

Computed axial stiffnesses for the six specimen groups ranged from 40 to 65 ksi (**Table 5a**). The relationships of spacing versus stiffness exhibit similar trends as that noted for ultimate strength values, with coated glass fiber-faced specimens having a somewhat higher (10% to 19%) stiffness than organic-faced specimens. The higher stiffness values for tighter adhesive ribbon spacing may be associated with the greater amount of contact adhesive area for 6 in. spacing as compared with 12 in. spacing. When there is less spacing, forces are distributed over more of the insulation surface, reducing overall axial strain at comparable loads.

Post-test Observations

The failure mechanisms in the full-size specimens were predominately delamination and separation of the facers (either the coated glass fiber or the cellulosic felt facers) and some cohesive failure of the foam core. Cohesive failure of the foam core was most prevalent in the specimens with 6 and 12 in. ribbon spacings and occurred to a lesser extent in the specimens with 18 in. ribbon spacing. For the specimens with 18 in. ribbon spacing, the primary failure plane was delamination and separations from the insulation facers. After testing, each specimen was placed on a table for examination and documentation. Representative examples are shown in **Fig. 21**, **22**, and **23**.

Facer type	Ribbon spacing (in.)	Axial stiffness (ksi)
A	6	65
	12	50
	18	44
B	6	58
	12	42
	18	40

Table 5a. ***Average axial stiffness for Type A and Type B specimens***

Facer type	Specimen ID	Test strength (lb/ft^2)	Average test strength (lb/ft^2)	Coefficient of variation
A	A1	700	673	3.4%
	A2	660		
	A3	660		
B	B1	660	485	32.2%
	B2	435		
	B3	360		

Table 5b. ***Test strength results for 12 × 12 in. panels with single low-rise foam adhesive ribbon***

Companion Specimens

1 × 1 ft Square Specimens

Direct tension testing of the six 1 × 1 ft square specimens (A1, A2, A3, B1, B2, and B3) was performed after a five-day cure period. Each specimen was loaded in 15 lb/ft^2 (240 lb) increments followed by 1-minute hold periods until separation failure occurred. Test strengths were computed as the maximum measured load divided by the nominal area of the specimen (1 ft^2). Average test strengths were 673 lb/ft^2 for Type A (polymer-coated glass fiber) specimens and 484 lb/ft^2 for Type B (cellulosic felt) specimens. **Table 5b** summarizes the testing results.

Testing of specimens FCA-1 (polymer-coated glass fiber facer) and FCB-1 (cellulosic felt facer) fabricated with full coverage of adhesive over the entire 1 ft^2 insulation surface had failure loads of 896 and 838 lb/ft^2, respectively.

General post-test observations for the specimens A1, A2, A3, B1, B2, and B3 included the following:

- Coated glass fiber facers: The predominant failure mechanism in the three specimens with a single adhesive ribbon was delamination and separation of the facers from the foam body of the insulation boards in conjunction with varying degrees of cohesive failure within the foam core.
- Cellulosic felt facers: The predominant failure mechanism in the three specimens with a single adhesive ribbon was delamination and separation of the facers from the foam body of the insulation.

General observations for the specimens FCA-1 and FCB-1 included the following:

- Coated glass fiber facers: The predominant failure mechanism in the specimen with the full-coverage adhesive layer was delamination and separation of the facer from the foam body of the insulation.
- Cellulosic felt facers: The failure mechanism in the specimen with the full-coverage adhesive layer was cohesive delamination and separation within the facer.

Puck Specimens

Direct tension testing of the six aluminum puck specimens (TBS-1 through TBS-6) that featured the ⅛-in.-wide foam layer was performed after a two- or five-day cure period. Each specimen was loaded in 15 lb/ft^2 (240 lb) increments followed by 1-minute hold periods until separation failure occurred. Test strengths were computed as the maximum measured load divided by the nominal area of the specimen (3.14 in.^{2}). Average test strengths were 1355 lb/ft^2 for two-day-old specimens and 3361 lb/ft^2 for five-day-old specimens.

The data clearly show that for the configuration tested, the adhesive gained appreciable strength between curing ages of two to five days for the nominal 70°F storage environment. **Table 6** summarizes the testing results.

Specimens ABS-1, ABS-2, and ABS-3 were tested at an adhesive age of four days, and their average measured strength was 295 psi (42,480 lb/ft^2). These values are substantially greater than for specimens fabricated with ⅛ in. of adhesive.

General post-test observations for specimens TBS-1, TBS- 2, and TBS-3 (two-day-old adhesive) revealed the failure mechanism to be cohesive failure of the foam adhesive.

In testing of specimens ABS-1, ABS-2, and ABS-3 with thin film adhesive (foam thickness less than 1⁄16 in.), the failure mechanism was a cohesive failure between the adhesive and the aluminum puck.

SUMMARY AND FINDINGS OF TEST PROGRAM

We have completed a research and testing program for the MRCA to determine the effect on bond capacity for various low-rise foam adhesive ribbon spacings used to adhere layers of polyisocyanurate roofing insulation boards. The program evaluated both polymer-coated glass fiber-faced and cellulosic felt-faced insulation board specimens prepared with 6, 12, and 18 in. ribbon spacings. The work featured fabrication of a custom test rig to accommodate and apply direct tension loading of full-size (4 × 4 ft) adhered insulation specimens, as well as testing on small-scale companion specimens and tensile tests of cured foam material.

Key findings of the test program include:

- Average measured direct tension strengths for full-size polymer-coated glass fiber-faced specimens tested at ribbon spacings of 6, 12, and 18 in. were 674, 497, and 342 lb/ft^2, respectively. Average test strengths for cellu-

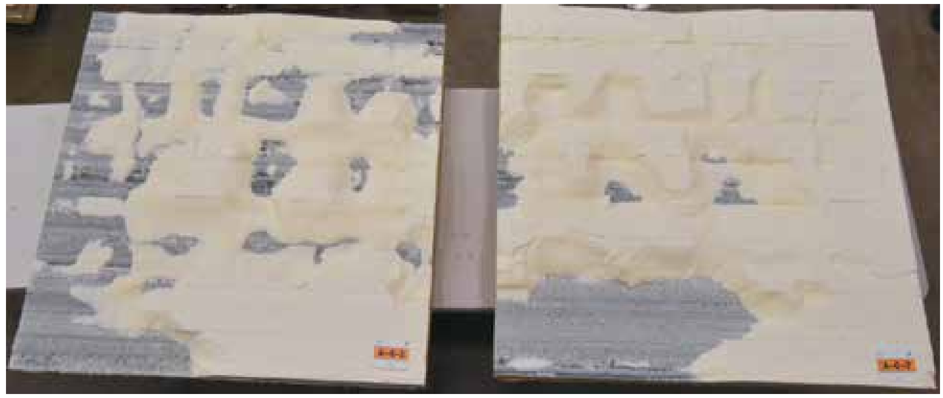

Figure 21. ***Specimen A-6-2 shown in separated fashion, similar to an opened book. The plane of failure was primarily within the foam core of the top facer of the insulation board (left), with some delamination at the bottom glass fiber facer of the board (right).***

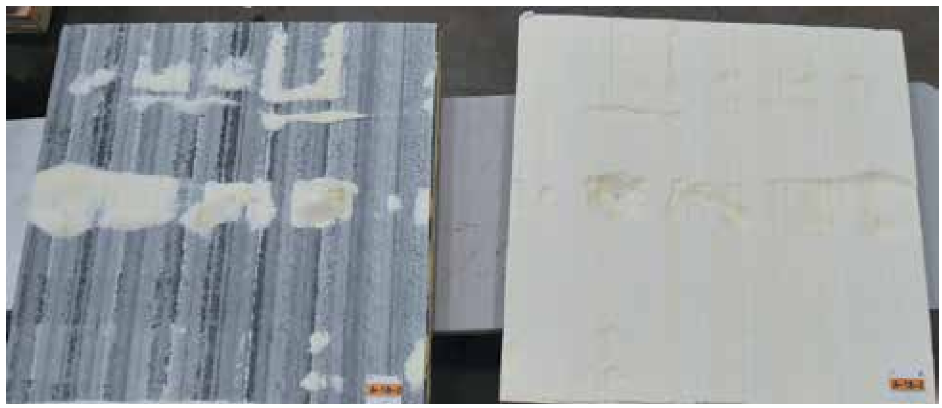

Figure 22. ***In specimen A-18-2, the primary failure was separation of the top facer of the bottom board from the foam core, with some cohesive bond separation within the foam core.***

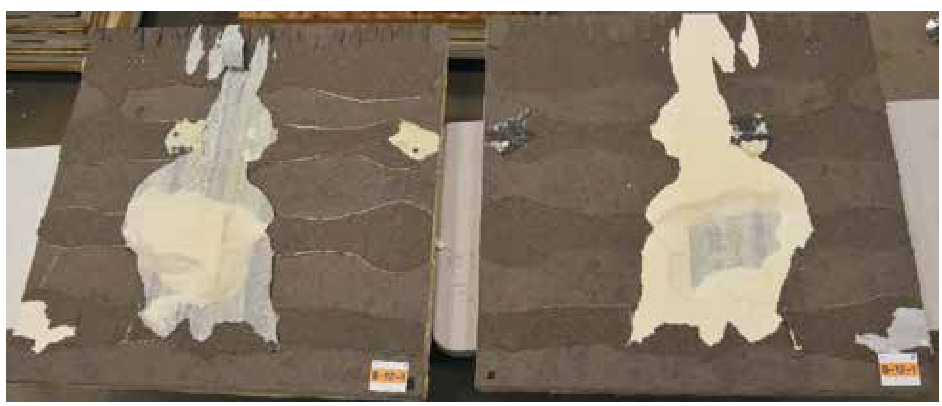

Figure 23. ***In specimen B-12-1, the failure planes were the bottom facer of the top board and top facer of the bottom board, with cohesive separation within the organic facer along the foam ribbons. The failure included some cohesive separation of the foam core.***

Age (days)	Specimen ID	Test load (lb-f)	Test strength (psi)	Test strength (lb/ft^2)	Average strength (lb/ft^2)	Coefficient of variation
2	TBS-1	36	11.4	1640	1355	33.9%
	TBS-2	35	11.1	1601		
	TBS-3	18	5.7	825		
5	TBS-4	80	25.5	3667	3361	8.0%
	TBS-5	69	22.0	3163		
	TBS-6	71	22.6	3254		

Table 6. ***Results for low-rise foam adhesive tensile test with ⅛-in.-thick foam beads***

To help put these test results into the context of industry practice and expectations, we recommend additional testing that can narrow other environmental, product, and installation variables inherent to insulated roofing systems.

losic felt-faced specimens for ribbon spacings of 6, 12, and 18 in. were 614, 379, and 307 lb/ft^2, respectively. These test results were fairly uniform based on computed coefficient of variation of 7% to 13% for each facer type.

- The test data clearly show that direct tension strength increased as adhesive foam ribbon spacing decreased, for both the polymer-coated glass fiber-faced and cellulosic felt-faced insulation specimens. This strong correlation confirms and quantifies industry knowledge and practice that greater adhered insulation board uplift resistance is achievable with closer foam adhesive spacings.
- For the specific polyisocyanurate insulation and foam adhesive used in this test series, boards with polymer-coated glass fiber facers exhibited approximately 9% to 24% greater strengths than cellulosic felt-faced specimens at equal adhesive spacings.
- Failure of the specimens primarily occurred as separations and/or delaminations of the insulation board facers from the foam body core along the lines of the adhesive ribbons, with secondary failures within the body of the insulation noted in some instances.
- As expected, specimens with greater ultimate strengths at decreased adhesive ribbon spacing also exhibited higher axial tensile stiffness characteristics. For a given uplift load, specimens with closer ribbon spacings would have less axial stretch or displacement than systems with greater adhesive spacing.
- As expected, the measured ultimate strength values of the full-size insulation-to-insulation adhered specimens tested in this program were found to be significantly greater than typical uplift ratings for complete roof systems.
- Testing of the 1 × 1 ft adhered insulation companion specimens, each with a single adhesive ribbon, revealed that polymer-coated glass fiber-faced specimens were 28% stronger than those specimens with cellulosic felt facers, with average strengths of 673 and 485 lb/ft^2, respectively. Companion specimens fabricated with full coverage of adhesive over the entire 1 ft^2 surface had substantially higher strengths of 833 lb/ft^2 for the cellulosic and 896 lb/ ft^2 for the glass fiber. These comparative test results confirm that, when greater amounts of adhesive are present over a given area, larger portions of the facer/insulation interfacial zone are mobilized to transfer loads between adhered boards.
- In general, strengths derived from companion tests are higher and not well correlated with the results for the full-size specimens with 12 in. adhesive spacings. Testing using larger (4 × 4 ft) specimens is considered more representative of real-world installations than testing using smaller (1 or 2 ft^2) specimen sizes because the larger specimens have greater surface areas.
- Tensile testing of the 2-in.-diameter pucks with ⅛-inch-thick foam adhesive indicated substantial strength gains between test ages of two and five days. Average measured strengths were 1355 lb/ft^2 at two days and 3361 lb/ft^2 at five days. As expected with two-part polyurethane-based adhesive, chemical cure and associated strength development continues well after initial setting, depending on environment conditions at the time of dispensing and thereafter.
- In limited testing, pucks with adhesive of minimal thickness (less than 1/16 in.) had substantially greater adhesive tensile strength than those specimens made with ⅛-in.-thick adhesive. This behavior is not necessarily unexpected, but it reinforces the value of restraining normal foam expansion by appropriate ballasting to minimize adhesive thicknesses (and also producing wider contact zones of the ribbons) in real-world installations.

The test values derived from this program are specific to the types of insulation boards and foam adhesive used. While overall general trends indicated by test data may be similar and characteristic of other manufacturers' products, the limitations of the values presented specifically in this report should be noted.

RECOMMENDATIONS FOR FURTHER TESTING AND RESEARCH

To help put these test results into the context of industry practice and expectations, we recommend additional testing that can narrow other environmental, product, and installation variables inherent to insulated roofing systems. Such additional testing may include assessment of insulation boards of varied thickness, as well as insulation and foam adhesives from additional product manufacturers; testing of installation and curing in other environmental conditions; and investigation of other factors that may influence adhesion and overall strength in the adhered foam interfacial regions. Panel orientations and cure times may also be explored in greater depth to obtain a better understanding of short- and longer-term performance.

As the assessment of additional testing is considered, we recommend that a careful review of safety factors for adhesives in insulation-to-insulation applications, as well as overall roofing applications, be included. Similarly, a review of ribbon spacings specified in fully tested and rated assemblies for uplift should be part of any further review.

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ABOUT THE AUTHORS

Randy Adams

***Randy Adams** is chair of the Midwest Roofing Contractors Association Technical and Research Committee. He has more than 40 years of specialized experience in the roofing industry and is owner and president of R. Adams Roofing Inc., Environmental Greenscapes Inc.*

Richard S. Koziol

***Richard S. Koziol** is a principal at Wiss, Janney, Elstner Associates Inc. He has more than 35 years of specialized experience in investigating and testing roofing systems. He has developed and designed repairs for water infiltration and condensation problems in new and existing building enclosures. Koziol is a graduate of the University of Illinois at Chicago and a licensed architect in five states.*