Wind Uplift Capacity of Foam-Retrofitted Roof Sheathing Subjected to Water Leaks

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ABSTRACT

This paper evaluates the use of closed-cell Spray-Applied Polyurethane Foam (ccSPF) as a structural retrofit of existing wood-framed roofs. ccSPF is used as a thermal insulator in the building envelope and it forms a tenacious bond to most construction materials. As a result ccSPF is used to strengthen the wind resistance of wood roof structures. ccSPF is currently being installed in houses in Florida although the long-term performance of the material in presence of water is unknown. This study seeks to evaluate the effect of water leaks on the moisture buildup and wind uplift capacity of ccSPF-retrofitted wood roof panels.

Nine full-scale roof attics were constructed and exposed to long-term environmental conditions and simulated rain in two phases, (five in Phase I and four roofs in Phase II). Numerous leak gaps were cut into the roofing systems simulating effects of long-term water leaks. It was found that moisture buildup occurs in roof sheathing and wood framing members, but it the increased wind uplift capacity of ccSPF-retrofitted roofs was not significantly affected. The high tensile strength of the water-saturated ccSPF to wood bond was confirmed in long-term tests using small-scale samples. While there was a reduction in tensile failure stresses after time due to exposure to moisture, the minimum values were more than xx psi, well above the wind uplift suctions producible by hurricane wind speeds. In the second phase, techniques to mitigate the moisture buildup were investigated. Preliminary results indicate that incorporating underside air vents within a ccSPF-retrofit may reduce the drying time of the roof sheathing. Further, installing a self-adhered waterproofing membrane underlayment on the roof deck substantially reduced the absorption of moisture into the wood roof system. A discussion of future testing is provided.

BACKGROUND

Failure of roof sheathing during extreme wind events is a common failure mode in residential roofs. The majority of hurricane-related losses are sustained by residential homes and 95% of these are from failures within roof-systems (Baskaran, Dutt, 1997). Inadequate fastening of wood sheathing to roof framing members is the most common failure mode. Roof sheathing failure causes major losses for two primary reasons: (1) the loss of diaphragm action weakens the lateral stability of the roof, leading to roof failure and progressive collapse of the building; and (2) openings made in the roof can allow water to intrude which severely damages interior components and building contents. Despite enhanced building code provisions that have improved the construction of newer homes, over 80% of the existing residential housing stock in these hurricane-prone regions were built before any building code changes (Datin, Prevatt *et al.*, 2011). Thus, a significant portion of the existing housing stock remains vulnerable to these damages. Therefore it is beneficial to identify viable retrofit options to improve the uplift capacity of these vulnerable roof systems.

Several studies have reported methods of using structural adhesives to retrofit wood (Jones, 1998; Turner, 2009; Datin, Prevatt *et al.*, 2011) and the uplift capacities are increased by three to five times when compared to minimum code-required fastening schedules and sizes. In addition to its effect on sheathing uplift capacity, ccSPF is also an attractive retrofit option due to its insulating properties and presence as a secondary water barrier. Despite the benefits of ccSPF to roof sheathing, certain performance issues have not been fully addressed, including their structural performance when exposed to water. Datin et al. (2011) postulated that water leakage into a ccSPF-retrofitted wood roof may become trapped between ccSPF and wood structural members and could cause diminished performance of the roof. This hypothesis led to the current study which consists of two phases.

The objective of Phase I was to determine if elevated moisture contents in a roof affected the bond strength of the ccSPF to the wood substrate, specifically with regards to the uplift capacities of the ccSPF-retrofitted panels. The objective of Phase II is to examine the mechanics of the moisture travel within a ccSPF-retrofitted roof system and evaluate possible techniques for mitigating the moisture intrusion and buildup. Phase I was completed in January 2011; Phase II is scheduled for completion in January 2013.

Datin et al. (2011) conducted wind uplift capacity tests on ccSPF-retrofitted panels using the following three configurations as shown in Figure 1: Level I - 3 in. triangular fillet of ccSPF at the wood framing to sheathing panel joint; Level II - 3 in. fillet plus ½ in. layer between fillets; Level III - continuous 3 in. thick ccSPF layer. Uplift tests showed that the ccSPF-retrofitted panels yielded two to three times greater capacity than the control panels. .

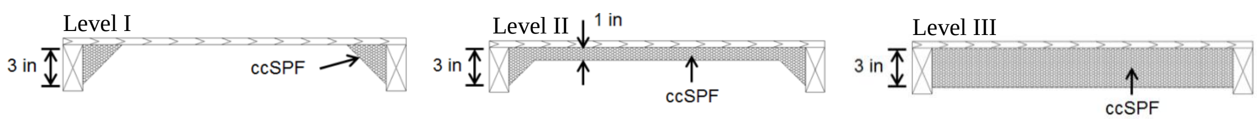


Figure 1. Retrofits Types

MATERIALS AND METHODS

Five full-scale attic structures were constructed at the University of Florida Hurricane Research Laboratory in Gainesville, Florida. Each structure had a 10 ft by 33 ft-6 in. footprint and was sloped at a 6-in-12 pitch. All roofs were oriented to face in a north/south direction. Construction materials consisted of 2x4 wood roof trusses, 4ft x 8 ft x 1/2-in. Oriented Strand Board (OSB) sheathing panels fastened with 6d nails at 6/12 spacing, 15# felt and asphalt shingles. Each roof was assigned a different combination of ccSPF retrofit (no retrofit, Level II, or Level III) and leakage condition (with leaks or without leaks) as shown in Table 1. Every roof was given the same leakage pattern, with approximately one-hundred 1/2-inch diameter leak gaps at 12 in. apart, cut through the roofing layer on each roof. Roofs were exposed to natural weather conditions and every other day, 15-minute simulated rainfall for 150 days commencing in late summer. Additionally eight lab-built samples were retrofitted (in two subsets labeled as LII and LIII) and stored in an unconditioned laboratory space for the duration of the exposure period of the roofs.

Table 1: Summary of Test Variables – Phase I

Roof 1	Roof 2	Roof 3	Roof 4	Roof 5
No Retrofit	Type II Retrofit	Type II Retrofit	Type III Retrofit	Type III Retrofit
Leak Gaps	Leak Gaps	No Leaks	Leak Gaps	No Leaks

Moisture content, temperature and relative humidity in the roofs were monitored throughout the exposure period using resistance-based, temperature-corrected moisture content devices placed into the wood members. Temperature/relative humidity probes monitored ambient temperature and relative humidity in the unconditioned attic space. Proprietary software developed by SMT collected and converted signals wirelessly from the sensors and stored the data in an internet-accessible database.

At the conclusion of the exposure period, panels were extracted from the roof and tested to determine their wind uplift capacities in accordance with Datin et al. (2011). The panel test setup and pressure loading actuator are shown in Figure 2. The static, “step and hold” pressure trace used is shown in Figure 3, applied pressure in 15 psf increments lasting for 10 sec. with a 5 sec. ramp transitioning between increments. Specimens are loaded to failure, which was defined as the point at which either the panel visibly deflects, a wood member fractures or a sudden drop in chamber pressure occurs.

Figure 2. PLA (left) and panel loaded upside-down in pressure chamber (right).

The panel displacements were measured in the center of each sheathing panel specimen using a string potentiometer, and pressure-displacement relationships were developed.

Immediately after wind uplift testing, the moisture content and specific gravity of each of the five framing members attached to every sheathing panel were determined using ASTM D 4442 and ASTM D 2395, respectively.

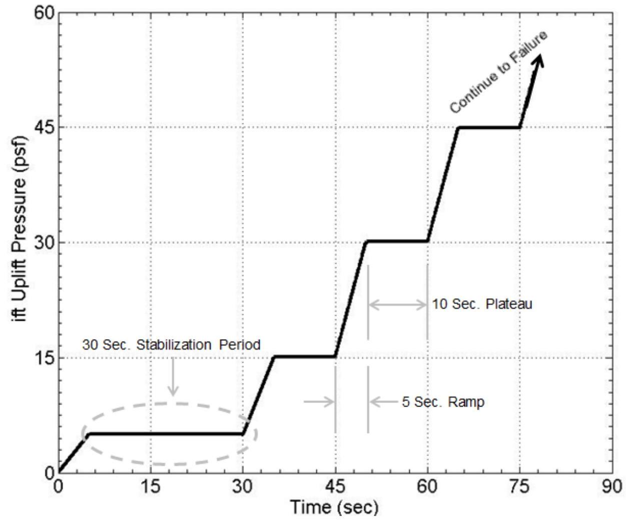


Figure 3. Wind uplift loading protocol.

Small-Scale Tensile Testing

Tensile tests were performed on 3”x3” samples of ccSPF-retrofitted sheathing panels. ccSPF was bonded to three surfaces: the smooth underside surface of OSB, the textured surface of OSB, and plywood. Samples were exposed to water in an enclosed chamber and tensile capacities were tested after 1 week, 2 weeks, 4 weeks, 8 weeks, 12 weeks and 16 weeks of exposure time. Testing was performed using an Instron 3367 Universal Testing Machine (UTM) as shown in Figure 4.

Mean tensile capacity of the ccSPF bond to the smooth and textured surfaces of OSB and to plywood over the sample exposure period is presented in Figure 5, with error bars representing the standard deviation of the testing results.

No statistically conclusive evidence was found to suggest that the ccSPF-to-sheathing bond weakened with length of exposure period. However, the tensile stress capacity of wetted samples was lower than control samples for all substrates tested.

Figure 4: Tensile capacity test setup

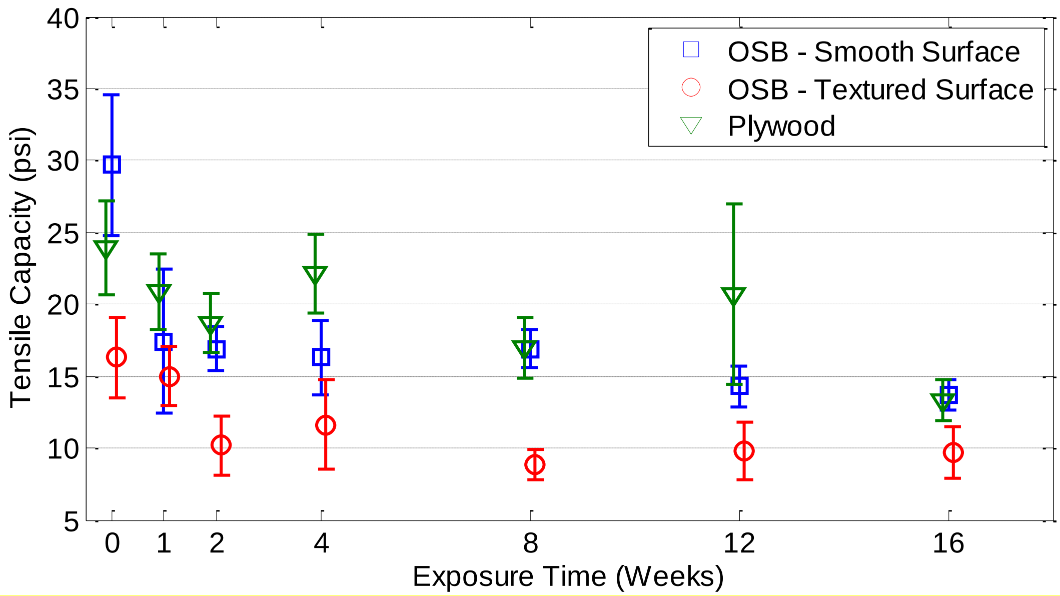


Figure 5: Tensile Capacity of ccSPF-retrofitted samples exposed to moisture

MOISTURE ACCUMULATION IN WOOD ROOF STRUCTURES

Time-histories from the full-scale attics of maximum daily truss member moisture contents during the weathering period indicate that the lowest moisture contents were observed in non-leaking roofs as expected; these moisture contents remained steady between 10% and 15% throughout the period. Roof 1, the leaking, un-retrofitted wood roof, had higher moisture contents ranging between 10% and 20%. The moisture contents in the ccSPF-retrofitted roofs with leaks rose throughout the exposure due to extent of regular water leakage, reaching as much as 70%.

At the conclusion of the exposure period, shingles and underlayment were stripped from each roof to prepare for panel removal and testing. It was observed that the 6 in. wide OSB strips directly below the leak gaps became more saturated than the full 4x8 panels, either due to proximity of water leaks or because water absorption increases along the horizontal joints in the OSB. As expected, the moisture content was highest in roof panels near to the eave, and it decreased in panels further up the slope of the roof. Panels on the south-facing roof slopes consistently had higher moisture contents than the equivalent panels in the north-facing slopes.

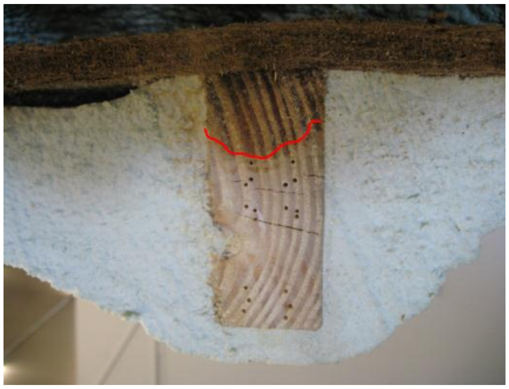


Figure 6: Moisture Build-up in Roof Framing Members

Elevated moisture contents and physical evidence of the moisture intrusion was seen in the top chord of the roof trusses in Roofs 2 and 4, as shown in Figure 6. Moisture contents as high as 63% were observed in the top chords of the roof trusses in these roofs, predominately near the eaves.

Uplift Failure Pressures of Sheathing Specimens

Table 2 and Figure 7 display failure pressures for all roof sheathing specimens. Means, standard deviations, and coefficients of variation (COV) are provided. In Figure 4, means with bars representing one standard deviation above and one below are displayed beside each sample set. COV values ranged from 17% to 21% in the built roofs and all results were within two standard deviations of the mean.

Table 2. Failure pressures (psf) of full-scale sheathing specimens.

	Roof 1	Roof 2	Roof 3	Roof 4	Roof 5	LII	LIII
Mean (psf)	53.6	270.0	271.6	383.3	294.1	253.0	254.3
St. Dev. (psf)	9.4	45.6	55.9	81.7	47.2	60.4	46.4
COV (%)	17.6	16.9	20.6	21.3	16.0	23.9	18.2

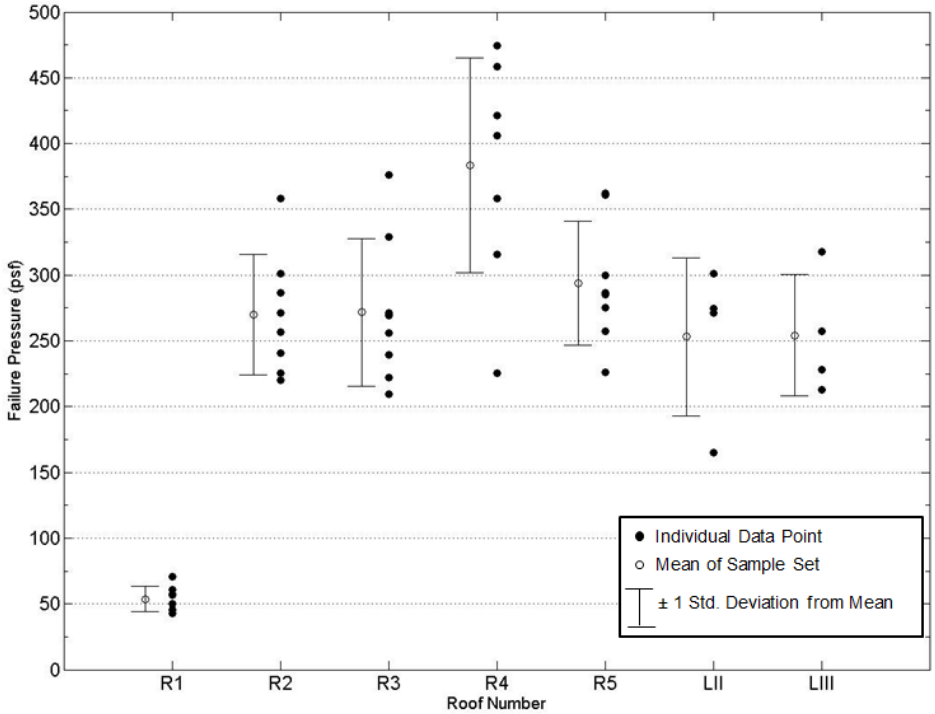


Figure 7. Individual results for failure pressures of full-scale roof sheathing panels.

Pressure vs. Deflection Relationships

The un-retrofitted panels in Roof 1 showed linear behavior for a short time until the nails began to withdraw from truss members. Relatively large deflections then continued until panel failure. In all ccSPF-retrofitted sample sets (Roofs 2 through 5 along with LII and LIII laboratory sets), the pressure-deflection relationship was initially linear. At greater loads, larger deflections per unit load were observed leading to failure, indicating the non-linear behavior of the bending stiffness past the proportional limit. Also at greater loads, deflections continued to occur even during constant pressure.

Discussion

Increased moisture contents in wood did not produce statistically significant changes in panel failure pressures over the 150-day weathering period. No strength reduction was seen between roofs exposed to leakage compared to non-leaking roofs containing the same retrofit.

Furthermore, no correlation was found between moisture content and failure pressure of individual panels within leaking roofs under wide ranges of truss moisture contents during structural testing of 8% to over 60%, suggesting that the presence of water has no measureable effect on wind uplift capacity within a 150-day period. Wind uplift capacity is directly related to the depth of the ccSPF retrofit layer. Roof 4 which had the greater average foam depth (4.20 in. between trusses), also had the highest failure pressure (383 psf), as compared with Roof 5 (3.49 in. foam depth and 294 psf failure pressure).

As expected, moisture content in leaking ccSPF-retrofitted roofs increased more rapidly than in leaking un-retrofitted roof panels. In fact, the un-retrofitted roof did not exhibit any sustained moisture content above 22%. The experimental setup is not meant to simulate a typical roof since it included more than 100 leak gaps that were left unrepaired and exposed to rain for many weeks. The moisture contents in ccSPF-retrofitted roofs with leaks often exceeded thresholds for fungal decay and decay, with moisture contents above 70% observed in Roof 2 and 60% in Roof 4 truss members. Truss moisture contents above 20% were observed for over three months in both Roofs 2 and 4. The presence of the impermeable ccSPF layer on the underside of the sheathing inhibits the removal of the moisture from the wood, which could increase the risk of long-term degradation.

Sheathing panel specimens continued to deflect during loading plateaus. This suggests that some creep effects is occurring. The tests were conducted only statically and as such may not be representative of load-displacement behavior under more dynamic loading, although it is expected the static tests provide a conservative result.

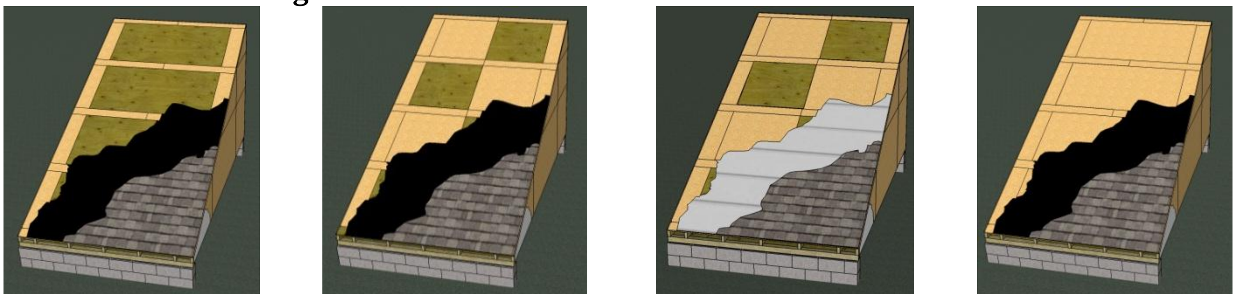
After eight weeks exposed to water spray and high moisture content environment, the mean tensile strength of the ccSPF to wood bond in the small specimens was reduced by as much as 50%, from 17 to 8 psi. However, the residual strength of the bond was still 6 to 10 times greater than wind uplift pressures of an extreme hurricane wind speed.

PHASE II RESEARCH: MECHANICS OF MOSITURE BUILD-UP

Because ccSPF is relatively water-impermeable, it is difficult to detect leaks in retrofitted wood roofs. It was shown in Phase I that if extended periods of water roof leaks will lead to elevated wood moisture content, and cause deterioration. As such, an important goal should be to identify better means of preventing leaks or methods to increase the drying rate and reduce moisture buildup in the wood. The objective of the Phase II study was to investigate how the mechanics of the moisture travel through the ccSPF-retrofitted roof system differs from a standard roof and to identify techniques to mitigate water buildup in the wood. Additionally, Phase II study compares the performance of plywood and OSB sheathing in cc-SPF retrofitted roofs subjected to water leaks and environmental exposure. Both large-scale and small-scale testing was utilized in Phase II.

Four monoslope attic roofs were constructed and oriented with south-facing slopes. Table 3 provides a summary of the test variables in each roof. Roofs were exposed to simulated and natural rainfall for over twelve months. Leakage and wetting patterns were reduced in three of the four roofs to simulate a less extreme leakage scenario. Moisture sensors were again installed to monitor the moisture contents over the course of the wetting period.

Table 3: Phase II Large-Scale Test Matrix



Roof 1	Roof 2	Roof 3	Roof 4
Plywood	Plywood/OSB	Plywood/OSB	OSB
Full Leakage	Reduced Leakage	Reduced Leakage	Reduced Leakage
	Vent System	Self-Adhered Membrane	

Phase II Results

At the time of writing, testing is currently in progress for both large and small-scale samples. Preliminary moisture content data from the continuous monitoring of the large-scale roof sheathing moisture contents indicate the vented retrofit reduces the drying time for ccSPF retrofitted roofs.

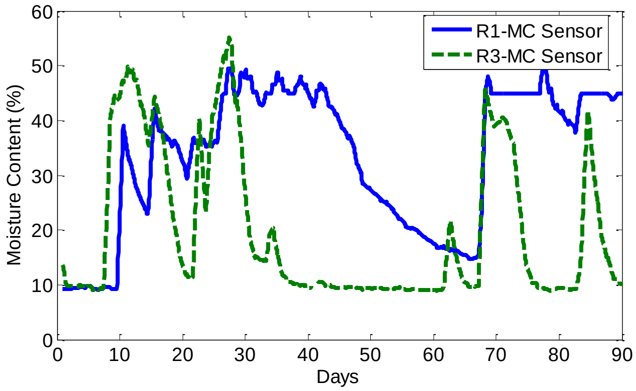


Figure 8: Moisture Content Time History for Select Roof 1 Sensors

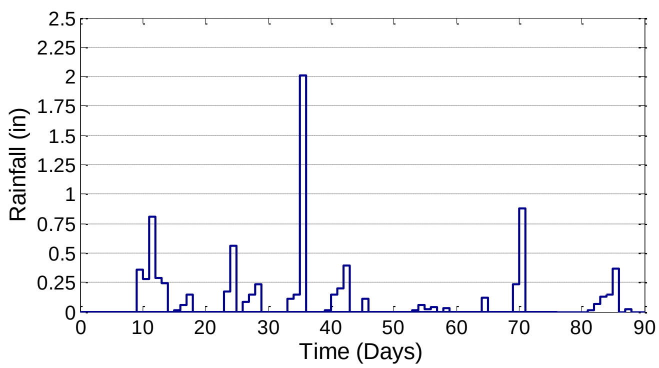


Figure 9: Rainfall Time History

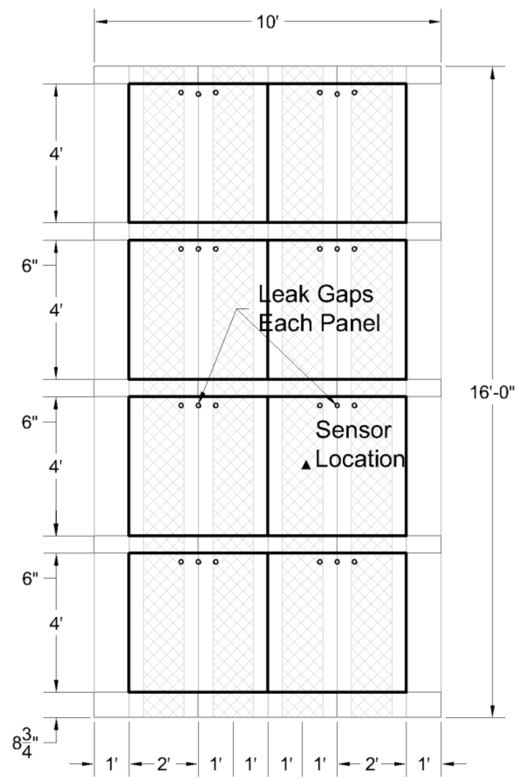


Figure 10: Location in Roofs 1 and 3 of Sensors Shown in Figure 9

For example, for the roof incorporating vents, moisture content was reduced from 40% to below 20% in 3 days, as compared to 12 days for the roof that did not have vents in its ccSPF retrofit. It was also observed that installing self-adhered waterproofing membrane, as roofing underlayment substantially reduced the amount of moisture intrusion into the roof system. Even with comparable number of leak gaps cut into the membrane, the moisture content in Roof 2 remained below 20% for the same time period.

Water Travel at Sheathing Joints and Framing

The small-scale testing in Phase II consisted of monitoring visual and physical changes in 6" x 6" samples, illustrated in Figure 11, exposed to a single water leak source. Water is applied at constant flow rate of ~1-3 mL/min to samples consisting both control roof decks and roofing and ccSPF-retrofitted ones. The study was designed to simulate several roof geometries that encourage water absorption, including presence of horizontal and vertical joints in the sheathing, wood framing , plywood versus OSB sheathing, roof slope and self-adhered waterproofing membrane underlayment.

Figure 11: 6"x6" samples representing typical roof conditions

A novel test setup was created, in order to accommodate tests on relatively large number of samples using very low water flow rates (Figure 12). A continuously-filled volume of water provided a constant head pressure to fourteen drip regulators. Each drip regulator was constructed with PVC pipe with a cross-section as shown in Figure 13, so as to provide a continuous drip at a rate of approximately 2 mL/min, arbitrarily chosen to simulate a possible leak rate into the roof system for a small leak during a typical rain event. Samples were mounted to basins with sloped sides constructed of sheet metal, serving to capture all water runoff. The captured water was directed through the tubing to collectors. The entire test setup was mounted on a frame oriented to a 6:12 or 4:12 slope.

Figure 12: Phase II Small-Scale Test Setup

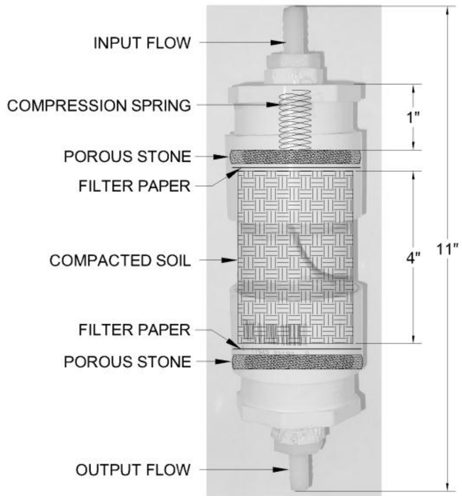


Figure 13: Cross-section of Drip Regulator

The samples consisted of 6” x 6” pieces of OSB or plywood roof decks as described above, with asphalt roofing shingles and felt underlayment placed on top. The roofing system was held in place but not permanently fastened to the deck, to simulate the weight, and proximity of materials in actual roof construction. A small funnel with its stem passing through the shingle and underlayment was used to ensure maximum volume of water is applied directly to the top surface of the wood roof sheathing. Temperature and relative humidity were monitored over the course of the testing. Results of the small-scale testing were not yet available at the time of writing.

CONCLUSIONS

When extensive and long-term roof leakage occurs, the framing members and sheathing panels in ccSPF-retrofitted wood roofs accumulate higher moisture contents than those in conventional wood roof construction. However, the wind uplift capacity ccSPF-retrofitted roof sheathing panels is not affected by high moisture contents in the wood. Although the uplift capacity of panels in leaking roofs was not significantly reduced, the elevated wood moisture content, (above MC of 20%) could accelerate wood decay, and over the long-term reduce wood strength and durability.

These results, while preliminary are considered conservative, since the underside of the test roofs were open to the environment and not conditioned. There is therefore minimal vapor drive to the interior with nearly the same ambient temperatures and relative humidity on both sides of the test assembly. Work continues to evaluate the effects of ccSPF on the mechanics of moisture travel using small-scale samples, around sheathing joints and framing members.

ccSPF is an effective insulator, secondary water barrier and structural retrofit but it should be used where reliable maintenance of the roofing system can be done to ensure any tears are promptly located and repaired to prevent long term water leakage. ccSPF-retrofitted roof do dry more slowly than un-retrofitted ones. However, the ability of ccSPF to prevent the uncontrolled leakage of water into a home is still seen as a solid benefit for installation. The substantial increase in wind uplift capacity it provides is also a benefit in hurricane-prone areas. The study has identified several techniques that can be used to minimize moisture buildup in the roof structure and to reduce the drying time should a leak occur.

The issues of moisture travel in wood and foam composites in building envelopes have broad implications extending beyond ccSPF-retrofit of roof sheathing. Structural adhesives and impermeable foams are used as composites with wood products in construction, including structurally insulated panels (SIPs). The potential exists in SIPs to retard water drainage where relatively impermeable material is bonded to a wood substrate. Trapped water will more rapidly degrade any water sensitive material, however, the techniques demonstrated in this research, i.e. incorporating air venting to increase drying potential, and installing waterproofing membranes that limit water absorption in the first place can mitigate problems associated with water leakage within the building envelope.

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