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

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ABSTRACT

A well-known source of damage to houses in hurricanes occurs when water bypasses failed roof coverings that allow water to enter the interior through joints in the wood roof decks. Closed-cell spray-applied polyurethane foam (ccSPF) sprayed to the underside of the roof functions as a secondary water barrier to mitigate this damage, in addition to its primary function as a thermal barrier. Recent studies at the University of Florida revealed that ccSPF also significantly increases the wind uplift resistance of a wood roof deck due to its strong bond to wood substrates. This presentation describes a research project that investigated the effects of incidental water leakage on the strength of the ccSPF-to-wood bond and on moisture retention characteristics in a wood roof.

The two-phased study consisted of the construction and long-term testing of full-scale roof attics exposed to outdoor environmental conditions in Gainesville, FL, and bench-type studies using small-scale roof deck samples. Each roof attic was retrofitted using ccSPF, self-adhered membrane underlayment and/or air gaps between the sheathing and ccSPF. Numerous ½ in. diameter holes (leak gaps) cut into the roofing created sources of water leaks, and we continuously monitored moisture content in the wood in real-time through a web-based application. The wind uplift capacity of roof panels (ultimate failure pressure), were determined at the end of each exposure period. Concurrently, small-scale testing was conducted to measure the tensile strength of the wood-to-ccSPF bond for samples exposed to up to 16 weeks of intermittent water sprays. The moisture distribution in 6 in. x 6 in. wood (OSB and plywood) roof deck samples was also determined, representing common construction patterns such as vertical or horizontal sheathing joints, and the configurations of full-scale retrofit systems.

While ccSPF remains highly effective as a structural retrofit despite significant wetting, elevated moisture content occurs within the wood substrate. Successful techniques were demonstrated to mitigate moisture retention, such as use of self-adhered waterproofing membrane or including an underside-deck air gap within the ccSPF retrofit layer that resulted in substantial reduction (90% and 80%, respectively) in moisture contents within the sheathing. The study has led to recommendations for the installation and maintenance of ccSPF-retrofitted residential roofs, and the use of similar wood-foam composite systems in wood-framed buildings.

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 and 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 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 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. .

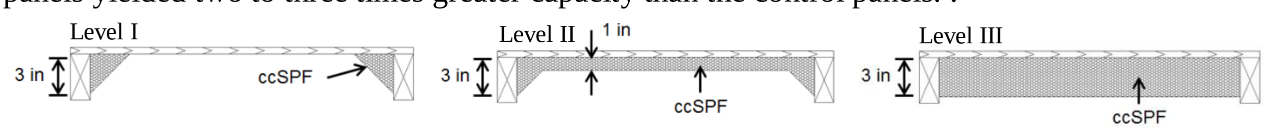


Figure 1. Retrofits Types

PHASE I SUMMARY

Full details of the Phase I study are available elsewhere (McBride, 2011) and will not be discussed at length here. The objective of the study was to identify if moisture buildup occurred and if so, quantify the effect it had on the uplift capacity of the roof sheathing. Both large-scale and small-scale testing was utilized to evaluate the effect of moisture on the ccSPF-to-wood bond. In the large-scale tests, five full-scale attic roofs were constructed out of wood trusses and OSB sheathing, and were retrofitted as shown in Table 1.

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

A hundred and four ½" leak gaps were cut into three of the five roofs, all of which were then exposed to both natural and simulated rainfall for 150 days. Moisture contents of the truss top chords, temperatures and humidity were continuously monitored for the duration of the exposure period. After the completion of the exposure period, eight 4'x8' panels were harvested out of each roof and tested to failure using a Pressure Loading Actuator (PLA) and steel chamber. Significant moisture buildup did indeed occur in the retrofitted roofs with leaks (shown in Figure 2) and not in the non-retrofitted roof, which also had leaks, but the moisture had no observable effect on the uplift capacities.

(a) Moisture Buildup in Sheathing (b) Moisture Buildup in Framing Members

Figure 2. Observed Moisture Buildup in Retrofitted Roofs with Leaks

Increased moisture contents in wood did not produce statistically significant changes in panel failure pressures over the 150-day weathering period. However, the moisture content in leaking ccSPF-retrofitted roof panels increased at a faster rate than in leaking un-retrofitted roof panels. In fact, the un-retrofitted roof did not see any sustained water content values above 22%. The moisture contents in ccSPF-retrofitted roofs with leaks often exceeded thresholds for fungal decay and strength loss, 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. Although wood degradation/rot was not measured during this experiment, the results of this Phase I study demonstrate that the presence of the impermeable ccSPF layer on the underside of the sheathing inhibits the removal of the moisture from the wood. This can increase the risk of degradation from long-term exposure to the elevated moisture contents.

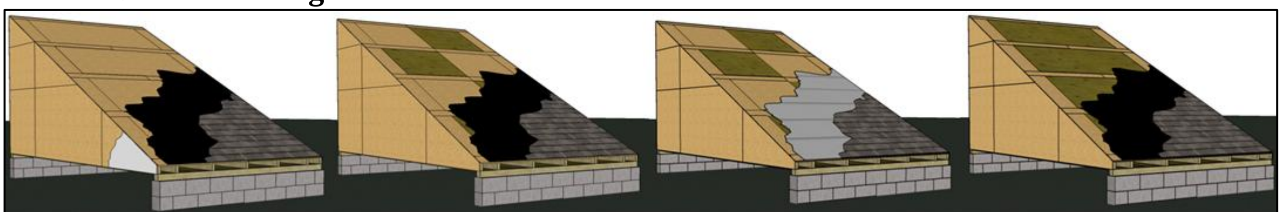
PHASE II RESEARCH: MECHANICS OF MOSITURE BUILD-UP

Due to the impermeability of ccSPF, it is difficult to detect leaks in retrofitted wood roofs, and it was shown in Phase I that if roof leaks are allowed to occur for long periods, the wood moisture content can remain at levels that lead to decay in wood. Hence 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 differed from a standard roof and identify techniques to mitigate water buildup in the wood. Additionally, since OSB was used exclusively in Phase I, evaluation is made on whether the use of plywood has further implications either in regards to the uplift capacity or moisture travel mechanisms. Both large-scale and small-scale testing was utilized in Phase II and the test methods and results are discussed.

Large-Scale Test Methods

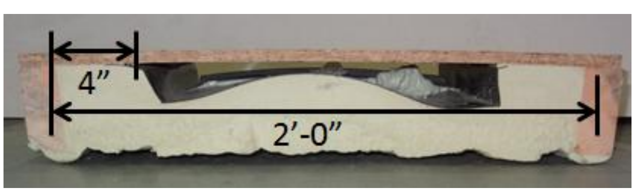
Four 10'x16' monoslope attic roofs were constructed at a 6:12 slope facing south using wood trusses and wood roof sheathing. Table 2 provides a summary of the test matrix.

Table 2: Phase II Large-Scale Test Matrix

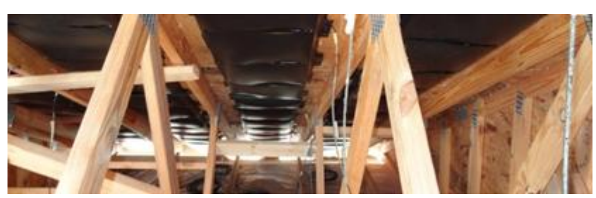


Roof 4	Roof 3	Roof 2	Roof 1
OSB	Plywood/OSB	Plywood/OSB	Plywood
Reduced Leakage	Reduced Leakage	Reduced Leakage	Full Leakage
	Air Gap	Self-Adhered Membrane	

Two techniques were evaluated for their effectiveness in minimizing moisture buildup and drying times in ccSPF-retrofitted roofs. Roof 2 used a self-adhered waterproofing membrane at the top surface of the wood sheathing in lieu of the felt used in standard roof systems. It was expected that the self-adhered membrane would limit the amount of moisture entering the roof system through the leaks, but there were also concerns that its use would prevent any moisture from leaving the roof sheathing due to the presence of vapor barriers on both sides of the sheathing. Roof 3 utilized a vented approach, whereby an air gap was provided at the underside of the sheathing through the use of a plastic vent system, installed prior to the installation of the ccSPF. The dimensions and installed view of the air gap is shown in Figure 3.



(a) Cross-section View



(b) Air Gap Prior to ccSPF Installation

Figure 3: Details of the Air Gap in Roof 3

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 sheathing. Proprietary software developed by Structures Monitoring Technology collected and converted signals wirelessly from the sensors and stored the data in an internet-accessible database. Placement of the sensors is shown in Figure 4.

Leaks were also provided through the waterproofing membranes to the sheathing, the locations of which are provided in Figure 4. The number and spacing of leaks in Roof 1 reflected that of Phase I, except that leaks were not installed at the very edge on the eave flashing as they were in Phase I. The number and spacing of leaks in Roof 2, 3 and 4 were reduced to represent more isolated leak conditions for each panel as shown.

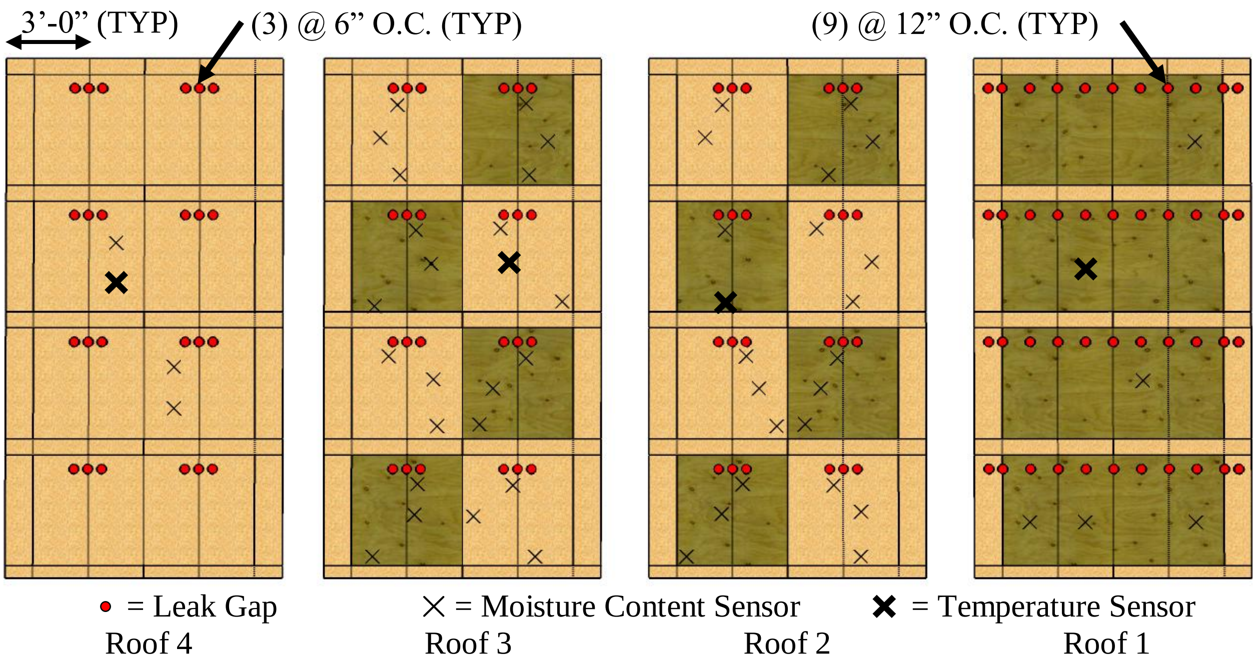


Figure 4: Location of Leaks and Moisture Sensors in Phase II Roofs

Bench-Top Test Methods

Bench-top testing was performed to examine in detail the effect of ccSPF on moisture buildup for several common roof scenarios, summarized in the test matrix in Table 3.

Table 3: Summary Small-Scale Test Matrix

Sample ID	ccSPF	Plywood	OSB	Horizontal Joint	Vertical Joint	Self-Adhering Membrane	Quantity
A	X	X					14
A-c		X					14
B	X		X				14
B-c			X				14
C	X	X				X	14
C-c		X				X	14
D	X		X			X	14

D-c			X			X	14
E	X		X		X		14
E-c			X		X		14
F	X		X	X			14
F-c			X	X			14

Samples consisted of 6"x6" sheathing specimens retrofitted with a 3" ccSPF layer as shown in Figure 5. Felt underlayment and shingle samples were fastened to the top of the samples to represent true roof conditions and the edges were sealed with a waterproofing sealant to restrict moisture absorption to the top surface only. Samples were oriented on a 6:12 slope and exposed to a continuous drip of water at a rate of 2mL/min for 24 hours in accordance with a modified ASTM D1037 procedure. Mass, dimensions and moisture contents of the samples were taken before and after the exposure period. Moisture contents were monitored for 96 hours after the exposure period ended using a Delmhorst BD-2100 Handheld Moisture Meter with 5/16" contact pins. Each sample was subdivided into nine subsections, 2"x2" as shown in Figure 6, when taking moisture contents in order to better quantify the distribution of moisture across the samples. Testing was performed in a conditioned environment with a temperature of 76°F and 45% RH.

Figure 5: Typical sample prior to testing

Figure 6: Nine subsections to each sample

RESULTS

Harvesting of the sheathing panels from the full-scale roofs was not due to be completed before the writing of this paper and thus only the results of the moisture content monitoring can be shown for the full-scale specimens. These results should be considered preliminary until the full condition of the roofs are observed at the conclusion of the exposure period.

Sheathing Moisture Contents in Full-Scale Specimens

Figure 7 presents a summary of the maximum observed moisture contents in the roof sheathing at each sensor location. The majority of the moisture was observed in the plywood rather than the OSB.

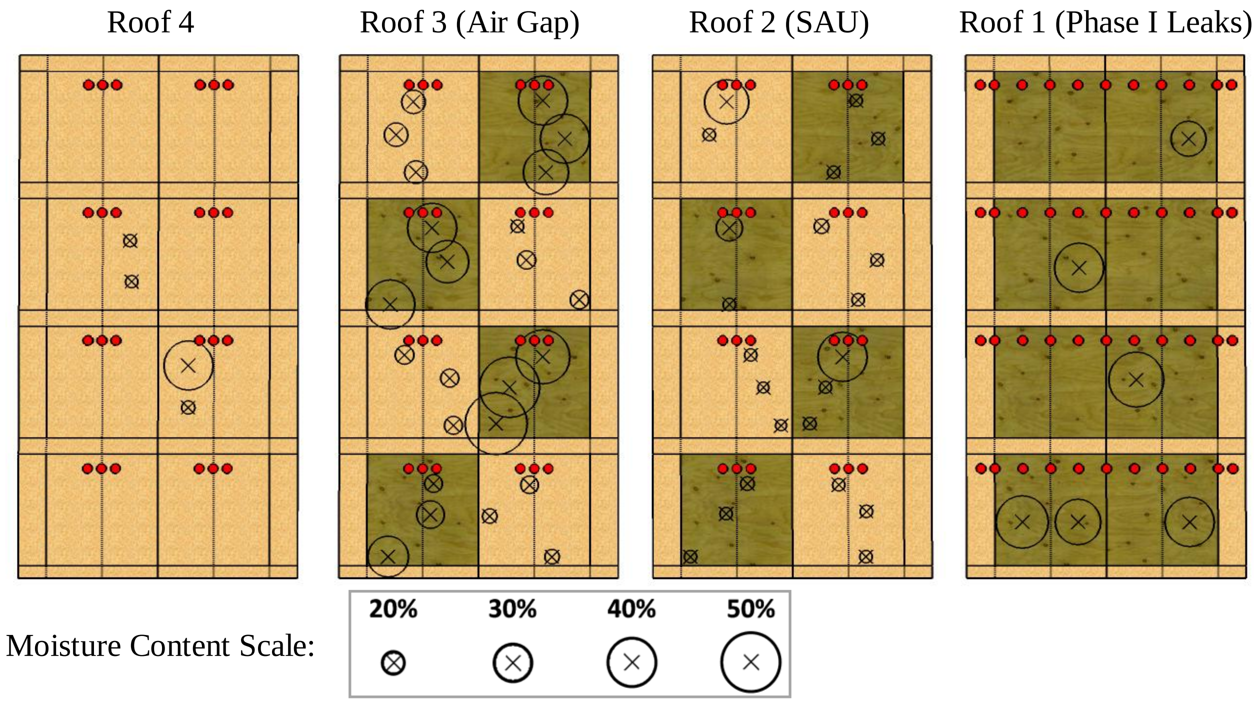


Figure 7: Maximum observed moisture contents in full-scale roofs

Table 4 presents a comparison of the number of days that each moisture sensor in a given roof recorded moisture content greater than 20%. This result illustrates more clearly the duration of the exposures to significant moisture contents rather than the maximum value recorded from possibly a single peak.

Table 4: Summary of Moisture Content Observations in Full-Scale Specimens

Roof ID / Description	Total Number of Sensors	Total Sensor-Days	Sensor-Days w/ MC ≥ 20%	% Sensor-Days of Significant Moisture
Roof 1 (Plywood, more leaks)	6	2388	417	17.5%
Roof 2 (Self-adhered memb.)	22	8757	26	0.30%
Roof 3 (Vented)	24	9553	367	3.80%
Roof 4 (OSB)	4	1592	170	10.7%

Sheathing Temperature in Full-Scale Specimens

Sheathing temperatures were continuously monitored over the duration of the exposure period at the mid-slope of the full-scale specimens. Locations of the temperature sensors were previously shown in Figure 4. Results are presented in Table 5 as the difference between maximum daily temperatures observed in Roofs 2 through 4 and those observed in Roof 1. Thus a negative value implies that the observed maximum daily temperature in the specified roof was lower than that observed in Roof 1. Distributions of the differences in maximum daily temperatures are illustrated in Figure 8.

Table 5: Observed Maximum Daily Temperatures Relative to Roof 1

Roof ID	Mean	Median	Std. Dev.
Roof 2	0.50°C (0.89°F)	0.46°C (0.83°F)	2.14°C (3.85°F)
Roof 3	-2.24°C (4.02°F)	-2.26°C (-4.07°F)	1.71°C (3.08°F)
Roof 4	0.52°C (0.94°F)	0.29°C (0.52°F)	2.20°C (3.96°F)

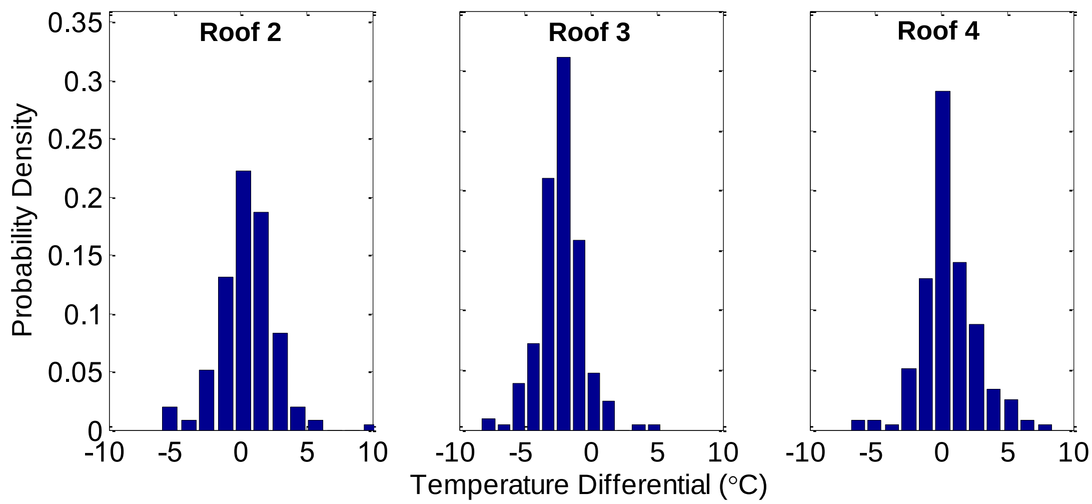


Figure 8: Distributions of Temperature Differentials as Compared to Roof 1

Bench-Top Test Results

Results from the bench-top testing consist of moisture contents, total absorption and drying times for the samples forming the test matrix shown in Table 6. As the drying rates were fitted exponentially, drying times are represented using the half-life measure.

Table 6: Summary of Bench-Top Testing Results (Samples without Joints)

Sample Description	Total Absorption (mL) [±Std Dev.]	Max. Moisture Content (%) [±Std. Dev]	Half-Life (hrs)
A (Ply w/ ccSPF)	28.0 [±15.8]	30.2 [±12.6]	32
Ac (Ply w/o ccSPF)	32.8 [±15.96]	35.2 [±7.0]	45
B (OSB w/ ccSPF)	9.93 [±2.8]	20.43 [±4.2]	62
Bc (OSB w/o ccSPF)	9.00 [±2.7]	19.25 [±4.1]	40
C (Ply, SAU w/ ccSPF)	14.79 [±4.6]	34.67 [±7.0]	110
Cc (Ply, SAU w/o ccSPF)	2.57 [±1.6]	16.58 [±3.7]	48
D (OSB, SAU w/ ccSPF)	4.21 [±1.3]	19.43 [±4.0]	70
Dc (OSB, SAU w/o ccSPF)	6.88 [±1.81]	15.33 [±4.2]	55

The effect of ccSPF on moisture accumulation at joints was also examined using samples with both horizontal and vertical joints, shown in Figures 9 and 10. In addition to the sheathing moisture contents monitored in all samples, moisture contents were also measured at ½” depths in eight locations along the exposed surface of the framing members present in samples with vertical joints. A summary of the results for samples with joints is given in Table 7.

Figure 9: Sample with Horizontal Joint (HJ)

Figure 10: Sample withVertical Joint (VJ)

Table 7: Summary of Bench-Top Testing Results (Samples with Joints)

Sample Description	Total Absorption (mL) [+Std Dev.]	Max. Sheathing M.C. (%) [+Std. Dev]	Avg. Framing M.C. (%) [+Std. Dev]
E (OSB, VJ, w/ ccSPF)	14.8 [+3.9]	30.2 [+12.6]	22.4 [+2.8]
Ec (OSB, VJ, w/o ccSPF)	47.6 [+20.7]	35.2 [+7.0]	38.5 [+1.9]
F (OSB, HJ, w/ ccSPF)	13.3 [+2.1]	20.43 [+4.2]	N/A
Fc (OSB, HJ, w/o ccSPF)	17.4 [+3.9]	19.25 [+4.1]	N/A

CONCLUSIONS

In Phase 1 of this study it was shown that when ccSPF-retrofitted roof sheathing panels were subjected to extensive, long-term roof leakage, the moisture contents in the framing members and sheathing panels are higher than those in conventional wood roof construction [6]. The study also confirmed that the wind uplift capacity of the retrofitted panels was not affected by the high moisture content, although it was observed that the durability of the wood itself could be adversely affected. As a result, Phase 2 evaluated techniques to mitigate water accumulation in the roof structure by installing a) under roof deck air gaps or b) self-adhered waterproofing membrane. In the self-adhering membrane roof specimen, moisture contents remained below 20% for all but a few instances, while in the roof with underside air gap the elevated moisture contents that did occur were quickly reduced in half the time it took for moisture level to fall in the roof without air gaps.

Bench-top studies demonstrated that the ccSPF did not have a significant effect on water absorption or drying over a 24-hr exposure period for standard roof configurations (i.e., wood sheathing, felt underlayment, asphalt shingles). However when used in combination with a self-adhered waterproofing underlayment, the samples with ccSPF had higher moisture contents and dried 130% and 30% slower, respectively for plywood and OSB sheathing. The effect of the ccSPF on moisture accumulation at sheathing joints was mixed, with the ccSPF actually being beneficial at reducing moisture contents in the framing members at vertical joints. The ccSPF layer functioned as secondary water barrier, preventing further downward travel of water into the joint and onto framing member. The moisture content in the sheathing near a horizontal joint increased slightly (by 4%) as compared to the sheathing samples with no joints.

The issues related to moisture travel and mitigation of moisture build-up in the wood roofs examined here has implications beyond that of ccSPF-retrofit of roof sheathing. New technological developments have produced structural adhesives and impermeable foams used in composite construction with structural wood framing and sheathing, and they are likely to experience (or exhibit) similar performance in presence of water leaks. Structural insulated panels (SIPs) are a case in point, and the authors have found no information in the literature addressing potential effects of water leakage on these systems. Any system that retards water from draining away from the wood can promote decay or insect infestation. The mitigation techniques described in this study can be applicable in minimizing potential damage to critical components of the building envelope.

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