WIND UPLIFT PERFORMANCE OF CCSPF-RETROFITTED ROOF SHEATHING SUBJECTED TO WATER LEAKAGE

By

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To my parents

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Abstract of Thesis Presented to the Graduate School
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WIND UPLIFT PERFORMANCE OF CCSPF-RETROFITTED ROOF SHEATHING SUBJECTED TO WATER LEAKAGE

By

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Chair: David O. Prevatt
Major: Civil Engineering

During hurricanes, light-frame wood roofs are subjected to high winds and heavy rainfall. When roofs fail, failure of surrounding structural elements may consequently occur. The entire building is exposed to extensive water intrusion, damaging the interior and destroying building contents at great cost to homeowners and insurers. Recent research at the University of Florida demonstrated that closed-cell spray-applied polyurethane foam (ccSPF) insulation applied to the underside of a roof deck can substantially increase its wind uplift resistance. Moreover, ccSPF acts as a secondary water barrier, minimizing the volume of water leaking through the roof structure. However, no studies were found that evaluated the effect of water leakage on the wood-to-ccSPF bond or the long-term behavior of the wood itself. This is the motivation for the research presented in this thesis.

This research study tests the hypothesis that the wind uplift capacity of ccSPF-retrofitted wood roofs is unaffected by seasonal leakage through roof covering. It is believed that although the ccSPF layer forms a Class 3 vapor retarder along the underside of the roof deck, a code-minimum conventional roof covering (asphalt shingles on 15 lb. felt underlayment) allows sufficient evaporation to occur to maintain

sufficiently low moisture content in wood structural members. ccSPF installers claim that water leaks in a roof covering will eventually flow to the exterior along the interface between the wood substrate and ccSPF. A secondary hypothesis that moisture buildup does not occur in leaking ccSPF-retrofitted roofs is tested.

To test the hypotheses, a two-part study was undertaken. In Part I, five attic structures were constructed. Four of the structures' roofs were retrofitted with ccSPF using two configurations. The fifth, a non-retrofitted roof, was used as a control. Numerous leak gaps (½ in. diameter holes), were cut through the shingles and underlayment of three of the roofs. All of the structures were exposed to natural and simulated rainfall for 150 days. The presence of moisture in wood was continuously monitored in truss members and on the underside of roof sheathing panels. At the conclusion of the exposure period, sheathing panels were harvested (removed) and individually tested to determine their wind uplift capacities.

In Part II, tensile tests were conducted on small samples consisting of approximately 3 in. cubic ccSPF blocks attached to 3 in. by 5 in. plywood and oriented strand board (OSB) samples subjected to varying water exposure (2 min. spray every 12 hr.) for periods of 1 to 16 weeks. Tests evaluated the effect of the water spray on tensile strength of the ccSPF-to-wood bond for three substrates: plywood, the smooth side of OSB, and the textured side of OSB. Tensile tests on the 131 samples were conducted in accordance with a modified ASTM D 1623 Method C test protocol.

Part I results revealed that water leakage from natural and simulated rainfall did not produce a significant reduction in the wind uplift capacity of ccSPF-retrofitted roof panels; however, considerable moisture accumulation was observed in the wood

framing members (up to 70%) of roofs with leak gaps. The moisture content of wood framing in the wetted, non-retrofitted control roof remained well below 20% for the duration of exposure period. The wind uplift capacity of ccSPF-retrofitted panels (wetted and not wetted) was over five times that of the control roof.

The results from Part 2 showed that the tensile capacity of control (dry) samples was greater than that of the wetted samples for all sheathing substrates tested (although only one substrate was statistically significant). An average loss in strength of 46% in smooth-face OSB samples (statistically significant), 33% in textured-face OSB samples, and 23% in plywood samples was observed. The mean tensile failure strength of wetted samples remained generally unchanged over time.

This research confirmed the hypothesis that in there is no loss in wind uplift capacity of ccSPF-retrofitted wood roof sheathing in a roof exposed to extensive water leaks during a 150-day period. The research also suggests that moisture build-up can occur in ccSPF-retrofitted roofs; claims that adequate drainage paths are provided along the bond line between wood and ccSPF were not supported. It should be noted, however, that the leakage (104 half-inch diameter holes per roof) and wetting conditions (every two days during Gainesville's dry fall and winter seasons) were highly conservative and unrepresentative of normal roof conditions. Further research using more realistic leakage schemes over a longer duration is necessary to establish the performance of ccSPF-retrofitted roof systems and develop guidelines for proper use.

CHAPTER 1
INTRODUCTION

Background

When roof sheathing is lost due to hurricane-induced wind uplift pressure, residential homes are vulnerable to substantial structural and water damage. In 1992, Hurricane Andrew demonstrated that connection requirements of roof sheathing to roof framing members were inadequate to resist hurricane wind loads. Over 100,000 homes were damaged, with 24% of homes surveyed losing at least one roof sheathing panel (HUD 1993). Following Hurricane Andrew, code changes strengthened the sheathing connection to roof framing members. Nonetheless, as of the 2000 Census, approximately 80% of the United States housing stock was built before these changes took effect (US Census Bureau 2003), leaving many existing homes still susceptible to roof damage in hurricanes.

Closed-cell spray-applied polyurethane foam (ccSPF), originally developed for buildings as an insulating material, develops a tenacious bond to many construction materials, including wood. It can be applied to the underside of roof decks and inside of wall cavities to act as a thermal, air, and water barrier separating the exterior environment from the temperature-controlled interior space.

The adhesion between ccSPF and building materials is useful for structural enhancement. Studies undertaken at the University of Florida (Prevatt 2007a; Prevatt 2007b) found that ccSPF provides structural benefits when applied as a retrofit to residential roof sheathing. The increased capacity was achieved regardless of the mechanical (nailed) fastening schedule or quality of fastener installation.

ccSPF also forms a durable secondary water barrier that minimizes water leakage through the roof structure, even when the primary roof cover (most often asphalt shingles and felt underlayment) is breached in an extreme wind event. Recognizing the structural and water-resistive benefits of the ccSPF retrofit, the Federal Emergency Management Agency (FEMA 2010) and the Institute for Home & Business Safety (IBHS 2011) have recommended using ccSPF in roofs to mitigate potential water and structural damage in homes. The International Residential Code (IRC) (ICC 2009) allows the foam to be sprayed to the underside of roof sheathing to achieve an unvented attic condition.

Despite the benefits of ccSPF retrofits to roof sheathing, certain performance issues have not been fully addressed, including the structural performance when exposed to water. Datin et al. (2010) 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. As a continuation of Datin et al. (2010), this thesis evaluates the structural performance of ccSPF-retrofitted light-frame wood roofs subjected to water leakage and environmental exposure. Results from the study will be later used to develop an acceptance criteria and guidelines for the installation and testing of ccSPF as a structural retrofit in light-frame wood structural roof systems.

Objectives

The goal of this research is to evaluate the structural performance of ccSPF-retrofitted wood roofs subjected to seasonal water leakage and environmental exposure. Experimental research evaluates the structural performance of retrofitted roof

systems exposed to moisture in full-scale wind uplift tests and small specimen tensile testing.

The central hypothesis is that seasonal water leakage does not decrease the wind uplift capacity of a ccSPF-retrofitted wood roof sheathing panel. A secondary hypothesis is that water does not build up in leaking ccSPF-retrofitted wood roofs.

Overarching objectives of this thesis are listed as follows:

1. to summarize components in and impacts of retrofitting a residential roof with ccSPF
2. to evaluate the effect of water leakage and environmental exposure on the wind uplift capacity of ccSPF-retrofitted wood roofs
3. to identify moisture properties of wood roof components within leaking ccSPF-retrofitted roofs

This thesis is organized in six chapters. Chapter 1 provides the thesis introduction and main objectives. A review of literature is presented in Chapter 2 detailing basic components, material properties of ccSPF-retrofitted wood roofs, performance objectives, and a summary of related research. Statistical methods used in the thesis are also briefly discussed in the review. Chapter 3 provides the materials and methods for the two experiments conducted: Part I) long-term exposure and wind uplift testing of ccSPF-retrofitted roof sheathing panels and Part II) tensile testing of small specimen ccSPF-retrofitted sheathing exposed to regular water spray. Results, analysis, and discussion are presented in Chapters 4 (Part I) and 5 (Part I). Conclusions, limitations, and recommendations for future work are presented in Chapter 6.

CHAPTER 2
LITERATURE REVIEW

This literature review presents relevant issues related to the installation of ccSPF as a structural retrofit in residential wood roofs. It provides context to understand the behavior of a composite roof system subjected to water penetration. A characterization of typical light-frame wood residential construction is provided with an emphasis on roof components and their vulnerability to wind and water damage during recent hurricanes. Previous studies investigating the performance of structural adhesive retrofits in wood roofs are summarized. Pertinent properties of polyurethane foam and wood roof materials are linked to expected in-service behavior of a composite roof system exposed to incidental leakage. A discussion of existing/proposed panelized residential roof systems illustrates potential avenues of residential roof development when all building enclosure loads are recognized. Finally, the literature review describes basic statistical methods used in this thesis.

Residential Light-Frame Wood Structures

Although no governing residential building code exists in the United States, the International Residential Code (ICC 2009) serves as the model for residential construction in most U.S. jurisdictions. It is estimated that over 90% of existing U.S. residences are of light-frame wood construction (van de Lindt and Dao 2009). The most common light-frame wood structural system is called platform framing, where walls for each floor are built upon the previous floor that is used as a “platform.” Figure 2-1 displays the structural components within platform framing.

Applicable statistical characteristics of new U.S. housing in 2009 from personal communication with Hudson (2010) are provided in Table 2-1. Asphalt shingles, gable-

end roofs with trusses, and wood framing are the most commonly used techniques in the U.S. This roof system will be referenced throughout this thesis as a “typical” residential structural system. This section of the literature focuses on the ways that the roof system that functions to transfer structural loads to walls while separating the exterior from the interior environment as part of the building enclosure.

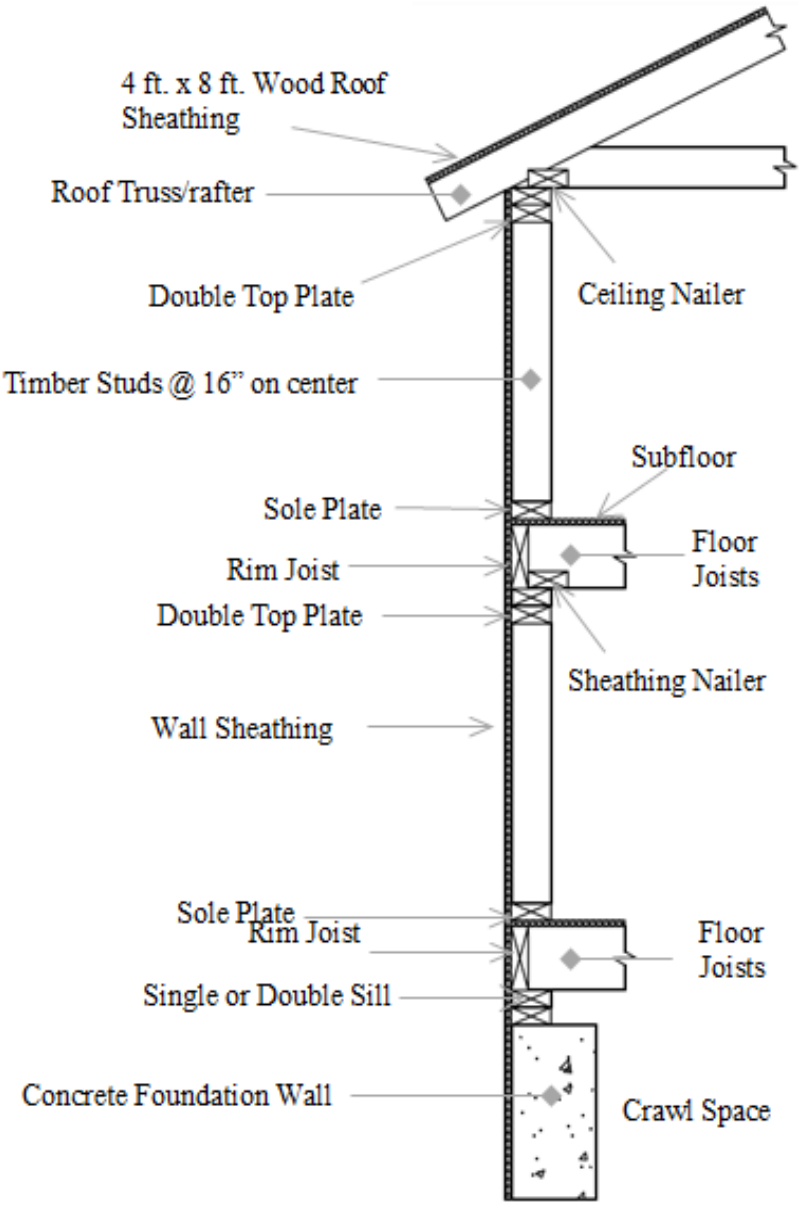


Figure 2-1. Structural components in platform framing after Ching (1991)

Table 2-1. Selected 2009 Characteristics of new housing

Roofing Type	Roof Framing	Roof Type	Wall Type	Attic Ventilation
83% Asphalt Shingles	55% Trusses	59% Gable	94% Wood	80% Vented
7% Clay/Concrete Tiles	42% Rafters	38% Hip	5% Concrete/Masonry	20% Unvented
7% Metal Panels	3% Other	3% Flat or Other	1% Steel	-
3% Other	-	-	-	-

Hudson, E. (2010). "Personal Communication about 2009 U.S. Housing Characteristics between K. McBride and E. Hudson." K. McBride, ed., Upper Marlboro, MD.

Roofing Materials

The primary purpose of roofing materials, most often asphalt shingles and felt underlayment in typical residential construction, is to protect the building interior and wood structural components from water intrusion. Shingles are most frequently composed of asphalt, granules, and other filling materials that are attached to a base felt or fiber mat. Granules protect the other shingle components from ultraviolet light and impact while improving fire resistance. Underlayment, which can be either 15 pound or 30 pound per “square” (100 square feet), protects the roof surface from water during construction and sheds water when moisture breaches the shingle layer (NRCA 2011).

Structural Materials

Roofing is fastened to 4 ft. by 8 ft. plywood or oriented strand board (OSB) roof sheathing panels (Spelter et al. 2006). Sheathing functions to transfer both vertical and horizontal loads through nailed connections to roof framing (trusses or rafters) spaced 24 in. on center. Roof framing transfers these loads to the walls via metal straps. In older construction, toenail connections were used to secure roof framing to wall plates. Rigid foam insulation (e.g., ccSPF) may be integrated with the roof structure to provide resistance to thermal, water, and even structural loads.

Wood perimeter walls are constructed using nominal 2 in. by 4 in. vertical studs spaced 8 to 24 in. (usually 16 in.) apart with a double horizontal wall plate that supports

the roof structure (ICC 2009). Walls are typically sheathed with plywood or oriented strand board and a siding material (Skaggs and Readling 2005). In some residential construction, walls may consist either of concrete block masonry or wood sheathing on cold-formed steel studs.

Attic Ventilation

A majority (80%) of newly built United States attics are vented (Hudson 2010), where unconditioned outside air is circulated into the attic space through vents located at roof ridges, eaves, or within gable ends. In vented attics, insulation is placed above the ceiling of the livable space to separate the conditioned and unconditioned space.

Unvented attics, conversely, do not allow outside air into the attic space. Unvented attics may contain roof insulation applied to sheathing with an interior finish, sheathing-applied insulation with no interior finish, or contain insulation only at the ceiling of the livable space. For the purpose of this thesis, “unvented” attics refer strictly to those with insulation built into the roof space.

Building Enclosure Loads

The roof is an element of the building enclosure. The most basic definition of a building enclosure (also referred to as a building envelope) is any part of a building that separates the exterior environment from the interior environment. It is a three-dimensional, multiple-layer element that extends from the outside-facing surface to the inside-facing surface (Straube and Burnett 2005). Walls (above- and below-grade) and base floor systems are other elements of the building enclosure.

In general, loadings on the building enclosure can be categorized by type and source. The types of loading are gravity-, ground-, heat-, moisture-, or air-related, while the sources of loading are the exterior environment, the interior environment, or the

enclosure itself. Within each of the three source categories, Straube and Burnett (2005) classify several specific sub-categories of loading source including climatic effects, natural phenomena, human effects, and the element itself to classify various loadings on the building enclosure. When considering the implementation of a building enclosure system (in this thesis the roof) all sources of loading must be acknowledged to best predict in-service behavior and lifespan of the enclosure.

Hurricane Performance of Roof Sheathing in Light-Frame Wood Structures

Damage to light-frame wood structures (LFWS) is the largest source of monetary loss from hurricanes (Lee and Rosowsky 2005; Shanmugam et al. 2009). The National Science Board (NSB 2007) estimates that hurricane damage loss, converted in this thesis to 2011 dollars for equal comparison (U.S Department of Labor 2011), was $1.5 billion annually from 1949 to 1989, $11.3 billion annually from 1990 to 1995, and $40.0 billion annually from 2001 and 2006. Individually (dollar totals again converted to 2011 dollars by the thesis author), Hurricane Andrew in 1992 cost $42.5 billion, Hurricane Charley in 2004 cost $17.9 billion, and Katrina cost $93.3 billion (Blake et al. 2007).

During hurricanes, strong winds approach residential structures, encountering the leading edge of the roof line. The edge causes the wind to detach from the roof surface, resulting in what is known as a separation bubble with differential pressure between the exterior of the roof and the interior space. This causes “uplift” forces that act perpendicular away from the roof surface. If these pressures exceed the strength of the sheathing to truss connection, sheathing can be lifted off of the roof structure.

Post-hurricane investigations report widespread structural damage to wood structures due to loss of roof sheathing and load transfer failure at mechanical connections (FEMA 2005; HUD 1993; van de Lindt et al. 2007). With over 1/3 of the

U.S. population living within 100 miles of hurricane-prone coastline, mainly in single-family, wood-frame residential structures (Datin 2010), there is a clear need to ensure that the coastal housing stock can adequately resist hurricane loads. Perhaps the best recent illustration of this need was Hurricane Andrew.

Impact of Hurricane Andrew

In 1992, damage from Hurricane Andrew demonstrated the inadequacy of roof sheathing fastening requirements when it struck the suburbs of Miami with Category 4 hurricane wind speeds. Over $20 billion in damage was incurred in the state of Florida alone, with over 25,000 homes destroyed and more than 100,000 homes damaged. Sheathing attachment failure was common; 24% of homes surveyed by the U.S. Department of Housing and Urban Development (HUD) lost at least one sheathing panel during the storm (HUD 1993).

When sheathing is removed from the roof structure, water intrusion and interior damage increase dramatically and other structural members are more vulnerable to failure. Sparks et al. (1994) associate sheathing panel, window, and door loss with the rise from 12% damage as a percentage of insured value at 155 miles per hour to 75% damage at 180 miles per hour (the upper limit of wind speeds in Hurricane Andrew). Figure 2-2 shows structural and interior damage as a result of roof sheathing loss.

Prior to 1994, the minimum fastening requirement for sheathing to roof framing in South Florida was 2 in. 6d common nails fastened at 6 in. edge and 12 in. field spacing (SFBC 1994). Outside of High Wind Zones in Florida, this fastening schedule was allowed until the inception of the Florida Building Code (FBC 2001). The wind uplift capacity of this nailing schedule ranges from 33 psf to 65 psf, which has been demonstrated as inadequate to resist hurricane loads (Datin et al. 2010; Hill et al. 2009).

A

B

Figure 2-2. Home damage due to sheathing loss. A) Exterior and B) interior

After Hurricane Andrew, substantial changes to code specifications for residential building constructions were made to improve hurricane resistances of these structures. Wood roof sheathing systems built after 1994 in High Wind Zones in Florida were required to use 8d nails at 6 in. spacing and 4 in. spacing at gable ends. As of the 2000 census, however, more than 80% of single-family residential buildings were still built before 1994 (US Census Bureau 2003), leaving a high number of homes in hurricane-prone areas susceptible to sheathing loss.

Wind Uplift Testing

No industry-accepted test currently exists for evaluating the wind uplift capacity of roof sheathing panels. Nonetheless, previous researchers have conducted uplift pressure studies. Hill (2009) conducted a thorough review of sheathing testing from 1993 to 2004, finding the following methods for loading roof sheathing:

- Cunningham (1993) - monotonic loading at 30-40 psf per minute
- Mizzell (1994) - step loading of 1 psf increase every 1.5 seconds
- Murphy et al. (1996) - step loading of 1 psf every 1.5 seconds
- Kallem (1997)- rapid monotonic loading (less than 16 seconds to failure)
- Jones (1998) - gradual monotonic loading (no stated loading rate)
- Sutt et al. (2000) – rapid monotonic loading (10-45 seconds to failure)
- NAHB (2003)– monotonic loading of 20 psf per minute
- IHRC (2004) – monotonic loading (no stated rate)

In an effort to use a standard method for quasi-static pressure testing of sheathing, researchers at the University of Florida (Datin et al. 2010) modified ASTM E 330 (ASTM 2002) to develop the University of Florida Wood Roof Sheathing Uplift Test (UF-WRSUT). ASTM E 330 has been used as an uplift test method for several building components (ASTM 2002). The UF-WRSUT method, described in Chapter 3, was adopted for structural testing of roof sheathing specimens in this thesis.

Hurricane Retrofits to Roof Sheathing

Recognizing vulnerability of the U.S. coastal housing stock built before 1994, the Federal Emergency Management Agency (FEMA 2010) and the Institute for Business & Home Safety (IBHS 2011) recommend the use of wind- and water-resistant retrofits to improve the hurricane performance of residential roofs. FEMA (2010) outlines three retrofit packages, summarized in Table 2-2. Note that the basic package must be completed before the intermediate package and the intermediate must be completed before the advanced package.

Table 2-2. FEMA hurricane retrofit packages

Basic	Intermediate	Advanced
Roof Sheathing	Gable Ends	Continuous Load Path
Soffits	Openings	Openings
Vents	Foundation Anchorage	-
Overhangs	-	-

FEMA. (2010). "Wind Retrofit Guide for Residential Buildings." *P-804*, U.S. Department of Homeland Security.

Within the basic package, two methods exist for strengthening the sheathing to roof framing connection: one with and the other without roofing replacement. In the first basic package method, roofing is removed, additional 8d nails are fastened to the sheathing to roof framing member connection, and new roofing is installed. If there is still usable life in the roofing and it is not to be removed, the connection is strengthened

by ccSPF at all intersections of sheathing and roof framing members. The foam is also applied to the joints between adjacent sheathing panels to reduce water ingress. This retrofit is shown in Figure 2-3.

Other adhesives have been used to strengthen sheathing panel connections (and may aid in reducing water ingress through sheathing seams). Turner (2009) investigated the contribution of strength of an acrylic tape adhesive and glue to the sheathing to truss member connection. Specimens consisted of a 16 in., nominal 2 by 4 framing board attached to a 20 in. by 20 in. by 7/16 in. sheathing panel with three 8d nails. Under a loading rate of 0.25 in./min., both the acrylic tape and glue strengthened the connection by over 250%.

Figure 2-3. Hurricane retrofit using ccSPF from FEMA (2010)

Performance of Foam-Insulated Wood Roof Decks

Energy Performance

Energy benefits may also be achieved by placing ccSPF in the roof space. The International Residential Code (ICC 2009) allows for air-impermeable insulation (e.g., ccSPF) to be applied directly underneath the roof deck as part of an unvented system. Unvented attics allow the attic space of the home to be integrated with the conditioned space by sealing the attic from outside air, bringing air ducts contained within the attic into the conditioned space. Rudd et al. (1998) conducted energy efficiency simulations for homes in Las Vegas, NV with unvented and vented attic configurations to determine the effects of placing air ducts in the conditioned space and of transitioning to unvented attics. The simulations were conducted using an FSEC 3.0 finite element modeling program. The Las Vegas simulations found that moving air ducts into the conditioned space saved 4.2% of annual energy consumption and 4.3% of energy costs. Furthermore, shifting from an unconditioned to a conditioned unvented attic reduced annual energy consumption by 3.6% and total annual cost by 2.2%. Rudd et al. (1999) noted that if typical air duct leakage is considered, energy savings from unvented attics in comparison to vented attics are even more significant.

Hendron et al. (2002) quantified the effects of duct leak rate in full-scale unvented vs. vented attics in Las Vegas and Tucson. The study found that when 10% air leakage, which translated to approximately 100 cfm in the test houses, was introduced into air ducts, approximately 8% in energy savings were realized in unvented roofs over vented roofs. When 200 cfm leakage was introduced, the energy savings for unvented roofs were increased to 11.5%, further illustrating the energy benefits from unvented construction.

Roofing Performance

Deficient shingles allow water ingress into roof sheathing. Berdahl et al. (2008) outlined several factors that contribute to roofing weathering in a comprehensive review. These factors include: ultraviolet rays, wind, water (in any form), gases, and biological growth. All of these factors adversely affect the performance of roofing, but none more than elevated temperatures.

Terrenzio et al. (1999) studied the effects of various temperature, light, and wetting conditions on the aging of asphalt and fiberglass-reinforced shingles using natural and artificial methods. The authors found that hotter climates showed more rapid rates of molecular increase (i.e., lower-weight molecules “diffused”) and increased flexural stiffness (i.e., shingles became more brittle). Thus, Terrenzio et al. (1999) concluded, higher temperatures contribute most to shingle aging.

Asphalt shingle manufacturers will often void their warranties when insulation (e.g., ccSPF) is applied directly to sheathing due to concerns that these systems increase shingle temperature (Parker 2005), encouraging earlier aging of shingle products. The Asphalt Roofing Manufacturers Association (ARMA 2006) recommends that ventilation space be integrated into roofs with sheathing-applied insulation to mitigate heat and water buildup to alleviate these concerns.

Studies have shown that insulating roof sheathing increases its temperature. Rose (2001) compared temperatures of a vented attic to attics containing several variations from 1994 to 1996. Temperatures at the top surface of wood roof sheathing were 19% greater with R-30 fiberglass batt and 23% greater with 1 in. of polyisocyanurate board with R-30 insulation than the typical vented attic configuration. Parker and Sherwin (1998) measured surface temperatures of a traditional roof and a roof with a radiant

barrier at the underside of sheathing, finding consistently higher temperatures (approximately 5 degrees Fahrenheit) during the hottest parts of the day and cooler temperatures at night (approximately 1 degree Fahrenheit) in the shingles for the radiant barrier roof system. Tenwolde and Rose (1999) noted that shingle temperatures in unvented attics are greater than 160 degrees Fahrenheit for a significantly longer time than shingles in traditional vented roofs.

Sheathing Structural Performance

ccSPF has been shown to strengthen the roof sheathing connection to framing members. Jones (1998) studied these structural effects with ccSPF applied in various configurations to both plywood and OSB specimens. Suction tests using gradual monotonic loading were conducted on 97 roof panels constructed using 19/32 in. thick OSB and 3-ply CDX plywood at 15/32 in. and 19/32 in. thicknesses. Sheathing panels were fastened to southern yellow pine (SYP) and spruce pine fir (SPF) framing members spaced at 16 in. or 24 in. on center with 8d smooth-shank nails at 6 in. edge and 12 in. field spacing. ccSPF retrofits were applied to the connection between sheathing and roof framing members in four unique configurations:

- Single pass full bead (fillet) of foam on both sides of each framing member
- Double pass full bead on both sides of each framing member
- Full bead on one side of each framing member
- Partial bead on both sides of the rafter

Compared to their respective non-retrofitted controls, plywood sheathing panels with a full retrofit on both sides showed a strength increase of 295%, while OSB panels showed an increase of 212% with the retrofit and 361% with a double-pass of the retrofit. Plywood panels with full beads on one side yielded a strength increase of 186%.

In 2007, Prevatt and Datin (Datin et al. 2010) conducted wind uplift capacity tests on 1/2 in. thick OSB sheathing fastened to SYP framing members with 2 in. long 6d smooth shank and 8d ring shank nails at 6 in. edge and 12 in. field spacing. All panels were retrofitted with ccSPF. A total of three retrofits and eight sample sets were tested in two studies (Prevatt 2007a; Prevatt 2007b).Three of these sample sets tested capacity of sheathing panels fastened only with ccSPF. In these two studies, individual panels were tested for their wind uplift pressure capacities according to the UF-WRSUT method detailed in Chapter 3. Specifically, the following retrofits were investigated:

- **Retrofit 1:** 3 in. triangular fillet of ccSPF at the wood framing to sheathing panel joint
- **Retrofit 2:** 3 in. fillet plus ½ in. layer between fillets
- **Retrofit 3:** Continuous 3 in. thick ccSPF layer

Retrofits 2 and 3 were utilized in this thesis (a 1 in. layer between fillets was used in this thesis for Retrofit 2). Wind uplift capacity results from Datin et al. (2010) are summarized in Table 2-3.

Table 2-3. Wind uplift capacities of ccSPF-retrofitted panels in previous testing at the University of Florida

Nail Type*	ccSPF Application	No. of Samples	Mean Uplift Capacity (psf)	COV (%)
8d Ring Shank	Retrofit 1	13	155	17
6d Smooth Shank	Retrofit 1	5	175	10
None	Retrofit 1	10	209	13
None	Retrofit 2	10	178	21
8d Ring Shank	Retrofit 3	5	245	16
6d Smooth Shank	Retrofit 3	5	250	13
8d Ring Shank	Retrofit 3	6	220	23
None	Retrofit 3	9	199	14
6d Smooth Shank	None	15	74	22
8d Ring Shank	None	25	169	15

Datin, P., Prevatt, D.O., and Pang, W. (2010). "Wind Uplift Capacity of Residential Wood Roof Sheathing Panels Retrofitted with Insulating Foam Adhesive." *Journal of Architectural Engineering*.

*Nailed at 6 in. 12. spacing.

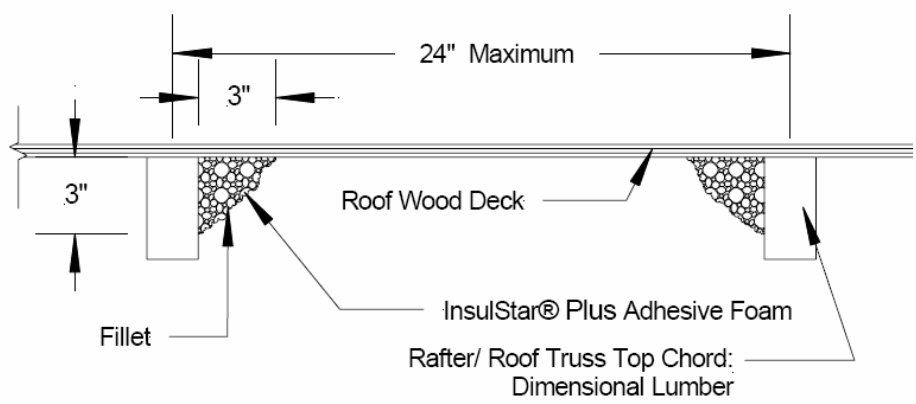
With 6d smooth shank nails, Retrofits 1 and 3 yielded 235% and 336% greater capacity than their respective controls. For 8d ring shank nails, Retrofit 3 contained 130% and 145% greater capacities for two separate sample sets. Surprisingly, panels with 8d ring shank nails complemented by Retrofit 1 were weaker than the equivalent control at 92% of the control set's capacity.

Florida ccSPF Retrofit Guidelines

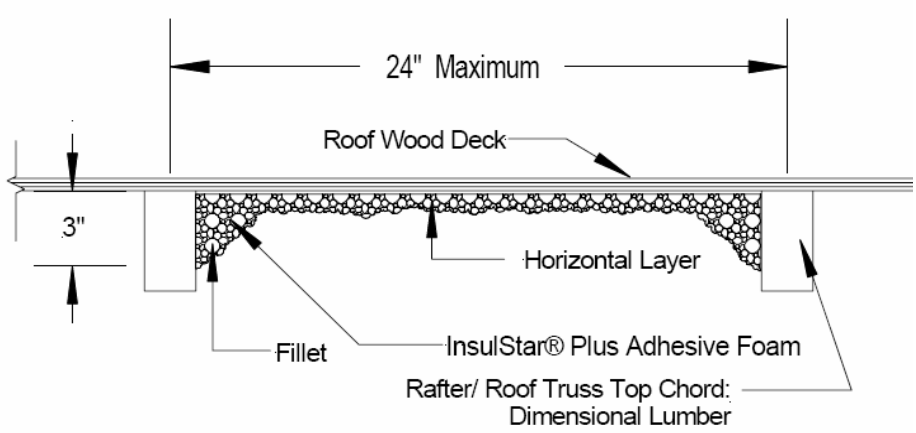
As a result of the testing presented in Datin et al. (2010), Florida Department of Community Affairs (FL DCA) Product Approvals FL9975-R1 (FL DCA 2007a) and FL13001 (FL DCA 2007b) were written. This section discusses existing specifications and instructions for the installation of ccSPF as prescribed by these two product approvals. For the purpose of this thesis, the three retrofits in the product approvals will henceforth be named Level I, Level II, and Level III protection. Level I protection consists of a 3 in. fillet at the roof sheathing to framing member connection. Level II consists of the fillet in Level 1 along with a minimum ½ in. thick layer covering protrusions. Finally, Level III is a minimum 3 in. thick layer between framing members. The three retrofits are displayed in Figure 2-4.

When installing the foam, any surface where ccSPF will be sprayed must be safe, clean of debris, and free of moisture and any substances (e.g., grease) that could reduce adhesion to the substrate. The foam is to be sprayed in multiple passes where necessary between ½ in. and 2 in. per pass. Manufacturer's guidelines must also be followed in the application of the ccSPF. The specifications do not address issues relating to water leakage and maintenance once installed.

Level I



Level II



Level III

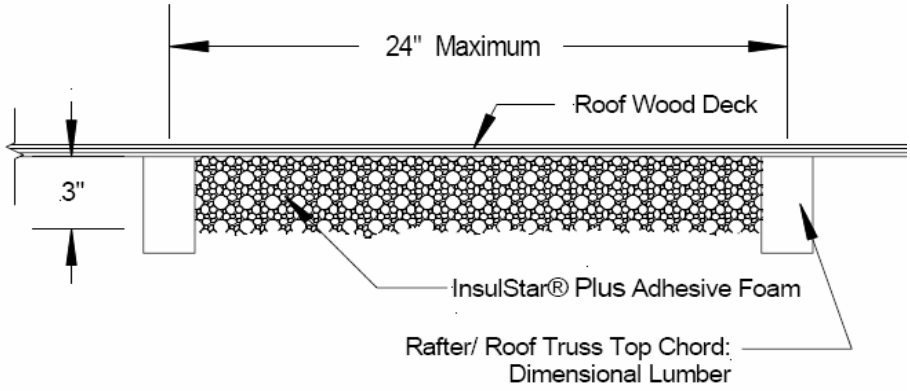


Figure 2-4. ccSPF retrofits for Levels I, II, and III Protection in (FL DCA 2007a)

Moisture Performance

The ccSPF used as a structural retrofit and insulation in wood roofs is a Class 3 vapor retarder. It is used by FEMA (2010) and IBHS (2011) as a secondary water barrier. At the conclusion of their study, however, Datin et al. (2010) expressed concerns about the effects of water leakage on the retrofitted system, stating:

> "It is hypothesized that water leaking through roof covering to the wood substrate can become trapped at the interface of the ccSPF foam and the underside of the roof. Without providing a reasonable path for this water to flow out from the cross-section, trapped water could in time lead to overall degradation of the ccSPF to wood bond and to the wood itself."

Because it is currently permissible to use this foam material as an insulating material applied directly to the underside of roof sheathing throughout a roof, concerns about moisture entrapment in the retrofitted system warrant investigation. The effects of water leakage into the ccSPF-retrofitted roof on the structural and serviceable performance of the roof are the main focus of this thesis.

Panelized Roof Systems

Knowledge gained from the study of the moisture performance of ccSPF-retrofitted sheathing panels may lead to the development of new panelized residential roof systems. Panelized systems integrate multiple functions into a factory-built product that can be quickly assembled on-site (Wherry 2009). Potential benefits of panelized construction are significant. The need for roof trusses and rafters is removed or greatly reduced, resulting in open and conditioned attic spaces. Long-term cost savings can be realized through the reduction in energy costs. Quality control of the building process is shifted to a controlled factory setting, ensuring repeatability and confidence in the structural reliability of the roof.

Several panelized systems found in the literature have already been developed. Structural Insulated Panels (SIPs), invented by Alden B. Dow, are perhaps the oldest and simplest form of modern panelized construction. Dow invented structural sandwich panels with 1 5/8 in. Styrofoam cores and 5/16 in. plywood faces. Dow, a student of Frank Lloyd Wright, built several houses with SIPs used in wall and roof elements. Some of the test houses built by Dow are still in use today (Morley 2000).

More recently, Crowley et al. (1993) designed a system expanding upon the SIPs concept. The system utilized 4 ft. wide panels with lengths of up to 24 ft. Panels were comprised of two 7/16 in. OSB sheathing panels joined by perpendicular OSB ribs running lengthwise within the panels. Between the ribs was an insulating layer. An air space was left above the insulation for ventilation parallel to the length of the panel. Semicircular notches were cut into the top portion of the ribs to allow for ventilation across the width of the panels as well. Figure 2-5 provides cross-sectional views of the panels. A full-scale roof with a straight gable, a turn gable, a hip, and a dormer was built as a proof-of-concept for Crowley et al. (1993). After several cycles of construction and deconstruction, it was found that this relatively complex roof structure could be constructed in three to four hours, demonstrating promise for the reduction of construction labor costs in panelized systems.

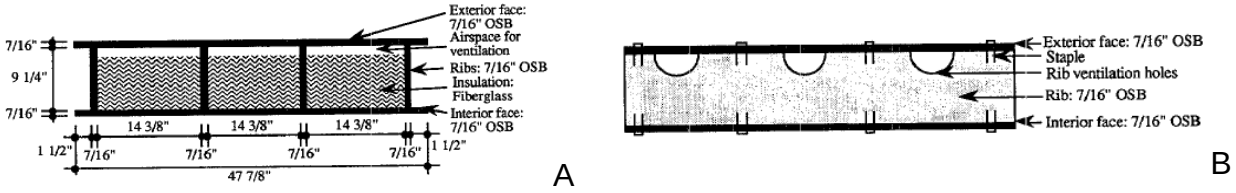


Figure 2-5. Two-way vented panelized roof system from Crowley et al. (1993). A) Horizontal cross-section. B) Panel longitudinal section.

Mantell et al. (2008) developed a system utilizing steel “truss-core panels” that separate the load-carrying components and the insulating components of the panel into different layers. The structural component was a steel v-shaped truss concept. Polyurethane foam was chosen as the insulator for its high range of service temperatures, suitability for manufacturing, good fire performance in relation to other foam options, and its resistance to mold growth. A design with the foam on top and a design with the truss core on top were both proposed. Renderings of both designs are provided in Figure 2-6.

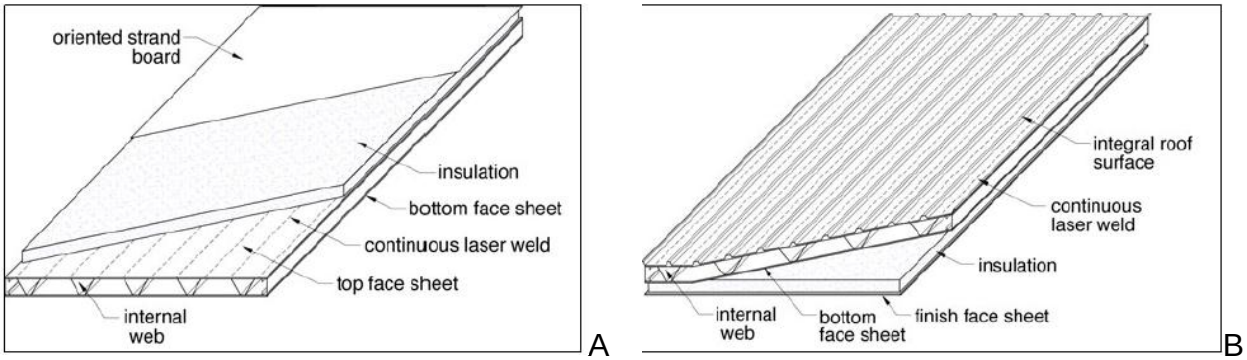


Figure 2-6. Panelized systems from Mantell et al. (2008). A) Foam on top. B) Truss on top.

WUFI hygrothermal analysis was performed for both systems in various climates. Mantell et al. (2008) concluded that the panel with foam on the exterior is effective for climates that contain a monthly average relative humidity less than 80%. The panel with structural members on the outside face showed a risk of metal corrosion in Houston, Las Vegas, and all of the cooler climates. The steel facing is vapor impermeable, and condensation caused by the presence of cooler foam insulation does not have a means of egress to the outside of the roof enclosure.

Thomas et al. (2006) and Briscoe et al. (2010) used analytical models to optimize the design of simple sandwich panels with several options for face and core materials

and panels containing steel webs in their cores. The importance of good connections between panels is emphasized, but neither connection details nor the potential effects of thermal bridging caused by panel connections are discussed. The potential removal of traditional roofing materials is highlighted but not discussed further, leaving opportunities for further research on how to complete panelized systems to avoid water penetration into the home interior.

Material Properties

Wood

Wood is an organic material, a natural composite of thin, long cellulose fibers embedded in a matrix of lignin that binds cells together. The length of cells runs parallel to the length of the tree and is often visualized as a “bundle of straws” (Figure 2-7 shows a drawing of individual cells). This cell alignment results in a wood structure very strong in axial tension and in compression, but weak in tension perpendicular to the tree length (Breyer et al. 2007). Softwoods, or coniferous trees, are used as the predominant material in residential construction in the U.S. and contain cells roughly 100 times longer in length (up to 10 mm) than in diameter (Forest Products Laboratory 2010).

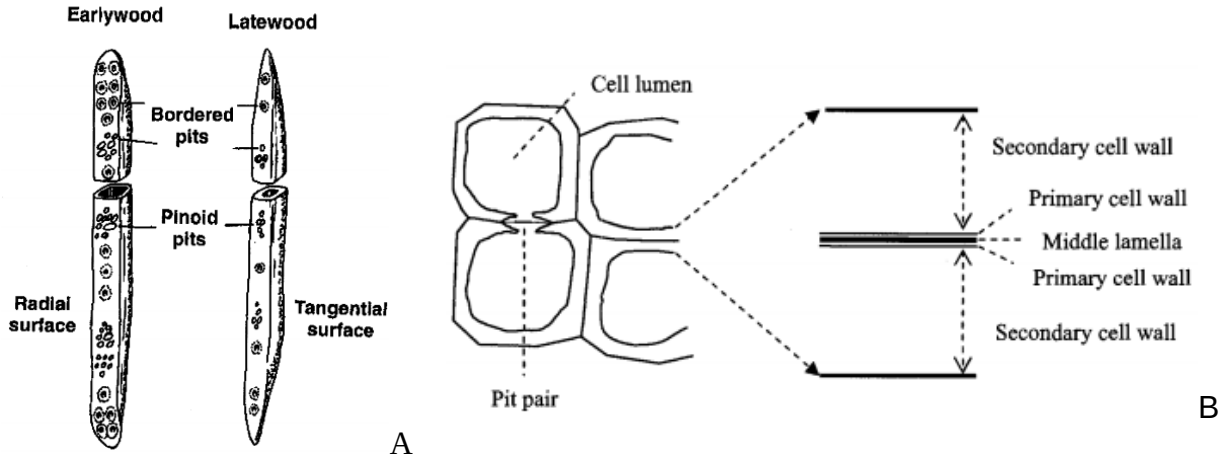


Figure 2-7. Renderings of wood cells from (Timusk 2008). A) Single cells. B) Simplified cell cross-section.

Moisture properties

The moisture content of wood, defined as the weight of water within wood divided by the dry weight of the wood itself, influences its structural performance and durability. Moisture content is controlled by ambient temperature and relative humidity conditions and by the presence of free water in wood.

Given a constant humidity and temperature for an extended period of time, an “equilibrium moisture content” (EMC) will be reached. The EMC is the moisture content at which wood neither gains moisture from nor loses moisture to the air surrounding the wood (Forest Products Laboratory 2010), thus reaching equilibrium. If the moisture content of wood is less than the EMC, moisture will travel into the wood via a process called water vapor sorption. Conversely, if the moisture content of wood is greater than the EMC, water will travel out of the wood to the surrounding air. Although roofs do not experience constant ambient conditions, the contribution of ambient conditions to the moisture contents in wood members can be approximated if average temperatures and relative humidity values are known. Table 2-4 provides the EMC values for a wide range of temperatures and relative humidity values.

Wood moisture content is also influenced by contact with liquid water, which is absorbed into wood via capillary action, or “wicking.” The rate of absorption of liquid water is affected by the location of water in comparison to the grain of the wood; the absorption rate is greatest when the end grain of wood is exposed to water.

The cellulose component of wood is much more hydrophilic (attracts water) than the lignin component. For this reason, when moisture is introduced to wood, it first travels into the cells of the wood through small holes called pits. The point at which the cells become filled with water is called the Fiber Saturation Point (FSP), which occurs at

approximately 30% moisture content for most wood species (Forest Products Laboratory 2010). The FSP also represents the greatest amount of water that can be introduced to wood cells from ambient conditions; i.e., for the FSP to be exceeded, liquid water must be present.

Table 2-4. Equilibrium moisture content for solid lumber

Temp (F)	Ambient Relative Humidity (%)																		
	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95
30	1.4	2.6	3.7	4.6	5.5	6.3	7.1	7.9	8.7	9.5	10.4	11.3	12.4	13.5	14.9	16.5	18.5	21.0	24.3
40	1.4	2.6	3.7	4.6	5.5	6.3	7.1	7.9	8.7	9.5	10.4	11.3	12.3	13.5	14.9	16.5	18.5	21.0	24.3
50	1.4	2.6	3.6	4.6	5.5	6.3	7.1	7.9	8.7	9.5	10.3	11.2	12.3	13.4	14.8	16.4	18.4	20.9	24.3
60	1.3	2.5	3.6	4.6	5.4	6.2	7.0	7.8	8.6	9.4	10.2	11.1	12.1	13.3	14.6	16.2	18.2	20.7	24.1
70	1.3	2.5	3.5	4.5	5.4	6.2	6.9	7.7	8.5	9.2	10.1	11.0	12.0	13.1	14.4	16.0	17.9	20.5	23.9
80	1.3	2.4	3.5	4.4	5.3	6.1	6.8	7.6	8.3	9.1	9.9	10.8	11.7	12.9	14.2	15.7	17.7	20.2	23.6
90	1.2	2.3	3.4	4.3	5.1	5.9	6.7	7.4	8.1	8.9	9.7	10.5	11.5	12.6	13.9	15.4	17.3	19.8	23.3
100	1.2	2.3	3.3	4.2	5.0	5.8	6.5	7.2	7.9	8.7	9.5	10.3	11.2	12.3	13.6	15.1	17.0	19.5	22.9
110	1.1	2.2	3.2	4.0	4.9	5.6	6.3	7.0	7.7	8.4	9.2	10.0	11.0	12.0	13.2	14.7	16.6	19.1	22.4
120	1.1	2.1	3.0	3.9	4.7	5.4	6.1	6.8	7.5	8.2	8.9	9.7	10.6	11.7	12.9	14.4	16.2	18.6	22.0
130	1.0	2.0	2.9	3.7	4.5	5.2	5.9	6.6	7.2	7.9	8.7	9.4	10.3	11.3	12.5	14.0	15.8	18.2	21.5
140	0.9	1.9	2.8	3.6	4.3	5.0	5.7	6.3	7.0	7.7	8.4	9.1	10.0	11.0	12.1	13.6	15.3	17.7	21.0
150	0.9	1.8	2.6	3.4	4.1	4.8	5.5	6.1	6.7	7.4	8.1	8.8	9.7	10.6	11.8	13.1	14.9	17.2	20.4
160	0.8	1.6	2.4	3.2	3.9	4.6	5.2	5.8	6.4	7.1	7.8	8.5	9.3	10.3	11.4	12.7	14.4	16.7	19.9
170	0.7	1.5	2.3	3.0	3.7	4.3	4.9	5.6	6.2	6.8	7.4	8.2	9.0	9.9	11.0	12.3	14.0	16.2	19.3
180	0.7	1.4	2.1	2.8	3.5	4.1	4.7	5.3	5.9	6.5	7.1	7.8	8.6	9.5	10.5	11.8	13.5	15.7	18.7
190	0.6	1.3	1.9	2.6	3.2	3.8	4.4	5.0	5.5	6.1	6.8	7.5	8.2	9.1	10.1	11.4	13.0	15.1	18.1
200	0.5	1.1	1.7	2.4	3.0	3.5	4.1	4.6	5.2	5.8	6.4	7.1	7.8	8.7	9.7	10.9	12.5	14.6	17.5
210	0.5	1.0	1.6	2.1	2.7	3.2	3.8	4.3	4.9	5.4	6.0	6.7	7.4	8.3	9.2	10.4	12.0	14.0	16.9
220	0.4	0.9	1.4	1.9	2.4	2.9	3.4	3.9	4.5	5.0	5.6	6.3	7.0	7.8	8.8	9.9			
230	0.3	0.8	1.2	1.6	2.1	2.6	3.1	3.6	4.2	4.7	5.3	6.0	6.7						
240	0.3	0.6	0.9	1.3	1.7	2.1	2.6	3.1	3.5	4.1	4.6								
250	0.2	0.4	0.7	1.0	1.3	1.7	2.1	2.5	2.9										
260	0.2	0.3	0.5	0.7	0.9	1.1	1.4												
270	0.1	0.1	0.2	0.3	0.4	0.4													

Forest Products Laboratory. (2010). "Wood Handbook: Wood as an Engineering Material." United States Dept. of Agriculture Forest Service, Madison, WI.

Beyond the FSP, water is absorbed into the lignin of the wood; this is known as free water. The presence of free water provides livable conditions for rot fungi and significantly decreases the structural properties of the wood (Carll and Wiedenhoeft 2009). The National Design Specification for Wood Construction (AFPA 2005) applies a strength reduction factor for solid wood that will hold moisture contents over 19% for solid wood products and 16% for engineered wood products to allow for variations in FSP values and the effects of moisture content on nailed connections in wood.

Although the National Design Specification for Wood Construction (NDS) does not recognize strength differences below 19% moisture content in sawn lumber and 16% in panelized products (AFPA 2005), wood structural properties increase as moisture content decreases with the greatest strength seen at 4% to 6% moisture content. Conversely, high moisture content in wood materials increases their susceptibility to other degrading forces such as fungal attack, insects, and stresses caused by swelling and contracting of wood fibers (Carll and Wiedenhoeft 2009). The strength of nailed connections in wood construction has shown to decrease with increasing moisture conditions (Chow et al. 1988).

Wood decay

Wood decay is caused by rot fungi specialized to eat the lignin that binds cells together. Five elements must be present for fungal decay to occur (Carll and Wiedenhoeft 2009):

- a wood rot fungus,
- a food source (wood)
- a regular source of water
- relatively high temperatures
- oxygen

The ideal conditions for fungal growth in wood are a range of 70 to 90 degrees Fahrenheit and 40% to 80% moisture content. However, these fungi can grow between 60 and 105 degrees Fahrenheit (Zabel and Morrell 1992).

Wang et al. (2010) studied the relationships between moisture content and time to decay of plywood, OSB, and solid wood materials in the presence of rot fungi. Samples were exposed to relative humidity levels of 90%, 95%, near 100%, and a nominal 40% moisture content level. At each relative humidity level, the moisture content of the different materials was different, with plywood containing the highest moisture content values followed by OSB and solid wood respectively. At a moisture content of approximately 25% resulting from the 95% relative humidity level, none of the wood materials lost any strength in 3.5 years of exposure to fungi. At 27% moisture content, however, the stiffness of OSB was reduced after 36 weeks. At 40% moisture content, both OSB and the solid wood specimens began to lose strength after 21 weeks; plywood showed no signs of decay after 74 weeks (at which point this portion of the experiment was terminated). Wang et al. (2010) concluded that the critical moisture content for decay initiation is 26% if all conditions are met for fungal propagation.

The critical moisture contents and times for fungal growth presented in Wang et al. (2010) were dependent on optimal fungal growth conditions and constant wood moisture contents. If any conditions were unfavorable for fungal growth, Wang et al. (2010) concluded that the time needed for rot fungi to affect the structural properties of wood would increase greatly. Furthermore, if the drying rate of wood is sufficiently fast and wood is able to dry to below the FSP, moisture contents in excess of the FSP may be regularly observed without structural consequences (Carll and Wiedenhoeft 2009).

Molds are fungi that do not cause structural damage since they grow on the wood surface alone without penetrating the substrate. Mold growth occurs at moisture contents greater than 16%, roughly translating to the EMC at 80% relative humidity at room temperature. Above 90% relative humidity, mold growth increases greatly (Carll and Wiedenhoeft 2009). Although mold fungi do not pose risk to the structural properties of wood, some molds can be harmful, and even deadly, to humans. Thus, the controlling factor for moisture control in wood may not be rot, but mold.

Closed-Cell Spray-Applied Polyurethane Foam (ccSPF)

Closed-cell spray-applied polyurethane foam is used in wood-frame residential buildings because of its light weight, high insulating properties (Bomberg and Lstiburek 1998) and strong chemical bond with both wood and metal substrates.

ccSPF is part of a class of foams composed of two main ingredients: polyisocyanate or “Component A” and polyhydroxyl compounds or “Component B”, which react to form polyurethane. Component B also contains other agents that control blowing, consistency, and stabilizing properties of the foam that beget the desired density and closed-cell content. Hoses containing Components A and B and a third hose containing compressed air are used to spray the foam onto the substrate.

The foam structure is formed through an exothermic reaction of isocyanate with the Component B polyhodroxyls and water molecules. This reaction produces carbon dioxide gas and the polyurethane structure. Polyurethane molecules link together in cohesive chains while the carbon dioxide expands to form the nuclear cell structure of the foam, expanding the foam to over 30 times the liquid volume (Dedecker 2002). The resulting cells are a collection of bubbles made of polyurethane “struts” that provide the structure of each bubble and thinner “windows” between the struts. For insulating foams

used in residential construction, cell sizes vary from 0.1 to 0.5 mm in diameter. Figure 2-8 shows the cell structure of ccSPF.

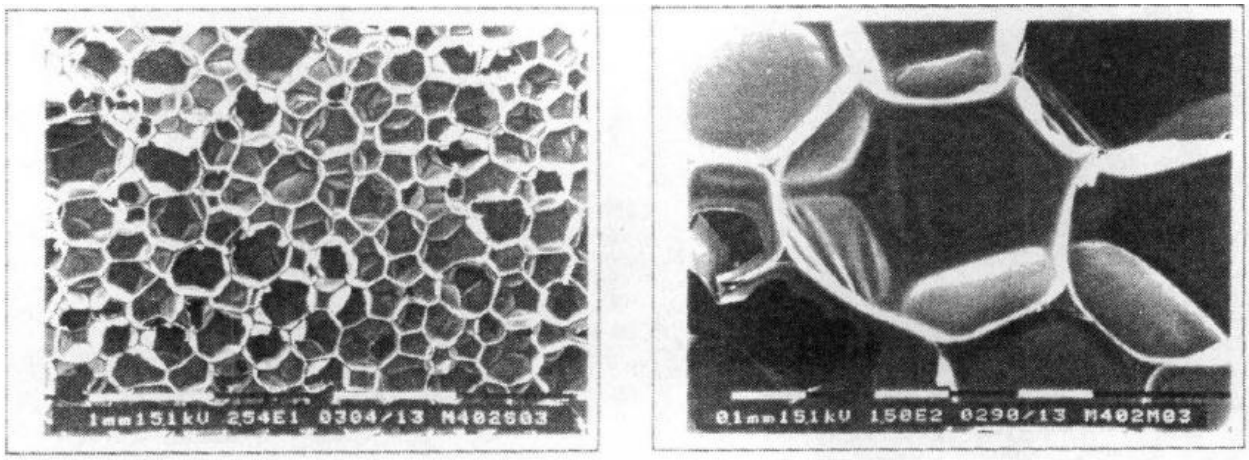


Figure 2-8. ccSPF cell structure at lens magnifications of 50 X and 300 X (Smits 1994)

Special blowing agents containing surfactants keep the cell windows from rupturing. It is the closed cell structure that provides the foam rigidity and minimizes the heat transfer through the foam cross-section. When sprayed to a wood substrate, the isocyanate chemical in Component A reacts with hydroxyls and water in the wood itself, forming a thin polyurethane layer and a covalent bond resistant to moisture (Dinwoodie 1983). In general, ccSPF is very dimensionally stable and unaffected by temperature, water, and ultraviolet light. ccSPF possesses a low permeability to water (Kumaran et al. 2002). For all of these reasons, it is attractive as an insulator, structural reinforcement, and secondary water barrier in residential roofs. However, water may be trapped between ccSPF and wood substrates. Although the bond may not be affected, moisture content of the wood may increase beyond critical limits for decay and performance reduction of nailed connections.

Statistical Methods Used

Two Population *t*-Tests

A two-population *t*-test is used to determine whether the means of two normally-distributed sample populations are statistically equivalent. The variances of the samples may be equal or unequal in performing this test. The null hypothesis is that both means are equal; thus, the alternate hypothesis is that the two means are not equal. To perform the test, a t statistic is calculated. The following equation generates the t value for equal sample sizes and variances:

$$t' = \frac{\bar{X}_1 - \bar{X}_2}{S_p \cdot \sqrt{\frac{2}{n}}} \qquad \text{Equation 1}$$

where

$$S_p = \sqrt{\frac{(n-1){s_1}^2 + (n-1){s_2}^2}{2n-2}} \qquad \text{Equation 2}$$

$\bar{X}_1$ is the mean of the sample group 1, $\bar{X}_2$ is the mean of sample group 2, s_1 is the standard deviation of group 1, s_2 is the standard deviation of group 2, S_p is the pooled standard deviation of both groups, and n is the number of samples in each group. If unequal sample sizes and variances are observed, the following equations are used instead:

$$t' = \frac{\bar{X}_1 - \bar{X}_2}{S_{X1-X2}} \qquad \text{Equation 3}$$

where

$$S_{X1-X2} = \sqrt{\frac{{s_1}^2}{n_1} + \frac{{s_2}^2}{n_2}} \qquad \text{Equation 4}$$

The test statistic t' is compared against a t value obtained from placing the number of degrees of freedom and the alpha (the acceptable probability of falsely rejecting the null hypothesis) value into a Student's t distribution table ($t_{\alpha,df}$); this table is provided in Appendix A. Note that the alpha value is divided by two if a two-tailed test is being conducted. Degrees of freedom are calculated by the following equation:

$$df = \frac{(n_1 - 1)(n_2 - 1)}{(1 - c)^2(n_1 - 1) + c^2(n_2 - 1)} \quad \text{Equation 5}$$

where

$$c = \frac{\frac{{s_1}^2}{n_1}}{\frac{{s_1}^2}{n_1} + \frac{{s_2}^2}{n_2}} \quad \text{Equation 6}$$

If the test t-statistic exceeds the tabulated $t_{\alpha,df}$ value, the null hypothesis is rejected and the conclusion is made that the two population means are unequal.

Analysis of Variance

A one-factor analysis of variance (ANOVA) test is used to determine if the means of three or more samples sets, generically known as "treatments", are statistically equivalent or statistically different. The test can also be used for two sample populations; however, the same result is achieved by conducting a *t*-test. For three or more samples, results of a one-factor ANOVA indicate whether the null hypothesis that all means are statistically equivalent or the alternate hypothesis that not all means are statistically equivalent is true. The test does not distinguish *which* sample sets are statistically different. To test the hypothesis, an F statistic is obtained. F is determined in the following manner:

$$F = \frac{MST}{MSE}$$ Equation 7

where

$$MST = \frac{SST}{t-1}$$ Equation 8

$$MSE = \frac{SSE}{N-1}$$ Equation 9

$$SST = n\sum_{ij}(\bar{y}_{i.} - \bar{y}_{..})^2$$ Equation 10

$$SSE = \sum_{i}(y_{ij} - \bar{y}_{i.})^2$$ Equation 11

MST is the Mean Square Treatment, MSE is the Mean Square Error, SST is the Between Treatment Sum of Squares, SSE is the Sum of Squares for Error, t is the number of treatments, n is the number of samples within each treatment, N is the total number of samples in the experiment, y_{ij} is the j^{th} sample taken from treatment i, $\bar{y}_{i.}$ is the mean of the samples in treatment i, and $\bar{y}_{..}$ is the mean of all samples in the experiment.

The F statistic is compared against the critical F value $F_{\alpha,t-1,N-t}$ from an F distribution table. If the calculated F value exceeds the tabulated F value, the null hypothesis is rejected and the conclusion is that not all means are statistically equivalent. The multi-population ANOVA has a lesser probability of error than separate *t*-tests in determining the equivalence of means.

Tukey-Kramer Honestly Significant Difference

If either a one-factor or two-factor ANOVA result in rejecting the null hypothesis that means between multiple datasets are unequal, post-hoc analysis is used to determine which means are statistically different from other means. The Tukey-Kramer Honestly Significant Difference (HSD) is an appropriate method that accounts for multiple sample sizes. Alpha and MSE values from the ANOVA test are utilized in the HSD method to find significance in results. The test places the difference between any two means in the experiment against an HSD value.

To begin, find the H value. In:

$$HSD = q_{dfE,t,\alpha} * \sqrt{\frac{MSE}{n}} \qquad \text{Equation 12}$$

$q_{dfE,t,\alpha}$ is taken from the Student's t-distribution table (provided in Appendix A), where dfE is the number of degrees of freedom for error in the ANOVA and t is the total number of means in the ANOVA. MSE is the Mean Square Error taken from the ANOVA, and n is the number of samples in each sample population. If sample sizes between sets of data vary, separate HSD values are calculated for each sample size.

To determine whether one mean within the experiment is statistically different from another, the absolute value of the difference between any two means is found. This value is compared against average of the calculated HSD values for each dataset. The null hypothesis is that any two means are statistically equivalent. The alternative hypothesis is that the two means are unequal. Thus, if the absolute difference between means exceeds the HSD value, the null hypothesis is rejected and it is concluded that the two means are different.

CHAPTER 3
MATERIALS AND METHODS

Full-Scale Wind Uplift Testing of ccSPF-Retrofitted Roof Sheathing Panels

Test Design

The effect of in-service water intrusion on the wind uplift capacity and moisture performance of roof sheathing retrofitted with ccSPF was investigated. To test the effect of leakage, 48 sheathing panel specimens were fabricated. 40 of the specimens were installed in five full-scale attic structures located at the University of Florida Hurricane Research Laboratory in Gainesville, Florida during the summer of 2010. The remaining eight panels were fabricated and stored in an unconditioned laboratory. Each full-scale structure was assigned a different combination of ccSPF retrofit (no retrofit, Level II, or Level III) and leakage condition (with leaks or without leaks). As the structural component studied was the roof, the structures are henceforth referred to as “Roofs”. Roofs were numbered in increasing order from easternmost to westernmost as shown in Figure 3-8 on page 58. An additional two sample sets were built and stored in the laboratory. Sample sets were organized as shown in Table 3-1.

Table 3-1. Description of full-scale sample sets

Sample Set	Retrofit	Leakage?	No. Samples
Roof 1	None	Yes	8
Roof 2	Level II	Yes	8
Roof 3	Level II	No	8
Roof 4	Level III	Yes	8
Roof 5	Level III	No	8
Laboratory II	Level II	No	4
Laboratory III	Level II	No	4

Leaking roofs contained approximately 100 manmade “leak gaps” distributed throughout the roof surface. Roofs were exposed to natural weather conditions and bi-daily simulated rainfall for a 150-day period commencing at the creation of the leak gaps

on August 13th, 2010. At the end of this period, specimens were removed, or "harvested", individually from the roofs and tested for the wind uplift capacity of their sheathing-to-truss connections according to the UF-WRSUT procedure.

Full-Scale Test Specimen Construction

Each sheathing panel specimen was comprised of a single 7/16 in. thick 4 ft. by 8 ft. OSB sheathing panel fastened to five truss members with 6d smooth-shank nails installed at 6 in. edge and 12 in. field spacing. To accommodate upside-down placement of specimens with framing members resting on the perimeter of a 50 in. wide steel chamber, framing members were made longer than the width of the 48 in. wide sheathing panel. A 3 in. extension was chosen, resulting in 54 in. truss members for each specimen. Figure 3-1 highlights major dimensions of the test specimens.

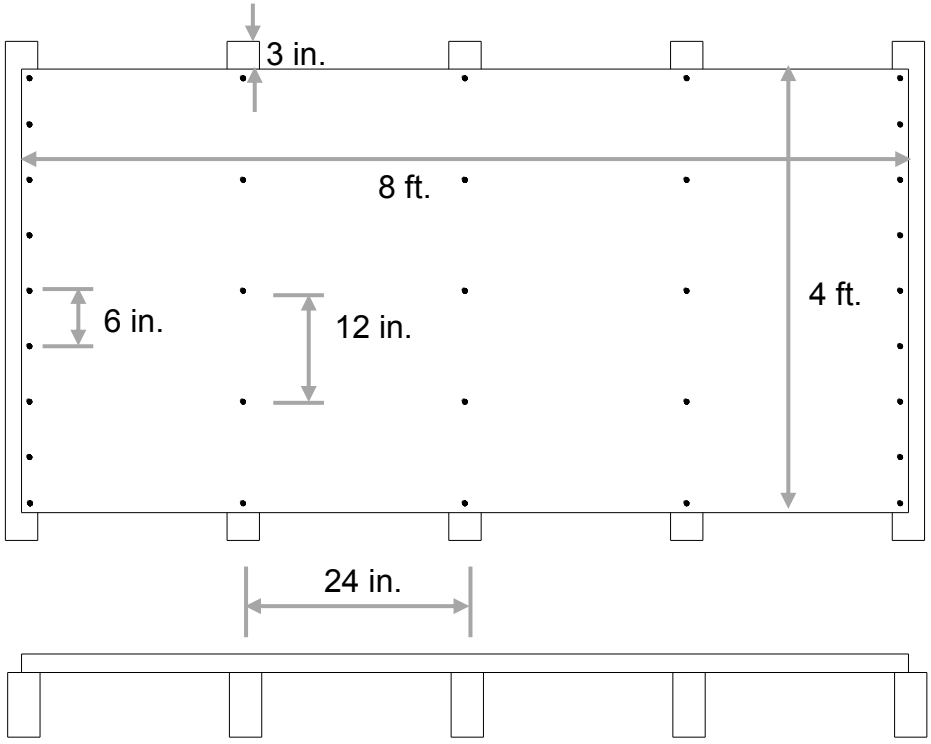


Figure 3-1. Test specimen dimensions

Two foam retrofits were investigated in the study; the retrofits are shown below in Figure 3-2 along with the non-retrofitted roof. The first retrofit (Level II) was composed of a minimum 3 in. fillet between truss members and roof sheathing and a minimum 1 in. layer between fillets. The second retrofit (Level III) was a minimum 3 in. retrofit between truss members.

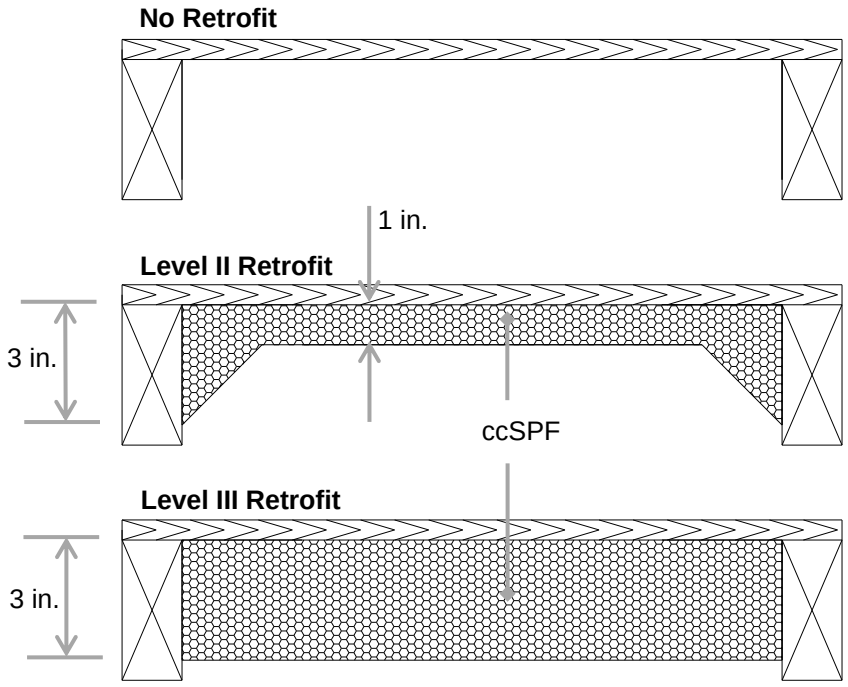


Figure 3-2. ccSPF retrofits used in full-scale testing

Construction of the five full-scale gable attic structures containing the 40 weathered test specimens occurred from May 11th to June 25th, 2010. Every structure had a 10 ft. by 33.5 ft. footprint and was sloped at a 6-in-12 pitch with roof faces directed north/south. Structures were elevated by two-course masonry walls that were in turn supported by 6 in. deep reinforced concrete foundations. The walls and foundations were fabricated by a concrete contractor. Trusses were connected to double 2 by 4 top plates with Simpson Strong Tie H8 hurricane straps, and top plates

were connected to the masonry walls by ½ in. diameter steel bolts. Figure 3-3 shows the eave cross-section of the structures.

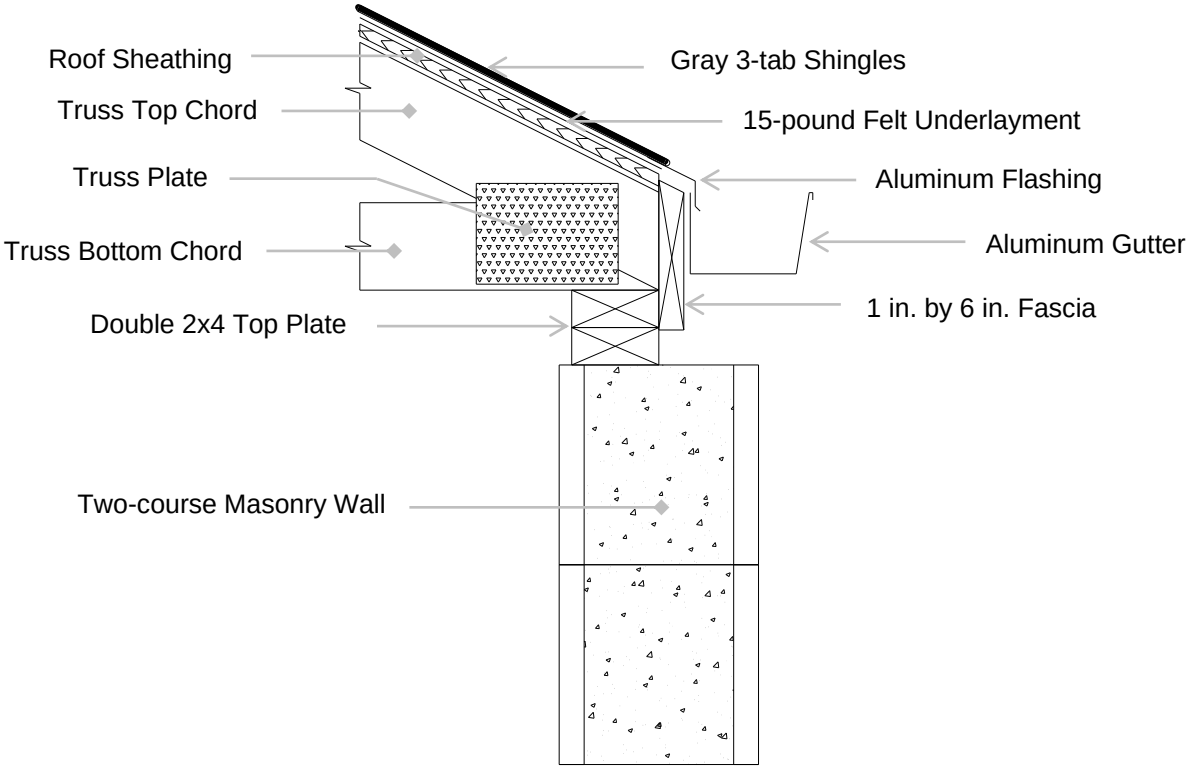
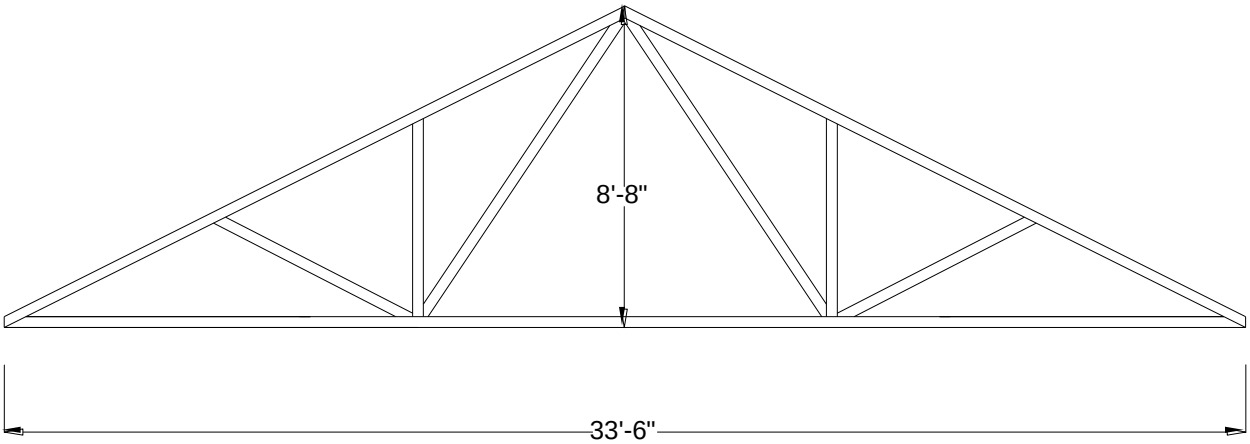
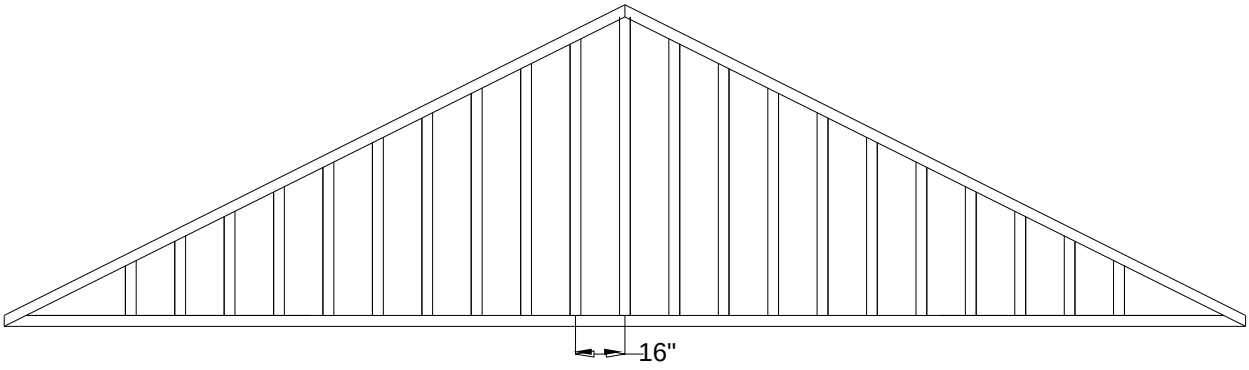


Figure 3-3. Eave cross-section of attic structures

Each structure contained seven trusses consisting solely of 2 in. by 4 in members. The five interior trusses were double-fan style and were spaced 2 ft. on center. Gable ends contained studs at 16 in. on center and were spaced 1 ft. apart from the nearest interior truss. A 3 ft. by 7 ft. doorway was placed on the east-facing gable end truss. The truss spacing scheme was chosen as part of an effort to maximize the use of roof area, minimize materials, and limit the cumulative footprint of the five attic structures, which is discussed subsequently in greater detail. Figure 3-4 provides drawings and dimensions for the three truss types and Figure 3-5 displays the truss spacing.



A



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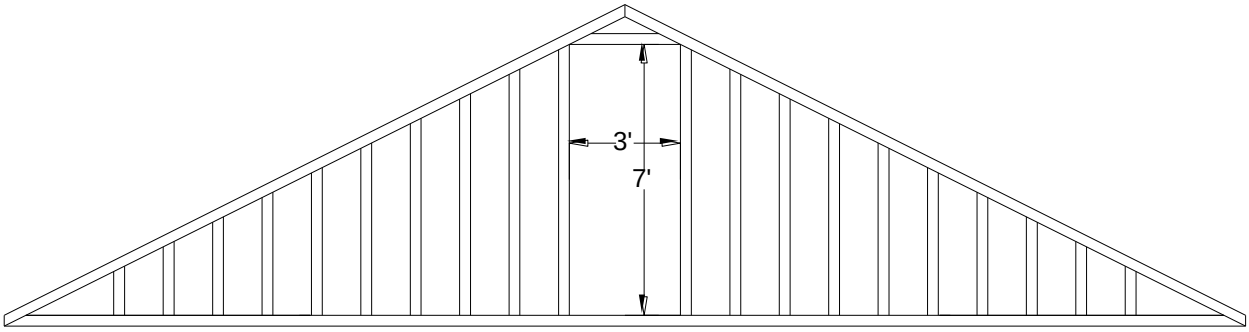


C

Figure 3-4. Trusses used in full-scale roofs. A) Interior double-fan truss B) Gable end truss C) Gable end with doorway

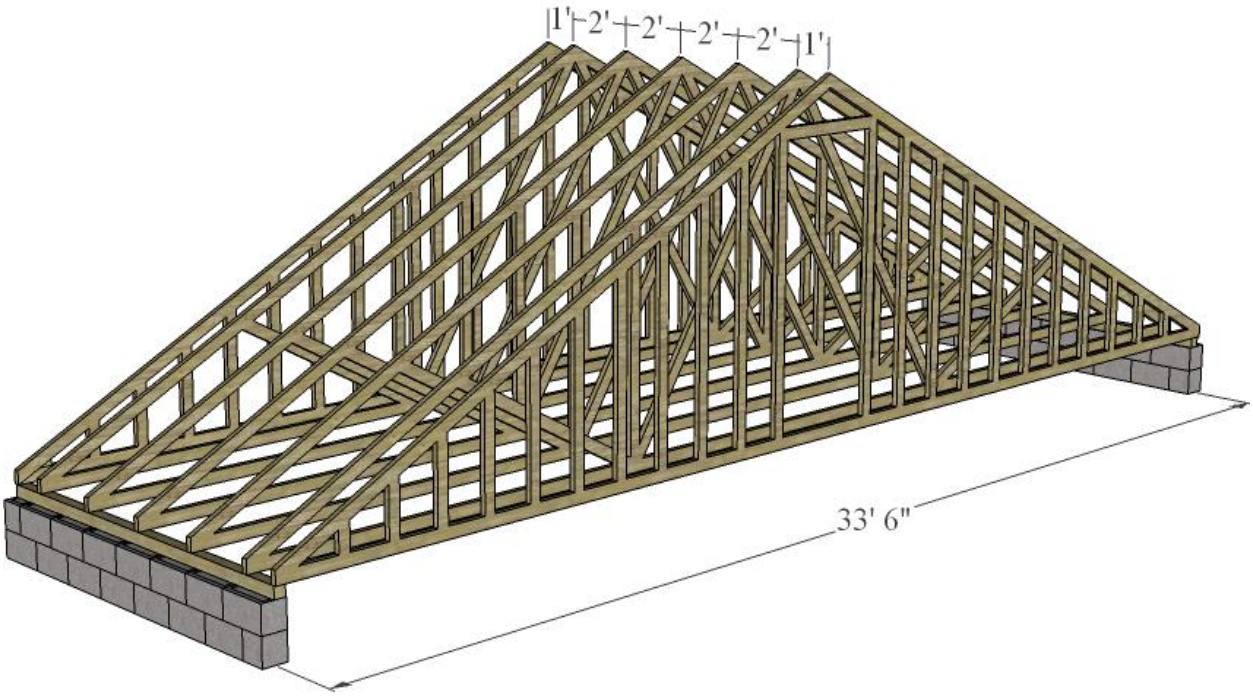


Figure 3-5. Spacing of roof trusses

Gable ends and the attic undersides were sheathed with 7/16 in. OSB. Because the clearance from the ground to the underside of the roof structures was limited to the height of the two-course masonry wall (16 in.), sheathing could not be installed with the structures in their in-service position. Thus, the entire roof frame was lifted with a large forklift, placing the frame on 6 ft. temporary walls, and fastening the sheathing from below using 8d ring shank nails at approximately 4 in. on center. The structure was placed back on the masonry walls. Gable ends were sheathed with the same 8d ring shank nails at approximately 8 in. on center. Tyvek HomeWrap was fastened with tabbed staples over the gable end sheathing to seal the walls from moisture.

Roof sheathing was fastened to the trusses with a 21° pneumatic nail gun (Model F21PL by Bostitch) using 2 in. long, 0.113 in. diameter smooth-shank 6d common galvanized nails at 6 in. edge and 12 in. field spacing. Three different sheathing sizes were used to maximize the use of available area while accommodating panel removal.

The staggered sheathing panel technique used in typical U.S. residential construction would have required that every other sheathing panel would need to be discarded to cut the extra 3 in. of framing member on either side to create full scale specimens. Due to limited available space and high amounts of wasted material, this technique was deemed infeasible for the study and a modified roof sheathing panel arrangement was employed, as follows.

A 10 ft. by 33.5 ft. footprint was used for the roofs. The 10 ft. width was chosen to place 8 ft. wide sheathing panel specimens fully within the roof surface with sheathing on either side of the panel, leaving the sides of each sheathing panel connected to interior trusses instead of gable ends. Thus, panels were not influenced by roof edge conditions. This A 1 ft. by 4 ft. section of sheathing was placed on either side of every specimen to provide an interior edge. To test the individual panels for their uplift capacity using the UF-WRSUT method, the trusses to which the panels are fastened were cut approximately 3 in. above and below each roof sheathing panel to provide bearing area for the test setup (see Figure 3-1 above). To accommodate the extra truss length for adjacent sheathing panel specimens, a minimum 6 in. wide space was placed between the panels. This space was bisected during panel removal. Two 6 in. by 5 ft. strips divided each panel; these strips met at the center truss to leave a seam above each to simulate typical residential staggered sheathing. The 33.5 ft. span of each roof was calculated to fit all full panels and spacing strips. Figure 3-6 shows the three sizes of OSB used to sheath each roof: 4 ft. by 8 ft. test specimens, 6 in. by 5 ft. spacing strips, and 1 ft. by 4 ft. outside sections. A plan and section view is provided.

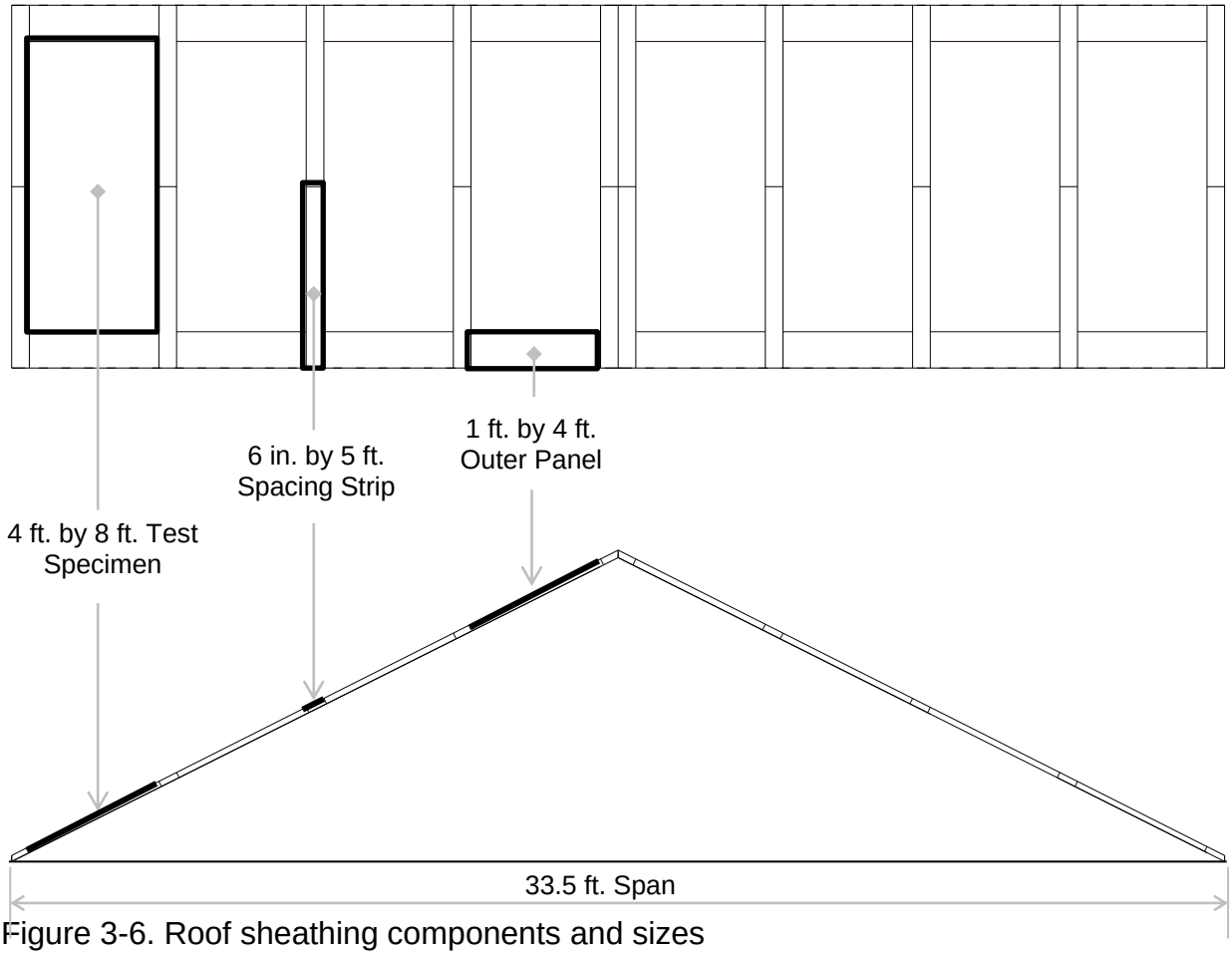


Figure 3-6. Roof sheathing components and sizes

Figure 3-7 (a) shows the roof sheathing installation for Roof 5 in progress. In this picture, the 48 in. by 96 in. sheathing panel specimens and 6 in. spacing strips between the panels have been installed. Gaps are seen where the 1 ft. by 4 ft. outside panels have not yet been placed.15 lb. felt underlayment was installed using tabbed tack nails. 3 in. flashing was installed around the perimeter of the roof surface above the underlayment. Figure 3-7 (b) shows one of the roofs after underlayment and flashing installation.

Gray three-tab shingles were installed above the underlayment using roofing nails. Nominal 1 in. by 6 in. fascia boards were attached at the eaves of the roofs, and gutters were fastened to the fascia. Water from the gutters was directed away from the

structures using a PVC pipe system. Figure 3-8 shows a picture of the five completed attic structures.

A B

Figure 3-7. Surface of Roof 5 during construction A) while sheathing and B) after underlayment and flashing installation

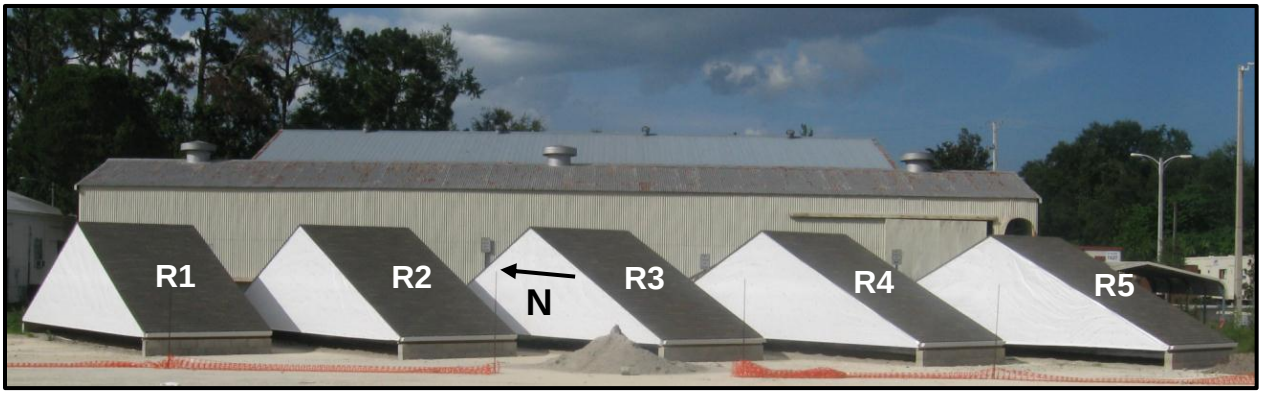


Figure 3-8. Completed full-scale roofs

It should be noted that full-scale roof construction was not entirely representative of actual residential roof construction. In addition to the unique sheathing arrangement (discussed above), the “attic space” of the full-scale structures was not conditioned as would normally be the case in typical unvented attic construction. Finally, 104 leaks with ½ in. diameters and bi-daily rainfall in Gainesville during fall and winter months (discussed later in this chapter) are highly exaggerated leakage or rainfall conditions.

These exaggerated conditions must be considered when interpreting the results presented at the end of this thesis.

ccSPF Installation

ccSPF was installed in the roofs by a professional contractor on July 27th and 28th, 2010. Relevant properties of the foam used are shown below in Table 3-2.

Table 3-2. Applicable properties of ccSPF used in thesis

Property	Unit	Value	Test Method
Density	pcf @ 2 in. lift	2.15	ASTM D 1622
Compressive Strength	psi	22	ASTM D 1621
Tensile Strength	psi	28	ASTM D 1623 Type C
Closed Cell Content	%	>90	ASTM D 6226
Initial R-value	per in.	6.9	ASTM C 518
Aged R-value	per in.	6.1	ASTM C 518
Permeance	perms	1.82	ASTM E 96
Air Permeance	L/s/m^2	0.00025	ASTM E 2178-01

As described earlier, two retrofits were chosen for the roofs. The first retrofit, sprayed in Roofs 2 and 3, was comprised of a minimum 3 in. fillet between truss members and roof sheathing as well as a minimum 1 in. layer applied to the sheathing between the fillets. This was called a Level II retrofit in this thesis. The second retrofit, sprayed in Roofs 4 and 5, was a minimum 3 in. layer applied to the sheathing between the truss members. This was called a Level III retrofit in this thesis. During ccSPF installation, foam depths were routinely checked by installers using a small knife or rod with appropriate depths marked. Resultant holes from taking measurements were sprayed with a small layer of foam. Despite these checks, the retrofits were sprayed to

thicker depths than specified; this is discussed later in the results section. Figure 3-9 shows ccSPF installation in progress.

A

B

Figure 3-9. ccSPF installation in A) roofs and B) laboratory-built panels

Wetting Regimen

On August 13th, 2010, 1/4 in. diameter holes were cut through the shingles and underlayment of the three leaking roofs (Roofs 1, 2, and 4) to allow water into the roof cross-section. The holes were expanded to ½ in. diameters on September 10th, 2010 to allow more water into the roof enclosure. The holes were located above and between every truss at the center of every 6 in. spacing strip between roof sheathing specimens, resulting in 13 leaks upslope of each sheathing panel specimen and a total of 104 leaks per roof. Leak locations are indicated in Figure 3-10.

All roofs were exposed to natural and simulated rainfall. Simulated rainfall commenced on September 29th, 2010. Six sprinklers with 10 ft. semicircular spraying radii were attached at gable ends. Sprinkler nozzles were arranged to provide maximum water coverage; the theoretical coverage is shown on the right side of Figure 3-10. A 250-gallon tank and ½-horsepower pump supplied water to the roofs as shown in Figure 3-11.

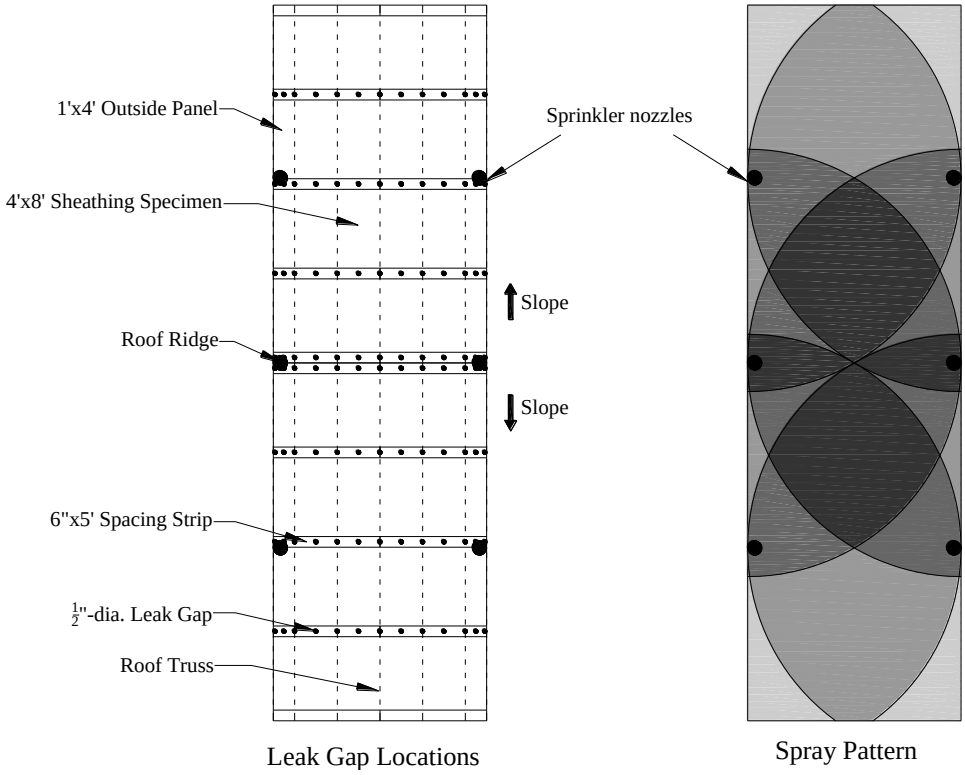


Figure 3-10. Location of leak gaps and sprinkler nozzles on the roofs and spray pattern

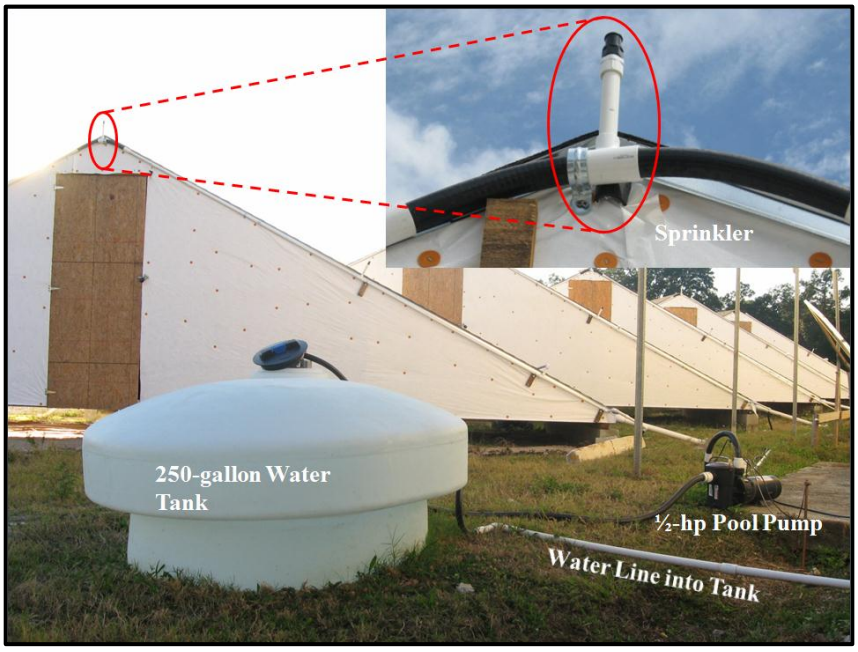


Figure 3-11. Installed sprinkler system and water supply.

Simulated wetting was applied to every roof for 15 min. bi-daily until the conclusion of the weathering period (approximately 20 additional water cycles were sprayed in late

December demonstration or measuring purposes). An average simulated rainfall height of 0.24 in. over the 15 min. of wetting was measured using an electronic rain gauge. A timeline showing relevant events after foam installation is provided in Figure 3-12. All rainfall during the exposure period recorded at the nearby Gainesville Regional Airport is provided in Appendix B.

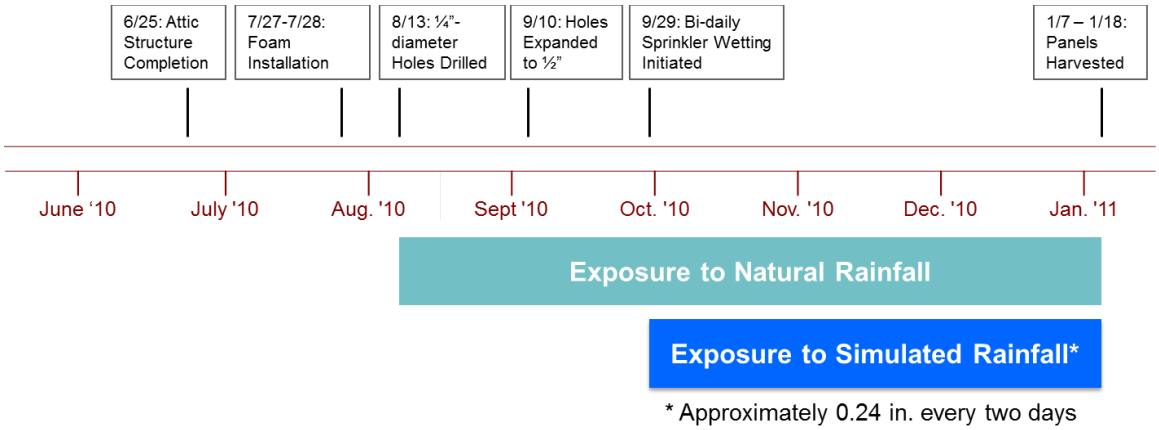


Figure 3-12. Full-scale weathering timeline

Instrumentation

Instrumentation monitoring moisture content, temperature and relative humidity in the roofs was installed. This instrumentation, purchased from Structure Monitoring Technology (SMT) Ltd., consisted of Point Moisture Measurement Sensors (PMM), Moisture Detection Sensors (MDS) and relative humidity/temperature sensors. The devices were interfaced with a Building Intelligence Gateway (BiG) laptop via Industrial Wireless Data Acquisition nodes (WiDAQ). Proprietary software developed by SMT collected and converted signals wirelessly from the sensors and stored the data in an internet-accessible database.

PMM sensors recorded moisture contents of wood members. PMM sensors were installed within the top chord of trusses as shown in Figure 3-13. 14 PMM sensors were

distributed across each roof, with one recording temperature; adjustments for the moisture contents recorded by all PMMs were made using this reading.

Moisture Detection Strips (MDS) recorded a “wetness level” (not to be confused with moisture content) of the underside of roof sheathing. MDS sensors consisted of two parallel copper wires between which resistance was measured. In the presence of water, this resistance decreases proportionally to the amount of moisture. MDS sensors were installed by taping the strips to the underside of the roof sheathing with the copper wire contacting the roof sheathing. In retrofitted roofs, foam was installed over the MDS sensors. 45 Moisture Detection Strip (MDS) sensors were installed in total.

A B

Figure 3-13. Moisture sensors used. A) Point Moisture Measurement (PMM). B) Moisture Detection Sensors (MDS).

Temperature/relative humidity probes monitored ambient temperature and relative humidity in the unconditioned attic space. These were installed approximately 1 ft. below the center of the ridgeline in each attic. The locations of all SMT sensors are displayed below in Figure 3-14.

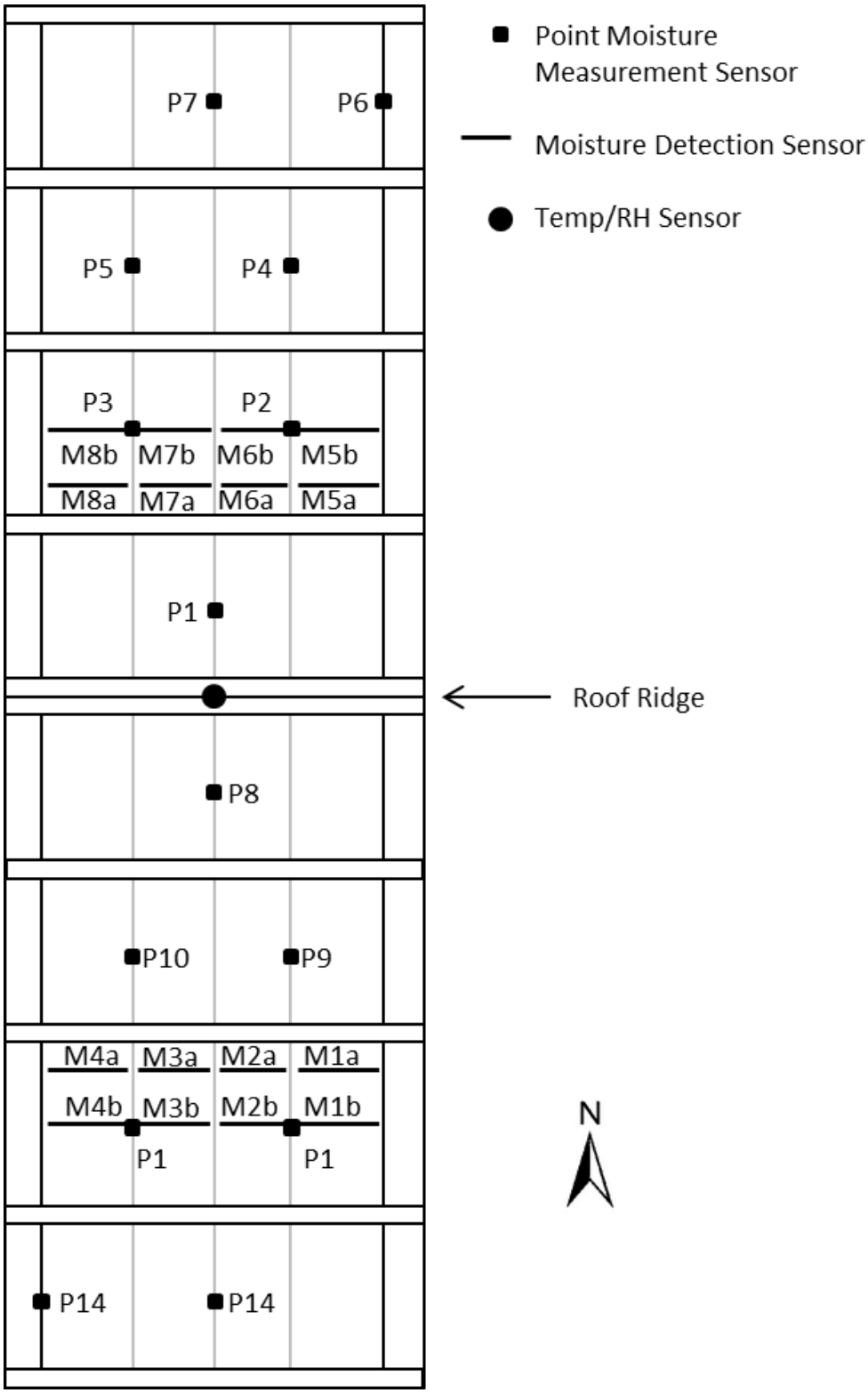
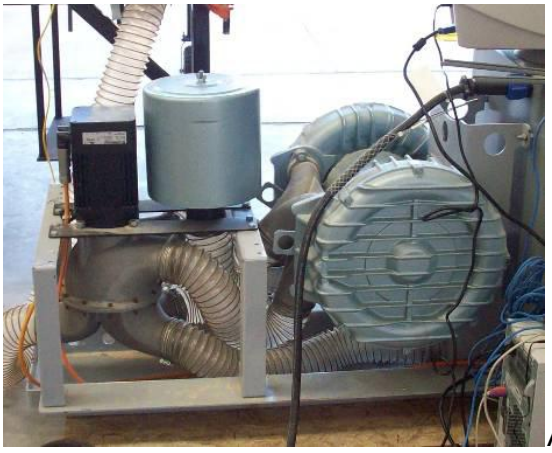


Figure 3-14. Plan-view locations of instrumentation in roofs

Panel Harvesting and Testing

At the conclusion of the 150-day weathering period, panels were removed, or "harvested" using circular handsaws. Panels were tested for their individual wind uplift capacity following the UF-WRSUT protocol described at the end of this chapter. Wind uplift tests were carried out in a 6 in. deep by 4.5 ft. by 8.5 ft. steel chamber connected to a Pressure Loading Actuator (PLA). Panels were tested by placing them upside-down in the chamber. The PLA and chamber setup are shown in Figure 3-15. Truss members extending beyond the 4 ft. panel width rested on the edge of the chamber; some were clamped to the edge of the pressure chamber (such panels are indicated in Appendices C and F). To seal the chamber from air leakage, 4-mil plastic sheeting was placed around the specimen and duct taped to the side of the pressure chamber.


A

B

Figure 3-15. Full-scale test setup. A) PLA B) Panel loaded upside-down in pressure chamber.

Suction pressure was generated in the chamber using the PLA system (Kemp 2008), which uses a 15-horsepower blower, a five-port flow-reversing valve, and real-time feedback from a pressure transducer to accurately produce pressures that follow numeric pressure traces. The loading scheme applied pressure in 15 psf increments lasting for 10 sec. with a 5 sec. ramp transitioning between increments. Loading of

specimens continued to failure, which was defined as the point at which the panel visibly deflected and a high drop in pressure was recorded in the pressure chamber. The loading protocol is shown in Figure 3-16.

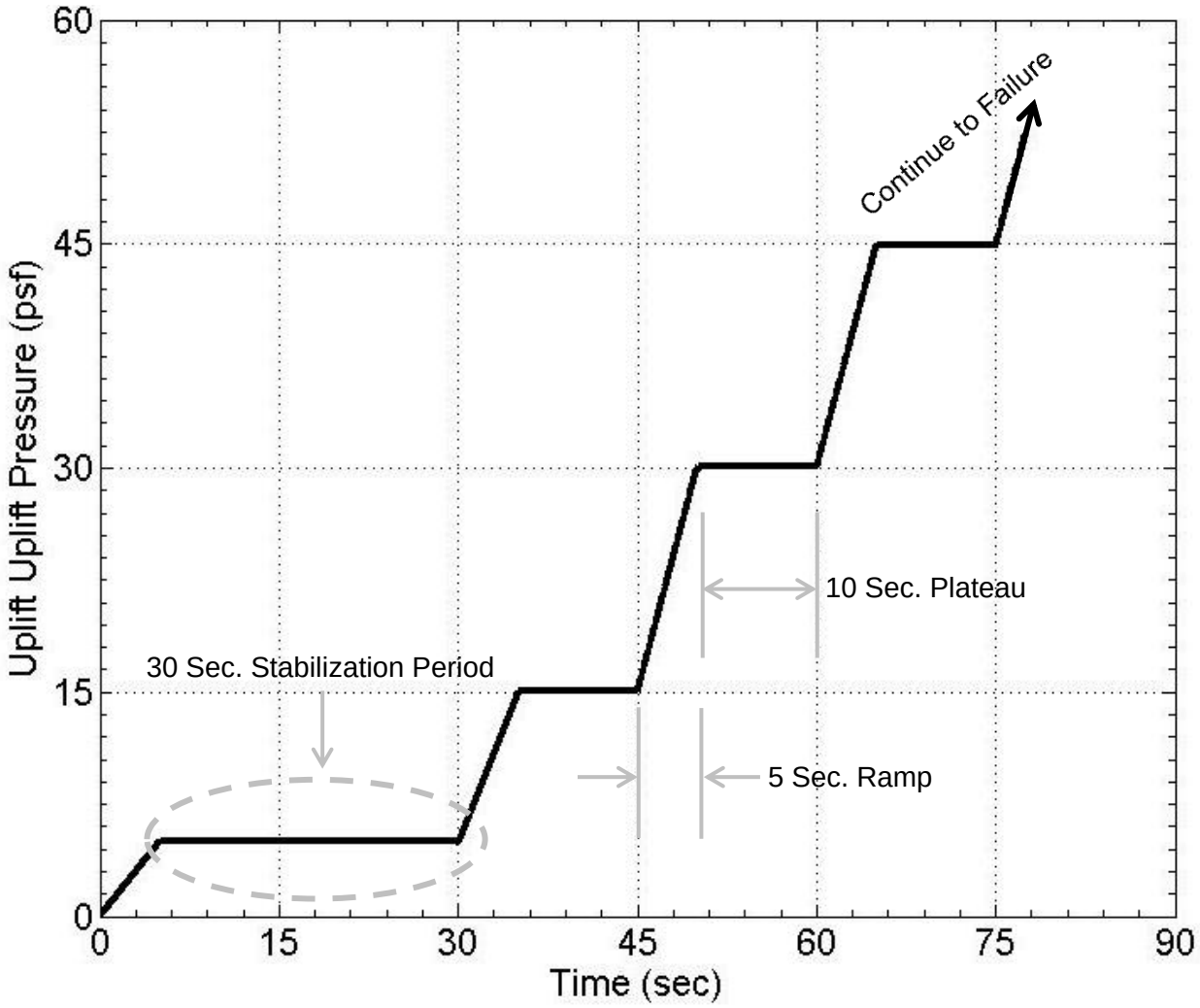


Figure 3-16. Full-scale pressure loading protocol

Displacement in the middle of each sheathing panel specimen was recorded using a string potentiometer. The potentiometer was attached to a screw drilled into the sheathing next to the center truss member. A second pressure transducer was used to match with the time step of the potentiometer to develop pressure-displacement relationships during panel testing. The locations of the potentiometer and the pressure transducer are shown in Figure 3-17.

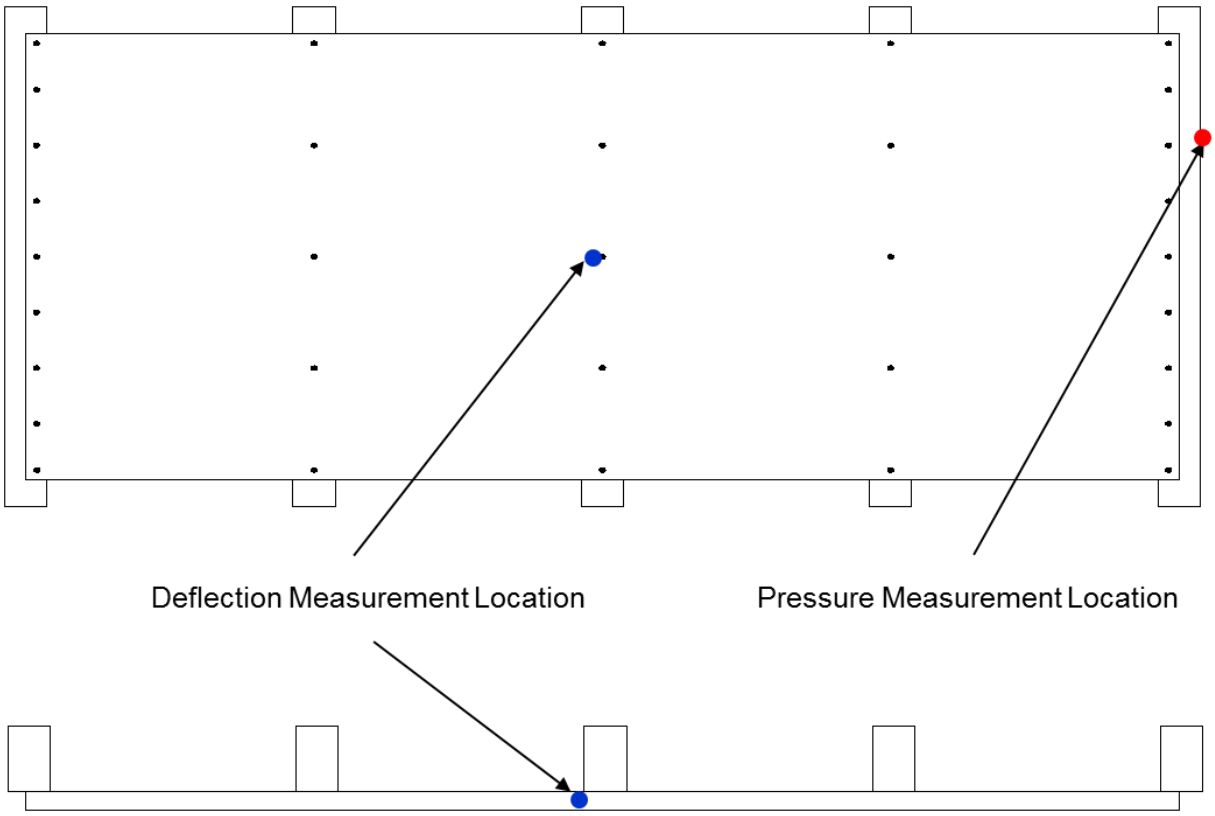


Figure 3-17. String potentiometer and pressure transducer locations

Immediately after wind uplift testing of sheathing panel specimens, 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. ASTM D 4442 specifies that 1 in. specimens should be extracted 18 in. from the edge to minimize drying effects; however, because the roof framing members often fractured near their midspans during wind uplift testing, the framing member cross-section was often compromised. For this reason, samples were taken from the framing members directly below the downslope edge of the sheathing panel specimens. Also after testing, the depth of the foam retrofit was taken in several locations on each panel.

Small Specimen Tests of ccSPF-to-Wood Bond

Test Design

To determine the effects of water on the adhesive strength and durability of ccSPF installed on wood, a total of 131 laboratory test specimens were fabricated. Each specimen was comprised of a 3 in. by 5 in. sample of roof sheathing, a nominal 3 in. wide by 3 in. long by 2.25 in. deep section of foam, and a 3 in. by 5 in. section of OSB. The adhesive strength of ccSPF on three types of sheathing faces was tested: ½ in. plywood, 7/16 in. OSB with foam sprayed on smooth, labeled side, 7/16 in. OSB with foam sprayed on textured side.

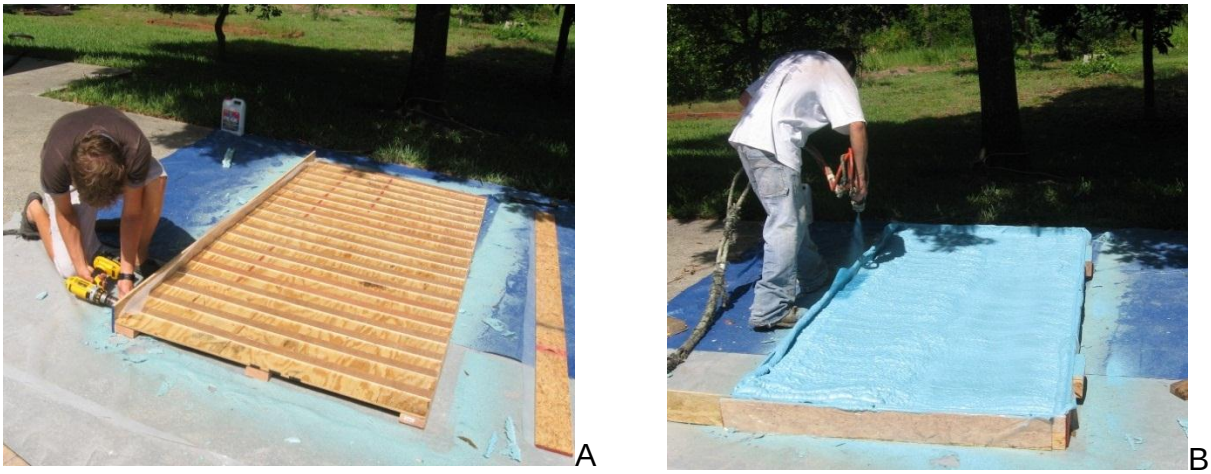
Test specimens of each sheathing face type were exposed to wetting for periods of 1, 2, 4, 8, 12, and 16 weeks, while another 12 specimens of each type were left unexposed to wetting cycles to serve as controls. During each period of testing, five test specimens (wetted) and two control specimens (unwetted) of each sheathing type were tested for the adhesive strength at the interface of foam and sheathing under tensile loading using a modified ASTM D-1623 test method.

Specimen Preparation

To build specimens, 4 ft. by 8 ft. roof sheathing panels were laid flat on the ground. Wooden strips 1/8 in. thick and 2 in. wide were stapled parallel to the 4 ft. dimension of the sheathing at 5 in. on center; these strips were used to space the flanges of the test specimens. Wood blocking was laid around the perimeter of the panels to both serve as a foam height reference and to contain the foam spray. 3 in. of foam was sprayed across the panel area; the application of foam is provided in Figure 3-18.

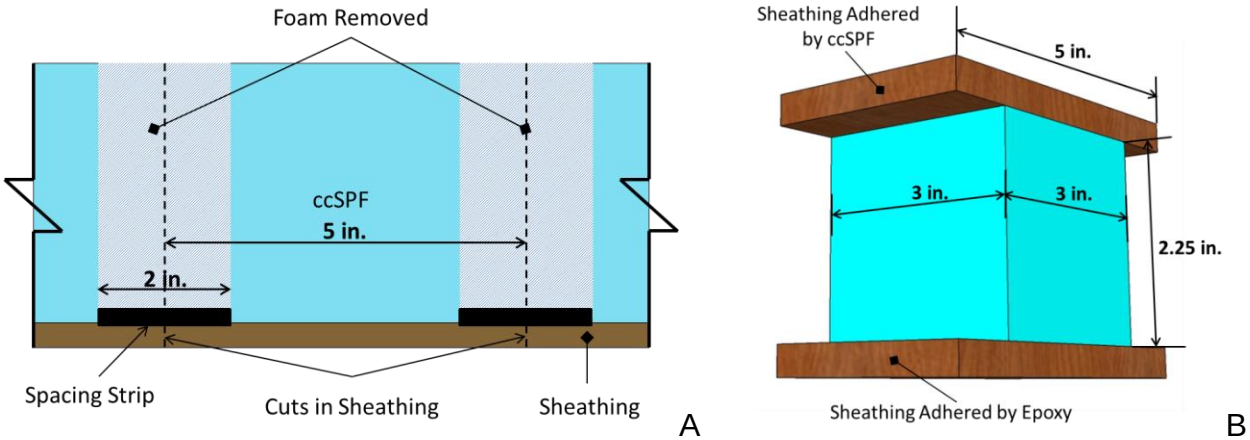
After ccSPF application, 2 in. spacing strips were bisected as shown in Figure 3-19. Any foam above the 2 in. strips was removed. These 4 ft. long sections were

divided into 3 in. segments, resulting in a 3 in. by 5 in. sheathing are. The foam was cut flat with a bandsaw to a 2.25 in. An identical OSB section was glued to the flat foam surface using a general-purpose bisphenol A and epichlorohydrin liquid epoxy resin. The epoxy was mixed with a hardener at a weight ratio of 3:1. The mixture was degassed by vacuum and applied. The adhesive was allowed to cure at room temperature for 24 hours. A dimensioned rendering of a small specimen is shown in Figure 3-19(b).



A B

Figure 3-18. Spraying ccSPF for small specimen samples. A) Preparation. B) Installation of foam on sheathing.



A B

Figure 3-19. Small specimen dimensions. A) Cross-section of cuts from sprayed panels. B) Complete small specimen.

Wetting Regimen

The test specimens were subjected to 4 min. of daily wetting in an indoor chamber split into two 2 min. periods at 12 hr. intervals. Figure 3-20 shows samples inside of the wetting chamber. The relative humidity within the chamber remained above 95% and room temperature was maintained throughout the experiment. Control samples were conditioned at room temperature and relative humidity.

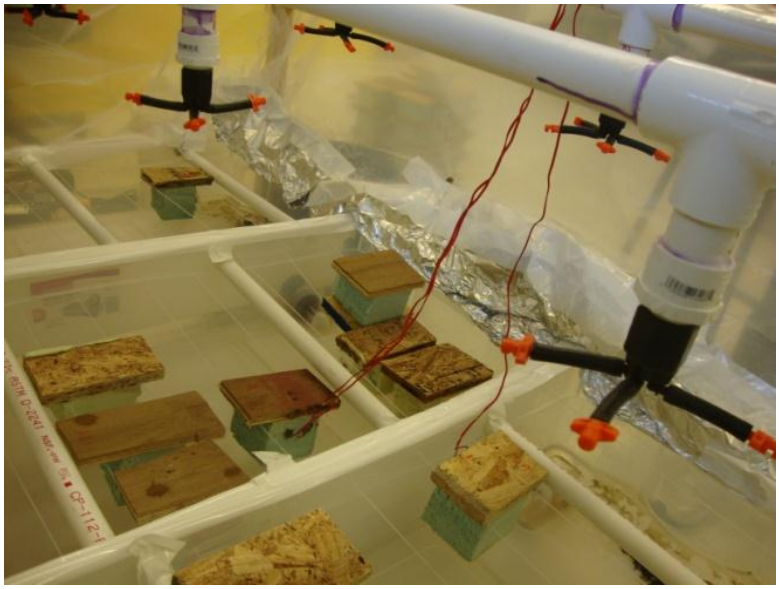
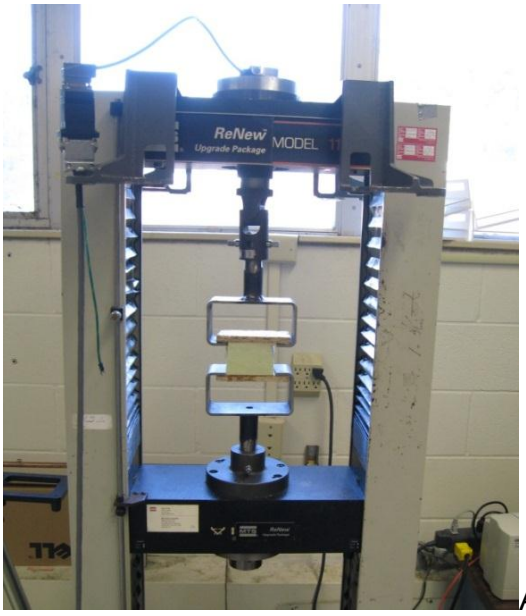


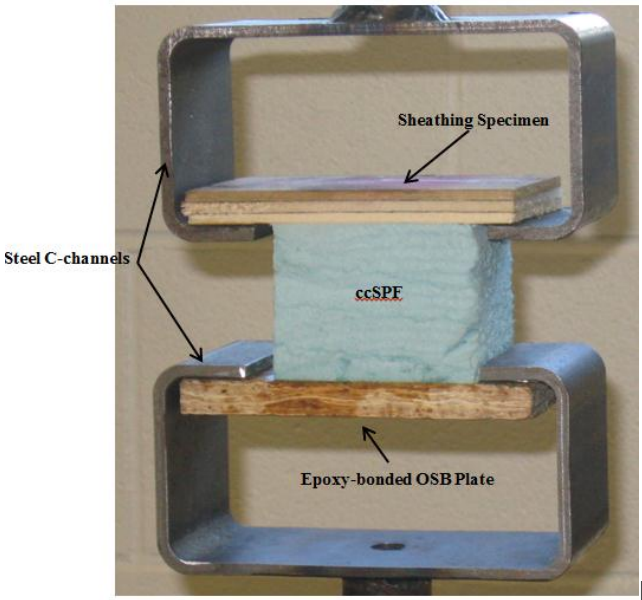
Figure 3-20. Laboratory test samples inside the wetting chamber

Test Procedure

At the culmination of each exposure period, tensile tests using a modified ASTM D1623 Method C were conducted on all of the small specimens. To perform the test, specimens were pulled by an Instron UTM machine (Model 1122) at 0.115 in./min. The method was modified by placing two C-channel sections around wood flanges (as shown in Figure 3-21) rather than adhering grips directly to the top and bottom surfaces of samples. An in-line load cell monitored recorded the tensile forces exerted on the test specimens.



A



B

Figure 3-21. Small specimen test setup. A) Full test setup. B) Close-up of sample.

Referenced Test Methods

Full-Scale Wind Uplift of Roof Sheathing Panels – UF-WRSUT

The wind uplift capacity of wood roof sheathing panels in the full-scale experimental study was determined in accordance with the University of Florida Wood Roof Sheathing Uplift Test (UF-WRSUT) outlined in Datin et al. (2010). The UF-WRSUT method utilizes a “step and hold” pressure loading approach based on ASTM E330 Method B (ASTM 2004). To adapt this test method to sheathing panels that have been extracted from roofs, individual panel specimens are placed upside-down (compared to their in-service condition) with framing members bearing on the edges of a 4 ft. by 8 ft. by 6 in. deep pressure chamber. Plastic sheeting is wrapped completely around the sheathing panel specimen and fastened to the outside of the pressure chamber to minimize air leakage.

As illustrated earlier in Figure 3-16 on page 66, air is drawn from the chamber in to produce 15 psf pressure steps held for ten-second periods and increased until panel

failure, defined as the point at which separation of sheathing from framing members, fracture in either member, or nail failure occurred. The UF-WRSUT method requires that the following information be reported: time between panel fabrication and testing, rate of loading, chamber dimensions, specific gravity and moisture content of wood framing members, and nail geometry.

For reference purposes, the modifications to ASTM E330, as written in Datin et al. (2010), are as follows:

- Allow a minimum curing period of 7-14 days between fabrication and testing of the roof panels (accounting for potential wood fiber relaxation and adhesive cure time).
- Eliminate the 50% pre-load step in Procedure B and the 1-5 min. recovery period for stabilization,
- Apply pressure in one direction only, i.e., suction (reduced chamber pressure) or pressure (increased chamber pressure), but not both,
- Step the test chamber pressure in 0.72 kPa (15 psf) increments and hold for 10 seconds, repeat until failure,
- Eliminate deflection readings to observe permanent deformation of the panels, and
- Eliminate the 1-5 min. recovery period for stabilization after testing (which was needed to allow seals to recover shape)

Tensile Testing of Small Specimens – ASTM D1623 Type C

Laboratory experiments testing the tensile strength of the ccSPF-sheathing bond over time and subjected to wetting was performed using a modified ASTM D 1623 Method C test (ASTM 2003). The scope of this test is to determine the adhesive properties under tensile loading of a cellular plastic (e.g., ccSPF) bonded to a substrate material (e.g., wood sheathing) under controlled temperature, humidity, and crosshead rate.

The testing apparatus for Type C specimens consists of a machine that provides a constant crosshead speed, grips specific to the type of specimen, a load indicator with precision to ± 1%, and an extension indicator (if desired).Type C specimens are to be square or rectangular with a minimum length and width greater than or equal to the thickness of the specimen; no other dimension requirements are given. Bonding method of grips is left to the discretion of the tester.

For at least 24 hours prior to testing, the specimen shall be conditioned at 23 ± 2 degrees Celsius and 50 ± 5% relative humidity. At least three specimens must be tested. If an obvious flaw that affects the performance of the tensile strength is detected, that specimen is to be discarded. Failure should occur between 3 and 6 min. The suggested crosshead speed is 1.3 mm/min./in. depth of the test specimen.

To perform the test, cross-sectional dimensions are measured at multiple points. A load indicator is calibrated and the specimen is placed into a grip assembly. The load is applied at a constant crosshead speed and the load at moment of failure is recorded.

Tensile strength is found by dividing load by cross-sectional area. Elongation may be calculated by taking the extension at moment of failure divided by the original distance between gage marks. The following information should be reported:

- ID of material tested (type, source, code numbers, form, principal dimensions, history, etc.)
- type of specimen (A, B, or C)
- conditioning procedure
- atmospheric conditions
- number of specimens tested
- crosshead rate
- tensile strength of each specimen, average, standard deviation
- percent elongation
- date

Moisture Content of Wood Members – ASTM D 4442 Method B

ASTM D 4442 Method B (ASTM 2006c) was used to determine the moisture content of solid wood, plywood, and OSB samples. Moisture content is defined as the mass of water contained in a material as a proportion of the dry mass of that material. Measurements of wood roof sheathing were taken for both full-scale and small specimen experiments and framing members in the full-scale experiments.

This method requires that samples be oven-dried to remove moisture from a specimen. Wood samples are prepared according to ASTM Guide D 4933 (ASTM 2006b). Samples are weighed with a balance sensitive to 0.1% of the estimated oven-dry mass of the specimen and placed in an oven at 103 ± 2 degrees Celsius. While drying, intermediate mass measurements are recorded after minimum four-hour intervals until no noticeable change in weight is measured. It is stated that a nominal 2 in. by 4 in. by 1 in. solid wood specimen will have an approximately 24-hour drying time. Dry samples are weighed as early as possible after removal from the oven to minimize the amount of water taken in from ambient air.

The moisture content is calculated as follows:

$$MC\ (\%) = \frac{A - B}{B} * 100 \qquad \text{Equation 13}$$

In this equation, MC is the moisture content of the specimen expressed as a percentage. A is the original mass that correlates to the moisture content reading and B is the oven-dry mass of the specimen. The method accounts for the weight of non-volatile chemicals in the wood if desired. Individual moisture content values must be given to the nearest integer percentage value for Method B. The following information is

to be reported, mean, standard deviation, number of specimens, and any deviation from the method.

Specific Gravity of Wood Members – ASTM D 2395 Method A

Specific gravities of roof framing member samples were determined per ASTM D 2395 Method A (ASTM 2006a). In this method, the sample is a 1 in. thick cross-section in solid lumber and a 3 in. by 6 in. sample in sheet materials. In full-scale testing, the 1 in. samples taken for moisture content measurements were also used for specific gravity. To avoid edge drying effects, the method states that samples are to be cut 18 in. from the free end of the member. However, because framing members in full-scale roof sheathing specimens often fractured in this location, the 1 in. specimen was cut 3 in. from the edge.

Initial weight/mass of the specimen is taken for moisture content calculations that follow ASTM D 4442 (ASTM 2006c), To bring the specimen to its dry weight, it is placed in an oven at 103 ± 2 degrees Celsius (the same as for ASTM D 4442). The standard states that 48 hours in the oven will be enough for a 1 in. cross-sectional sample to reach constant mass. When oven-drying is complete, the specific gravity is calculated as follows:

$$SG = K * \frac{W}{1 + \left(\frac{M}{100}\right)} * L * w * t \qquad \text{Equation 14}$$

W is the weight of the specimen, M is the moisture content of the sample as a percentage. The quantity $\frac{W}{1+\left(\frac{M}{100}\right)}$ is the calculated oven-dry weight of the specimen. K is a conversion factor based on weight in grams and volume in cubic centimeters; for weight in grams and volume in cubic inches, K is equal to 0.061.

Reported information should represent the material as well as possible. The following should be given the method for obtaining samples, the procedure for finding specific gravity, and conditions for determining weight and volume measurements

CHAPTER 4
RESULTS FOR WIND UPLIFT TESTING OF FULL-SCALE ROOF SHEATHING PANELS

Introduction to Full-Scale Results

48 full-scale roof sheathing specimens were constructed at the University of Florida's Eastside Campus to study the effect of in-service water leakage on their structural and moisture characteristics. Of these specimens, 40 were constructed in five full-scale roofs, every roof containing eight panels. Every roof was given a different combination of retrofit type and wetting condition as shown in Table 3-1 on Page 50. Four panels of each retrofit were fabricated and stored in an unconditioned laboratory building located at the Eastside Campus.

Each roof exposed to leakage contained 104 half-inch diameter circular holes cut throughout the asphalt shingles and felt underlayment. Wetting of all roofs, with and without leakage, entailed allowing natural rain to fall while spraying water with the sprinkler system for 15 min. every two days. All five roofs were exposed to the natural and simulated rainfall for 150 days. At the end of the weathering period, panels removed from the roofs and tested individually for their wind uplift pressure capacity and the moisture content of their framing members.

In-Service Instrumentation Measurements

In-service temperature, humidity, truss moisture content, and sheathing moisture level (note that these do not translate to an actual moisture content value) measurements were taken during the weathering period from early August 2010 to early January 2011. Figure 4-1 through Figure 4-12 provide time-histories of maximum daily values of each sensor in the full-scale roofs. Figure 3-14 on Page 64 shows the locations of sensors referenced in the following graphs.

Figure 4-1. Maximum daily internal temperature in full-scale roofs

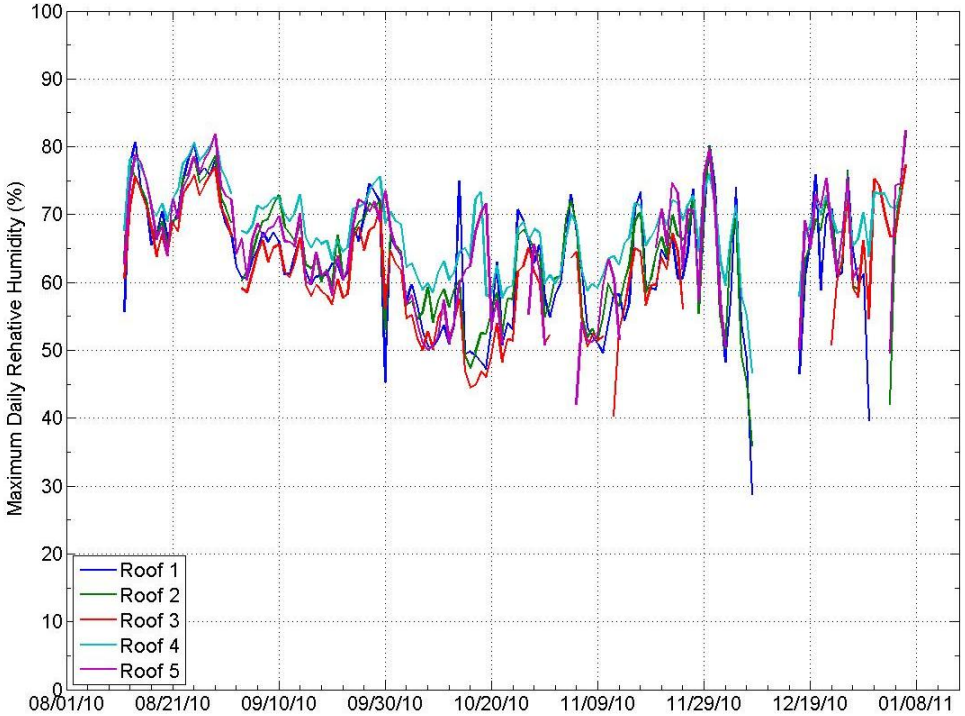


Figure 4-2. Maximum daily internal relative humidity in full-scale roofs

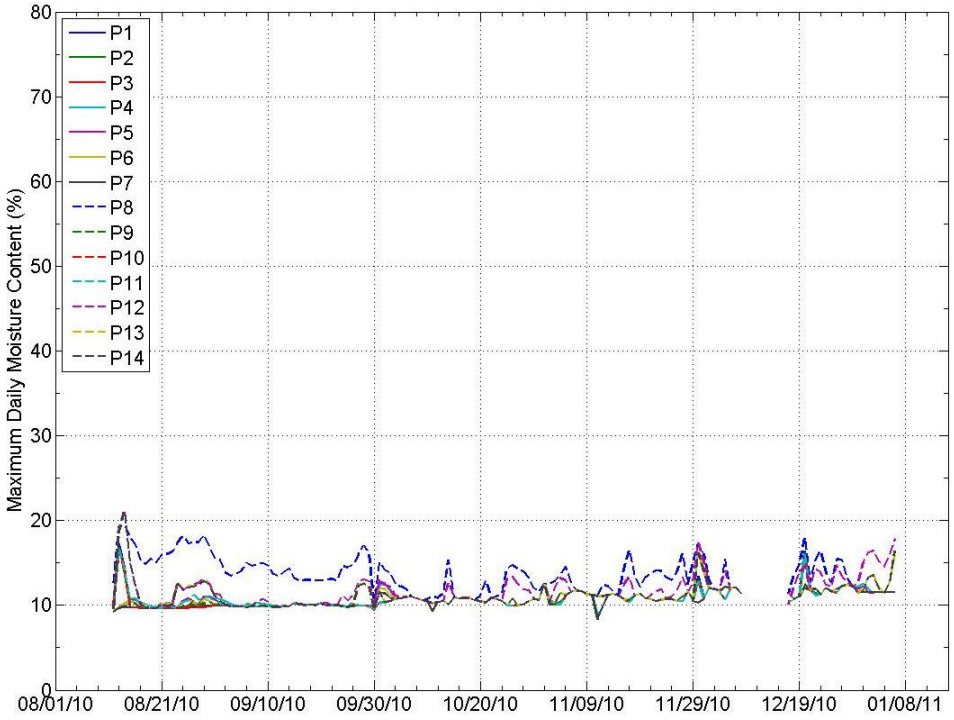


Figure 4-3. Roof 1 maximum daily truss moisture content readings

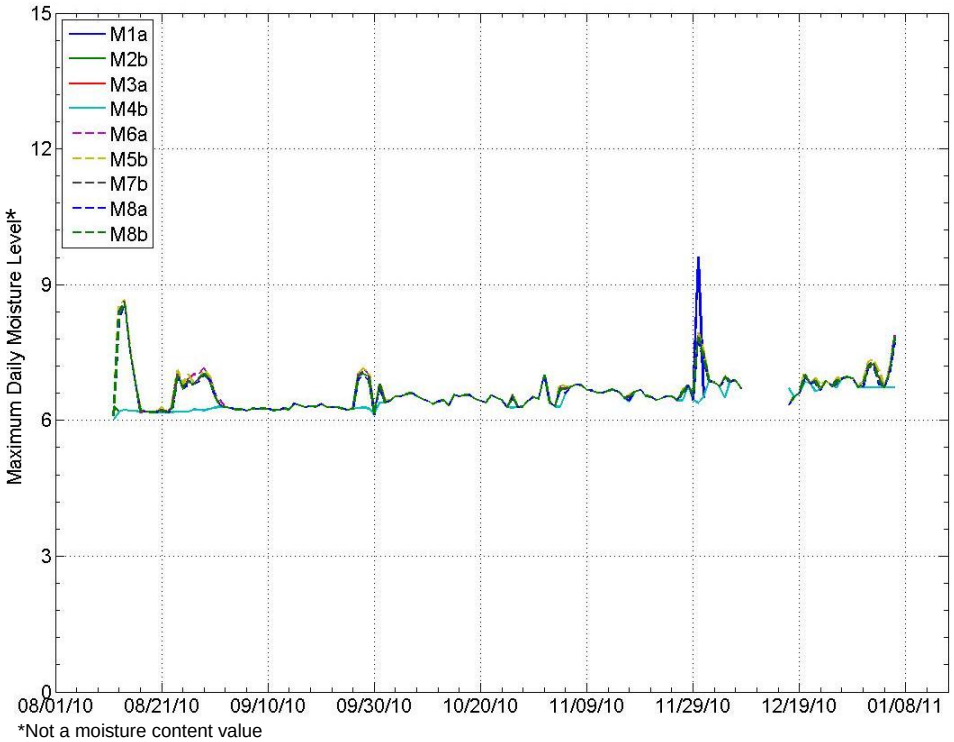


Figure 4-4. Roof 1 maximum daily moisture level readings below sheathing

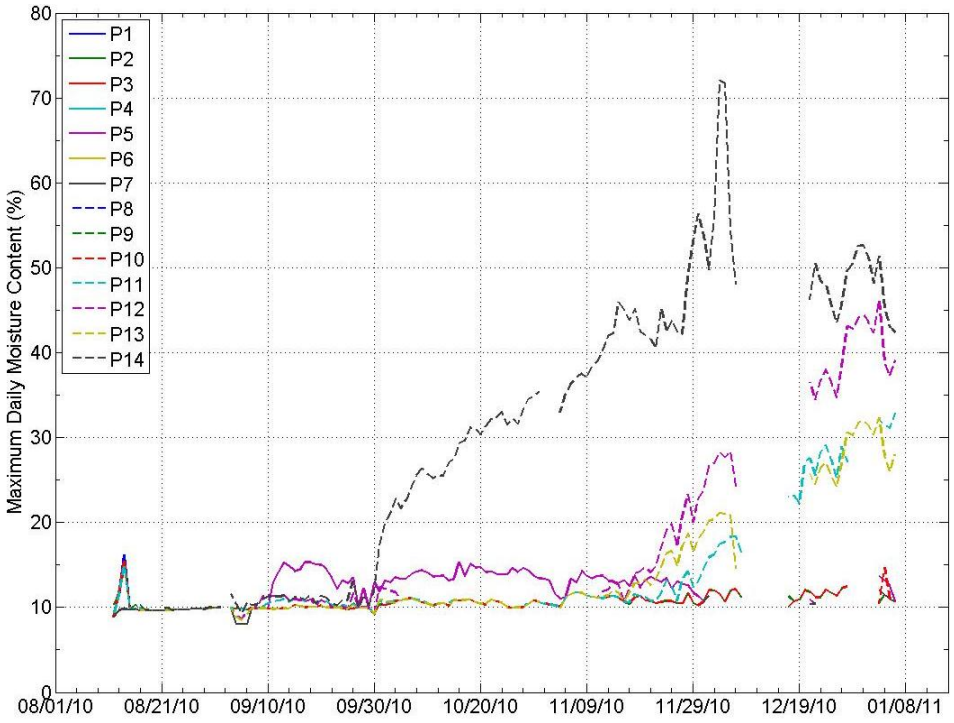


Figure 4-5. Roof 2 maximum daily truss moisture content readings

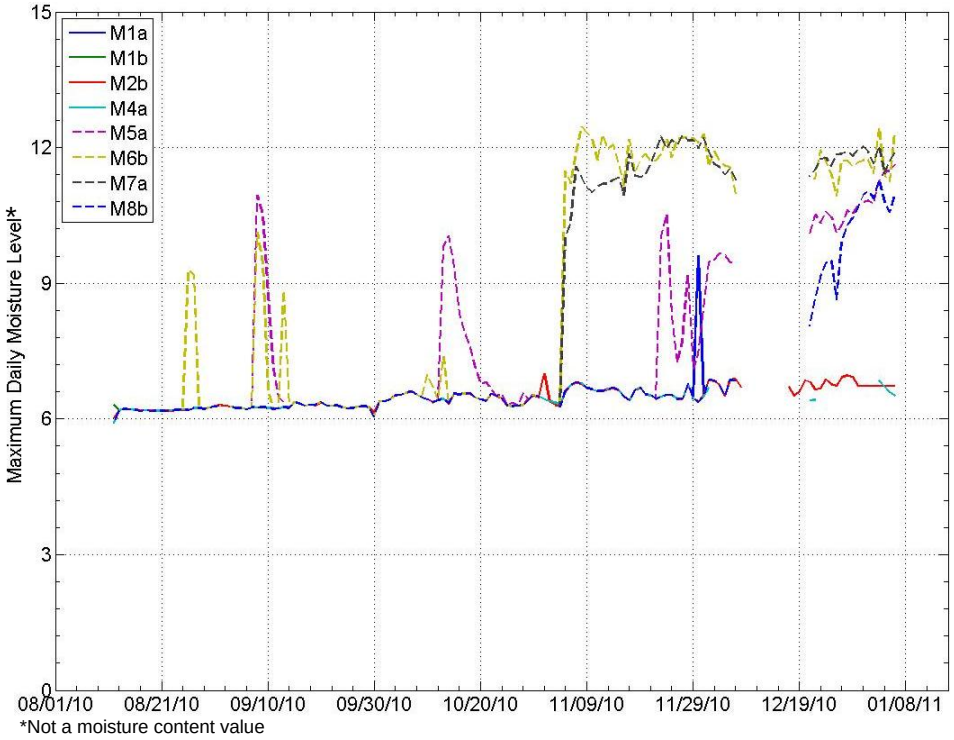


Figure 4-6. Roof 2 maximum daily moisture level readings below sheathing

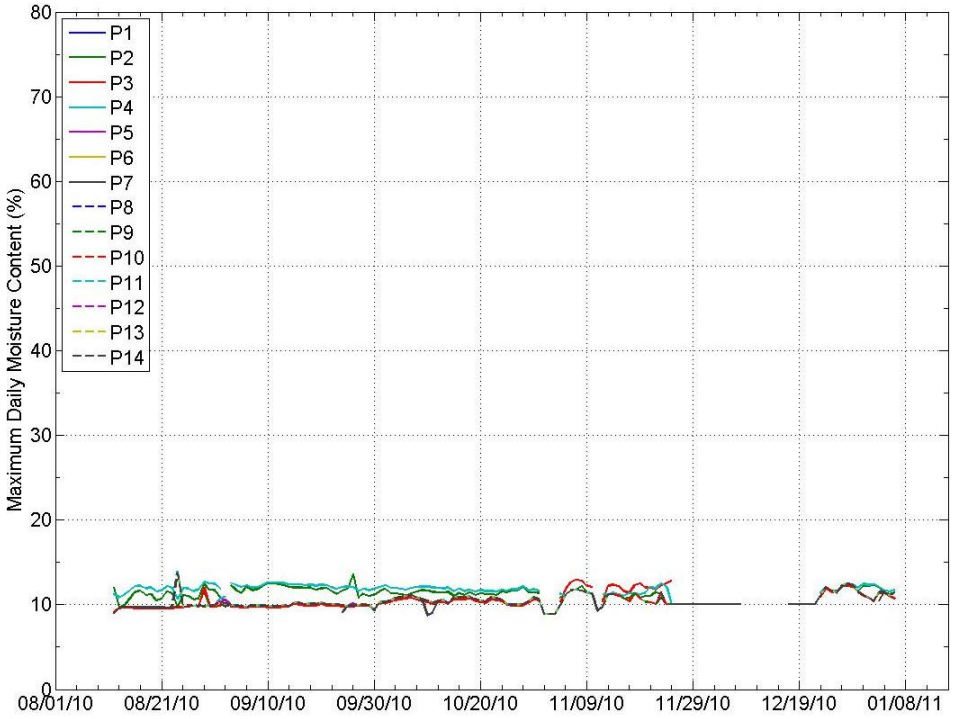


Figure 4-7. Roof 3 maximum daily truss moisture content readings

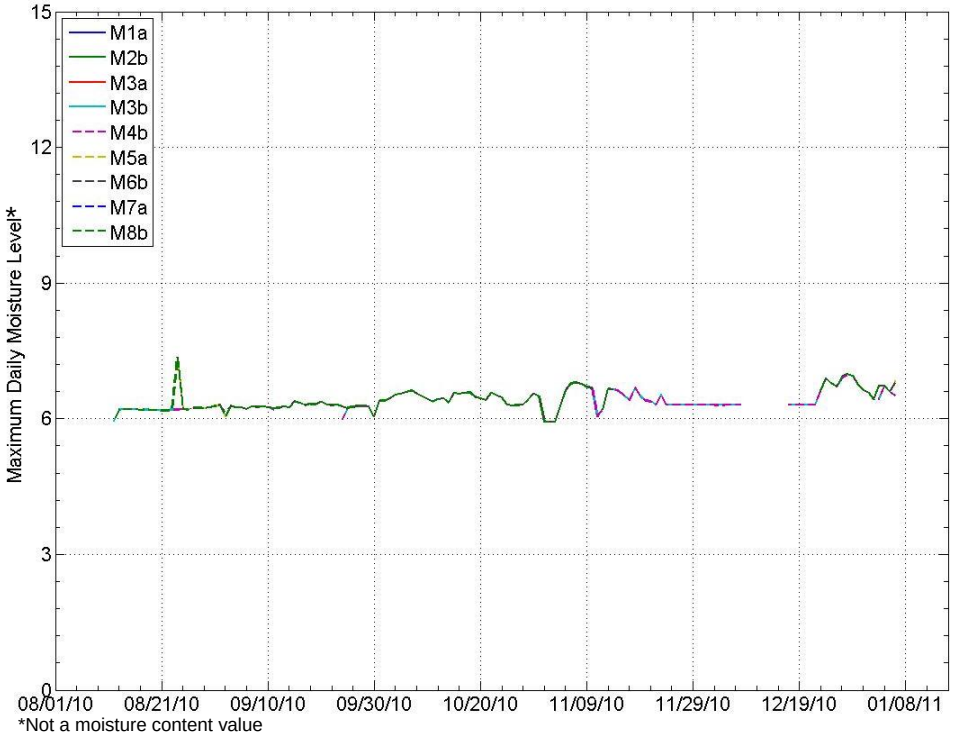


Figure 4-8. Roof 3 maximum daily moisture level readings under sheathing

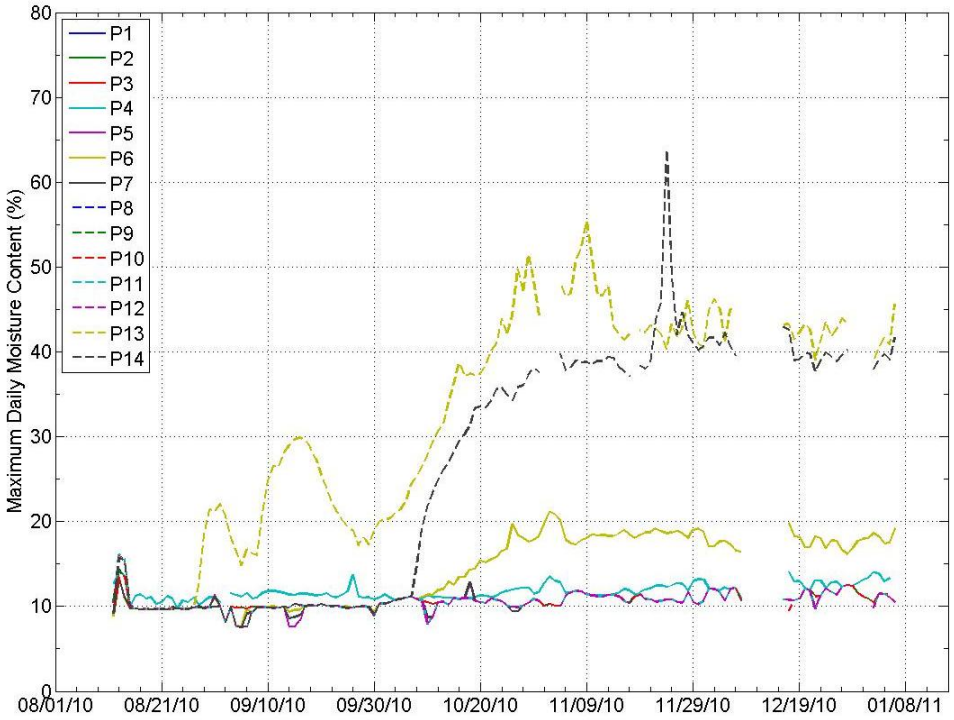


Figure 4-9. Roof 4 maximum daily truss moisture content readings

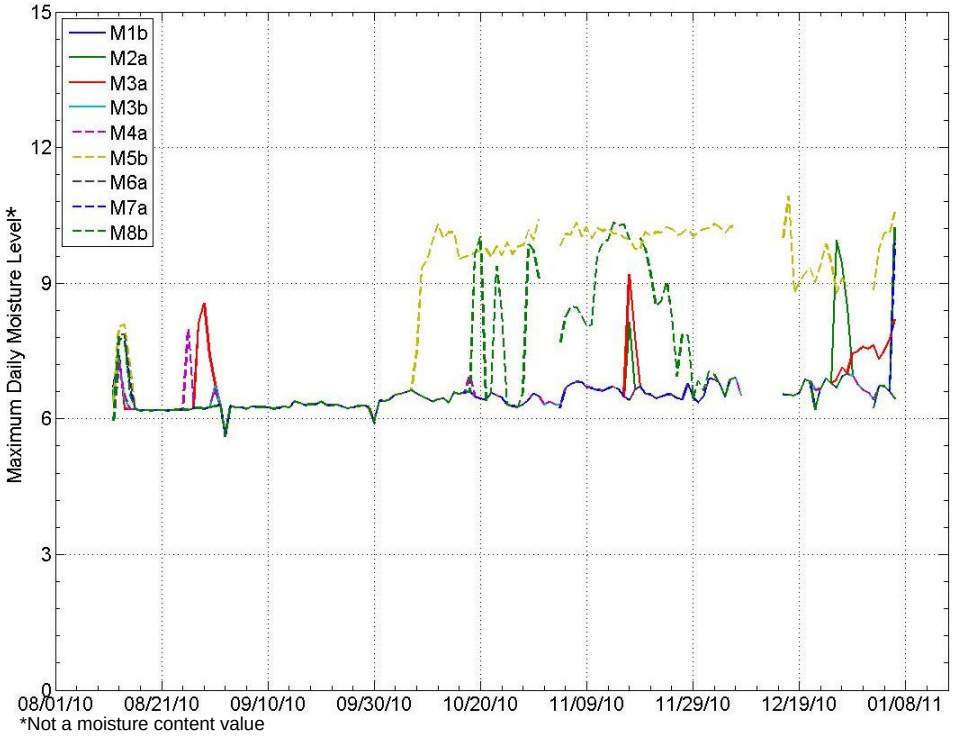


Figure 4-10. Roof 4 maximum daily moisture level readings under sheathing

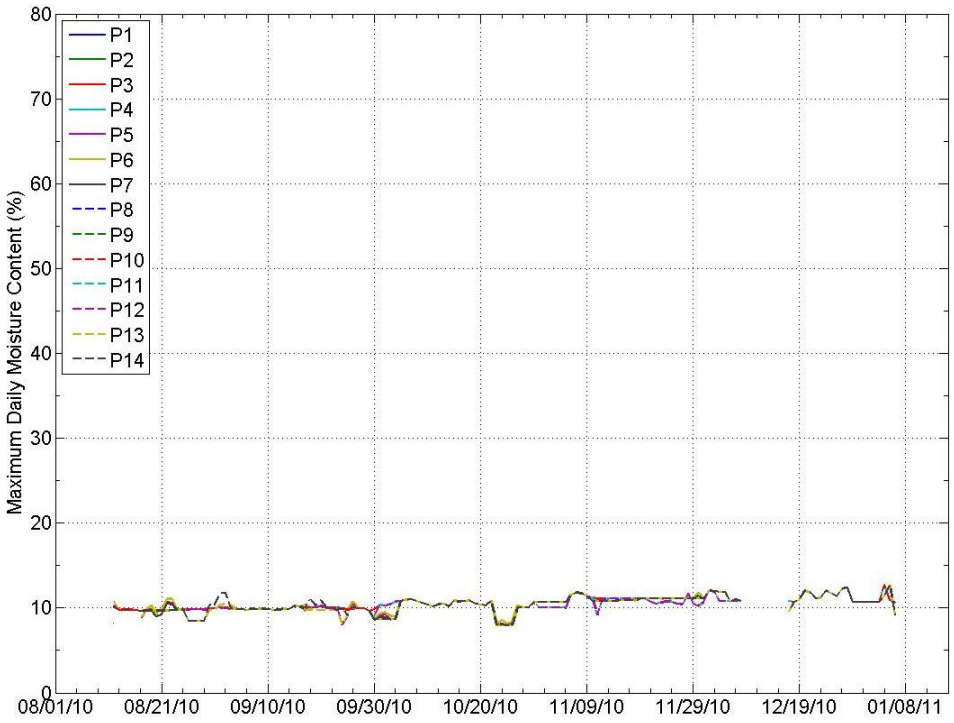


Figure 4-11. Roof 5 maximum daily truss moisture content readings

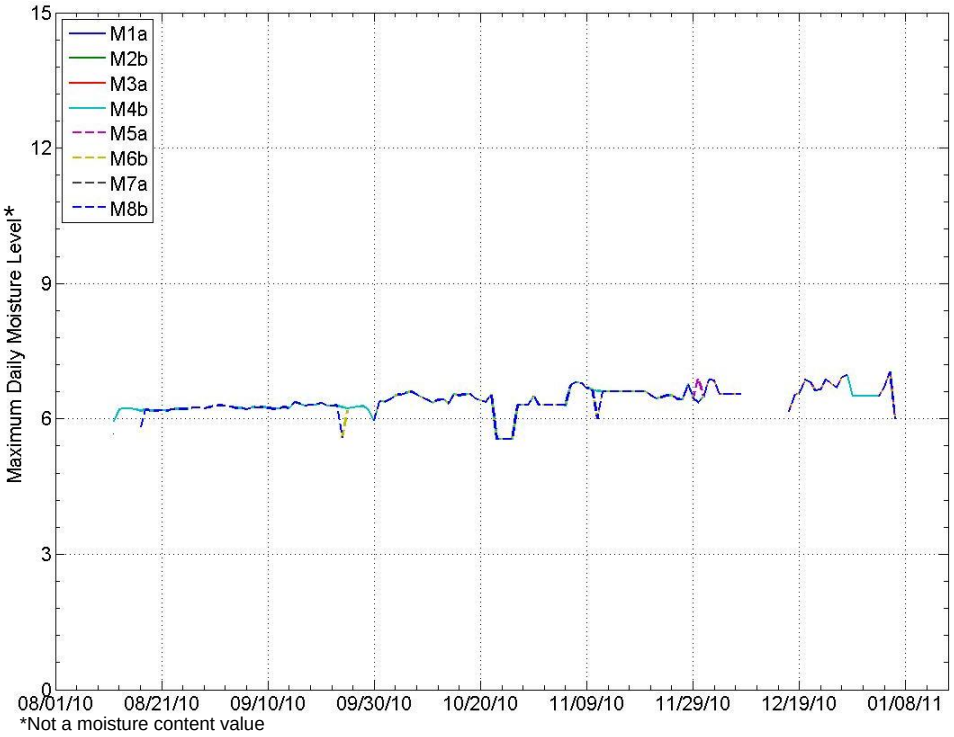


Figure 4-12. Roof 5 maximum daily moisture level readings under sheathing

The maximum temperature in all of the roofs declined throughout the weathering period. The attic space in Roof 1 was consistently hotter than the ccSPF-retrofitted roofs. In general, the relative humidity of the attic space of all five roofs was similar. Truss moisture contents in Roofs 2 and 4 (the leaking ccSPF-retrofitted roofs) steadily increased throughout the weathering period, especially toward the eaves of the south faces of the roofs. Moisture content values as high as 72% were recorded in Roof 2. Moisture contents in Roof 1 trusses did not noticeably increase during the weathering period. The moisture level readings below sheathing increased and decreased dramatically in Roofs 2 and 4, particularly on the south face of the roofs. In Roof 1, a limited number of spikes in moisture level below sheathing were recorded, but each quickly returned to levels observed in other sensors. As expected, both truss moisture content readings and sheathing moisture level readings in Roof 3 and Roof 5 (the non-leaking ccSPF-retrofitted roofs) did not increase over time. Cyclical fluctuations in their data appear to be temperature induced.

Visual Observations during the Wetting Period

During the weathering period, noticeable water intrusion into the attic space was observed in the three roofs with leaks. As expected, much more intrusion was noticeable in the non-retrofitted Roof 1 than either of the foam-retrofitted Roofs 2 and 4.

Figure 4-13 and Figure 4-14 display evidence of the leakage as observed on November 4th, 2010 during that day's 15 min. simulated rainfall period. After five minutes, water dripped through the 1/8 in. wide seam between the sheathing panels on the south side of the non-retrofitted control roof (Figure 4-13). No leaks were observed in the north side of the roof.

Figure 4-13. Evidence of leakage in Roof 1

Water leaks were also present in Roof 2 (Level II retrofit) near its south face eave (Figure 4-14). This was the same location within the roof where the greatest moisture content in framing members and sheathing samples were recorded (discussed later in this section). The leakage paths through the roof system were not found directly. However, during installation, installers made numerous holes in the ccSPF to measure/validate foam depth and covered the holes with a small additional layer of ccSPF. These holes, although sealed at the surface, may have provided a path for water to flow through. It is also possible that water locally saturated roof sheathing and ccSPF below, after which no more water could be held by the foam. Figure 4-15 on page 87 shows the roof sheathing surface immediately after shingles and underlayment were removed in preparation for panel extraction. The highest amount of water saturation was observed on the south faces near the eaves, which is consistent with attic leakage locations and truss moisture content readings.

Figure 4-14. Evidence of water intrusion in corner of Roof 2

At the conclusion of the wetting period, shingles and underlayment were stripped from each roof in preparation for panel removal and testing. Before panels were removed, the following observations were made:

- The 6 in. OSB strips became locally saturated before water traveled down the slope of the roofs. This is best demonstrated in the north faces of the two roofs in Figure 4-15.
- Water accumulated as it moved down the slope of the roofs. All four of the roof faces showed greater magnitudes of water toward their eaves despite the even distribution of leaks throughout the roof surfaces.
- The south face of the roofs showed greater accumulation of water than the north face of the roofs.

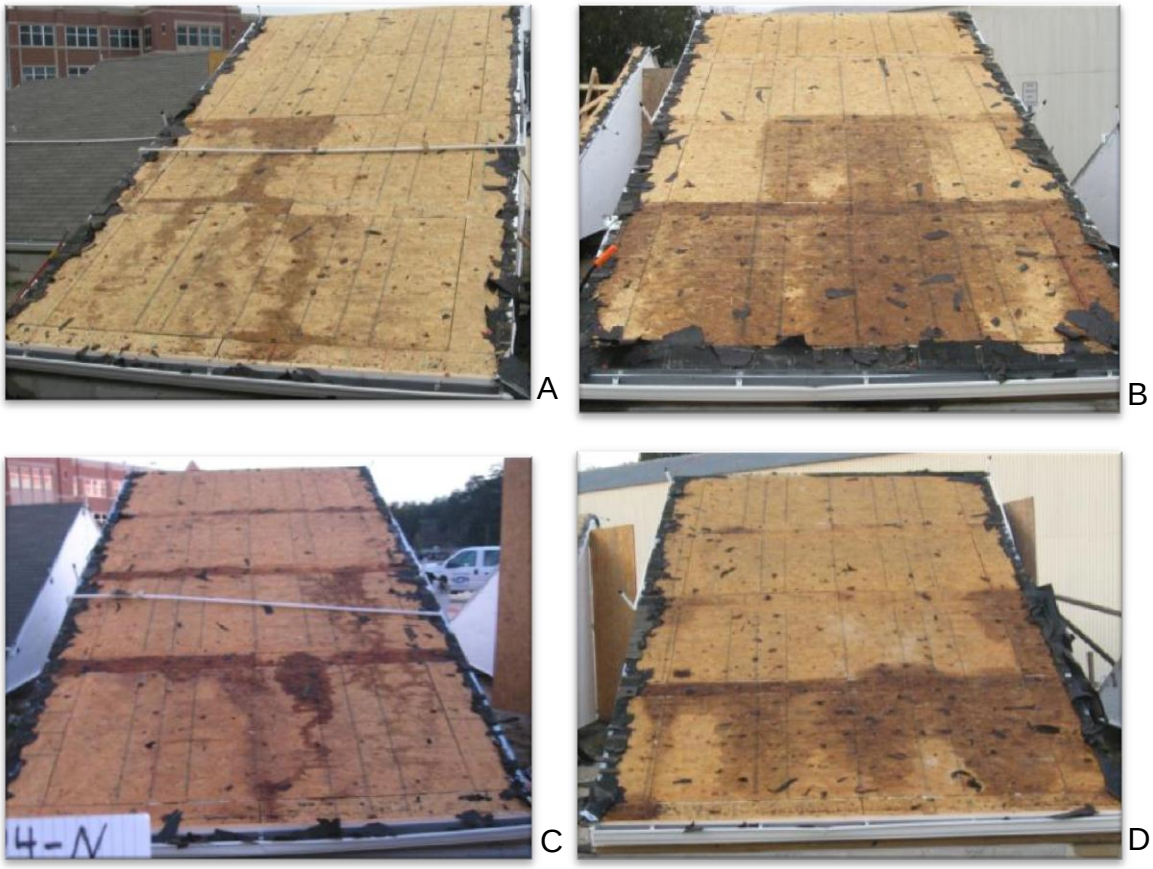


Figure 4-15. Sheathing surfaces of Roofs 2 and 4. A) Roof 2 north. B) Roof 2 south. C) Roof 4 north. D) Roof 4 south.

Failure Pressures of Sheathing Specimens

Failure pressures of roof panels were found by placing each panel into a 4 ft. by 8 ft. steel chamber and applying suction pressure. Panels were step-loaded until failure, which was defined as the point when sudden, visually detectable deflections and loss of chamber pressure occurred. Table 4-1 provides failure pressures for all roof sheathing specimens with outliers indicated at the $\alpha = 0.01$ level by the Modified Thompson Tau test (Wheeler and Ganji 2004). Means, standard deviations, and coefficients of variation (COV) are also provided. COV values ranged from 17% to 21% in the built roofs and were slightly higher in laboratory-built specimens.

Table 4-1. Failure pressures (psf) of full-scale sheathing specimens

Panel	R1	R2	R3	R4	R5	LII	LIII
A	60.7	271.2	269.1	458.8	361.1	164.7	318.0
B	50.0	240.9	256.0	315.9	286.2	301.17	228.4
C	45.4	301	329.2	421.5	362.2	274.9	257.6
D	42.8	286.3	271.2	406.2	299.7	271.2	213.0
E	56.6	220.4	209.6	474.5	226.1	-	-
F	45.6	358.4*	239.2	406.1	257.6	-	-
G	57.5	225.1	222.4	225.1*	275.5	-	-
H	70.6	256.5	376.3*	358.5	285.0	-	-
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

*Outlier **Includes Outliers

Raw data points for failure pressures are shown in Figure 4-16. Outliers are shown; note, however, that outliers were not removed due to the small sample sizes and that the test was not run for sets with four samples. Means with bars representing one standard deviation above and one below (again including outliers) are displayed beside each sample set.

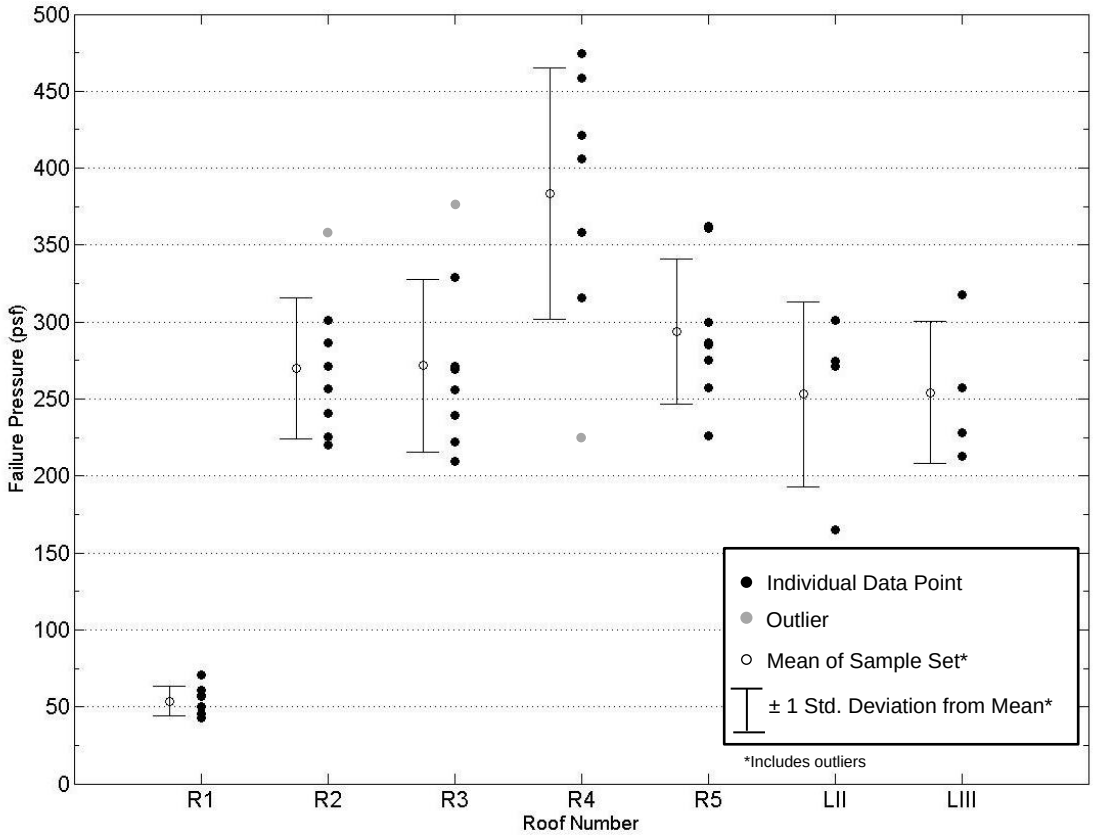


Figure 4-16. Individual results for failure pressures of full-scale roof sheathing panels

All ccSPF-retrofitted roofs showed a wind uplift strength increase of over five times that of Roof 1. Although exposed to water leakage, Roof 4 panels failed at much higher pressures than every other sample set. Meanwhile, results from Roofs 2 and 3 were comparable. These results suggest that moisture exposure for 150 days has no effect on the wind uplift performance of retrofitted panels. A summary of each panel test is provided in Appendix C.

Moisture Content of Framing Member Specimens after Structural Testing

The moisture content of all five framing members in each specimen was taken per ASTM D 4442 as described in the literature review. These values represent the moisture content immediately after testing of each specimen; therefore, the specimens were exposed to open air for different amounts of time before these measurements were taken. The number of days that each panel was held in the laboratory after removal from roofs is provided within the full-scale summary results in Appendix C.

Raw data and three-dimensional plots of the moisture contents of all framing members at the time of structural testing are shown in subsequent tables and figures (all specific gravities are provided in Appendix D). As shown previously in Figure 4-15, elevated moisture contents were observed in Roofs 2 and 4, where moisture contents were highest toward eaves and on their south faces. Roof 1 contained slightly higher moisture contents than Roofs 3 and 5, but resembled these two roofs much more closely than it resembled Roofs 2 and 4.Thus, the water intrusion had little effect on the moisture content of the non-retrofitted Roof 1. Moisture contents observed in the non-leaking roofs 3 and 5 can be explained by equilibrium reached from relative humidity and temperature conditions as described by Table 2-4 in the literature review.

Table 4-2. Roof 1 moisture contents (%) at time of structural testing

Panel	2	3	4	5	6
A	12	12	11	11	12
B	12	11	12	12	11
C	12	11	9.6	11	11
D	9	9.4	9.6	9	9.8
E	8.5	8.9	9.3	8.4	8.9
F	11	11	10	11	11
G	12	11	11	10	10
H	12	11	11	11	12
	Truss Number				

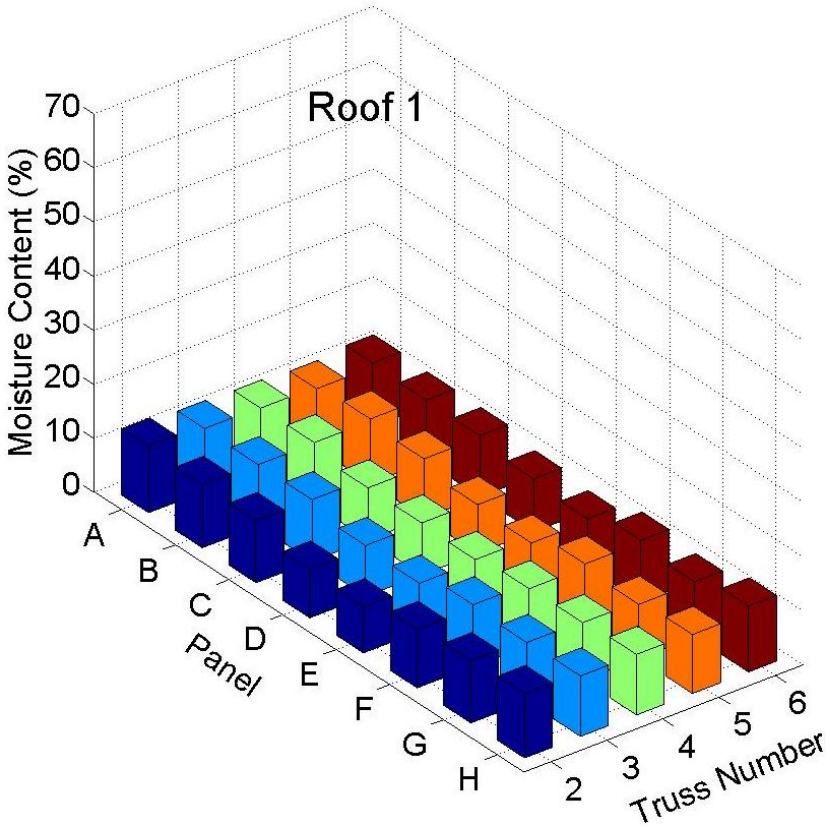


Figure 4-17. Roof 1 moisture contents (%) at time of structural testing

Table 4-3. Roof 2 moisture contents (%) at time of structural testing

Panel						
	A	12	21	17	12	14
	B	8.6	11	14	24	15
	C	10	9.3	17	12	11
	D	10	11	9.3	9.9	9.6
	E	9.3	7.8	8.6	8.9	15
	F	8.9	11	23	13	19
	G	15	16	19	33	19
	H	11	27	38	48	31
		2	3	4	5	6
		Truss Number				

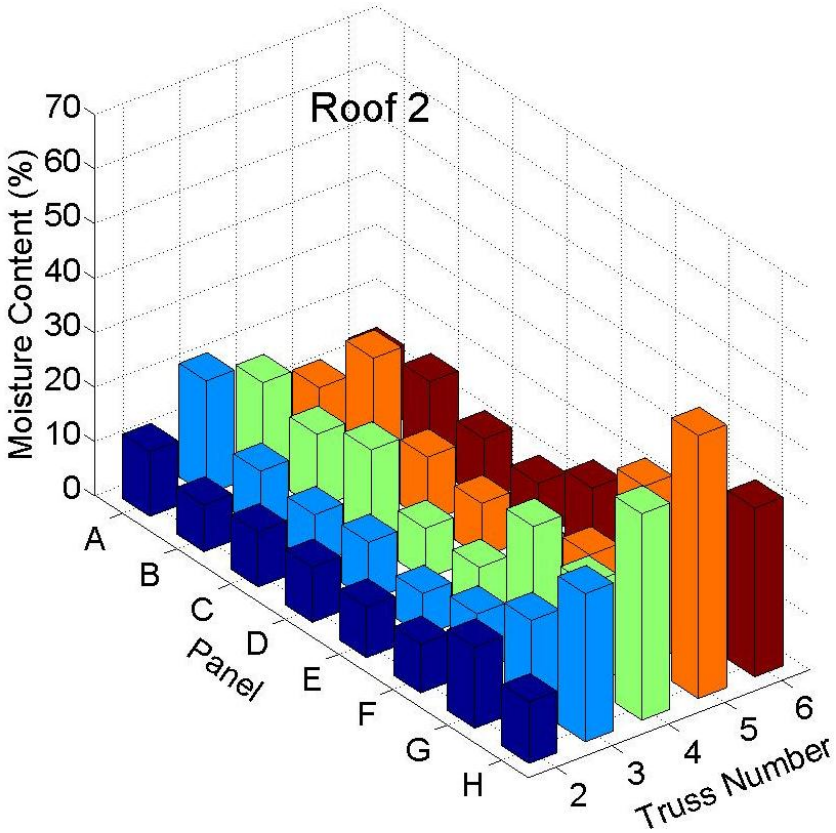


Figure 4-18. Roof 2 moisture contents (%) at time of structural testing

Table 4-4. Roof 3 moisture contents (%) at time of structural testing

Panel	2	3	4	5	6
A	11	10	-	11	9.8
B	9.9	9.8	10	10	10
C	9.7	10	10	9.5	10
D	9.2	10	9	10	9.4
E	8.8	8.4	8.6	9	8.9
F	9.1	8.4	8.5	8.4	9.4
G	8.7	8.5	8.6	8.8	9
H	8.9	8.7	9	9.3	9.2
	Truss Number				

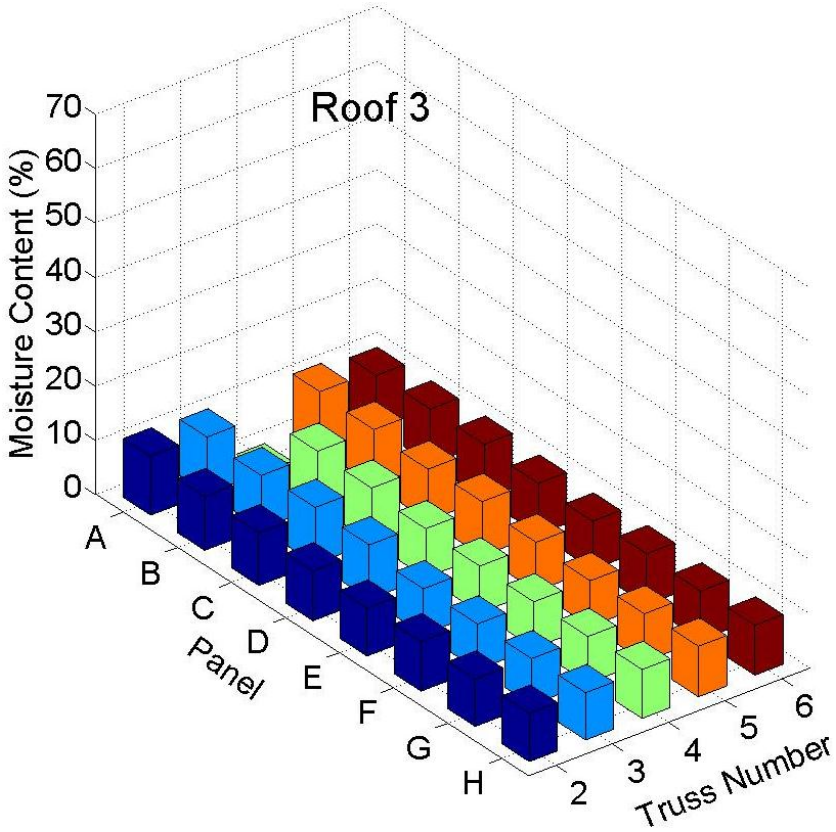


Figure 4-19. Roof 3 moisture contents (%) at time of structural testing

Table 4-5. Roof 4 moisture contents (%) at time of structural testing

Panel						
	A	12	11	16	10	10
	B	12	10	18	13	12
	C	55	11	10	20	13
	D	9.2	14	11	11	10
	E	9.1	8.9	9.4	7.7	9.4
	F	15	15	9.5	8.7	21
	G	29	15	44	23	42
	H	34	12	63	10	36
		2	3	4	5	6
		Truss Number				

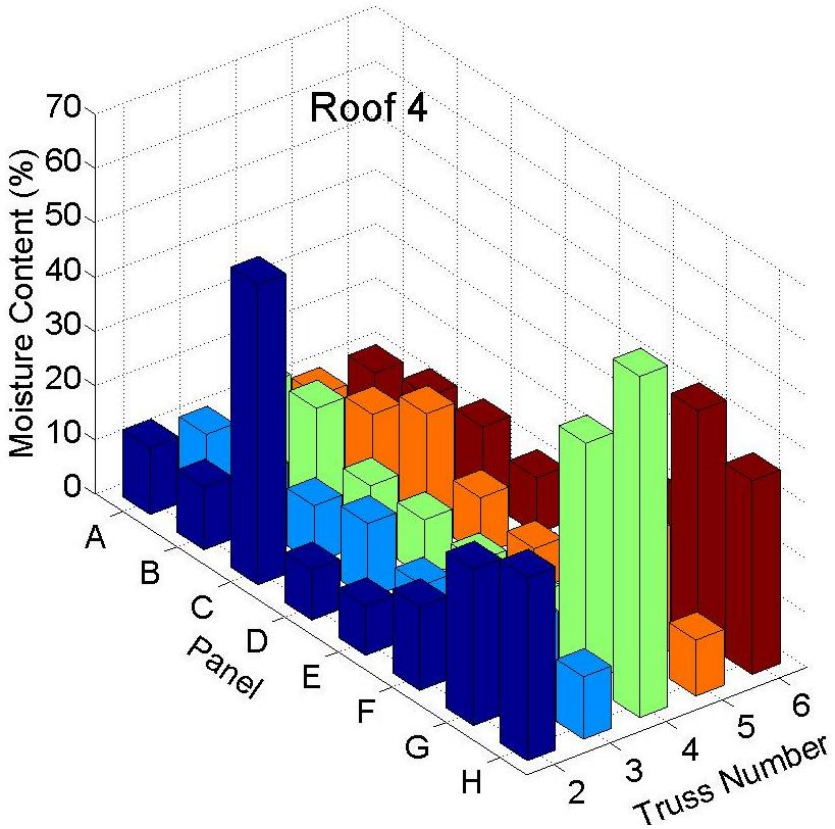


Figure 4-20. Roof 4 moisture contents (%) at time of structural testing

Table 4-6. Roof 5 moisture contents (%) at time of structural testing

Panel						
	A	11	10	10	9.6	9.8
	B	10	10	9.8	9.7	10
	C	9.5	9.1	10	8.4	10
	D	9.6	9.5	9.3	9.3	9.6
	E	8.6	8	8.2	9	9.1
	F	8.6	8.7	8.8	6.9	8.7
	G	7.9	7.6	7.7	8	6.8
	H	8.5	8.7	8.1	8.4	8.5
		2	3	4	5	6
		Truss Number				

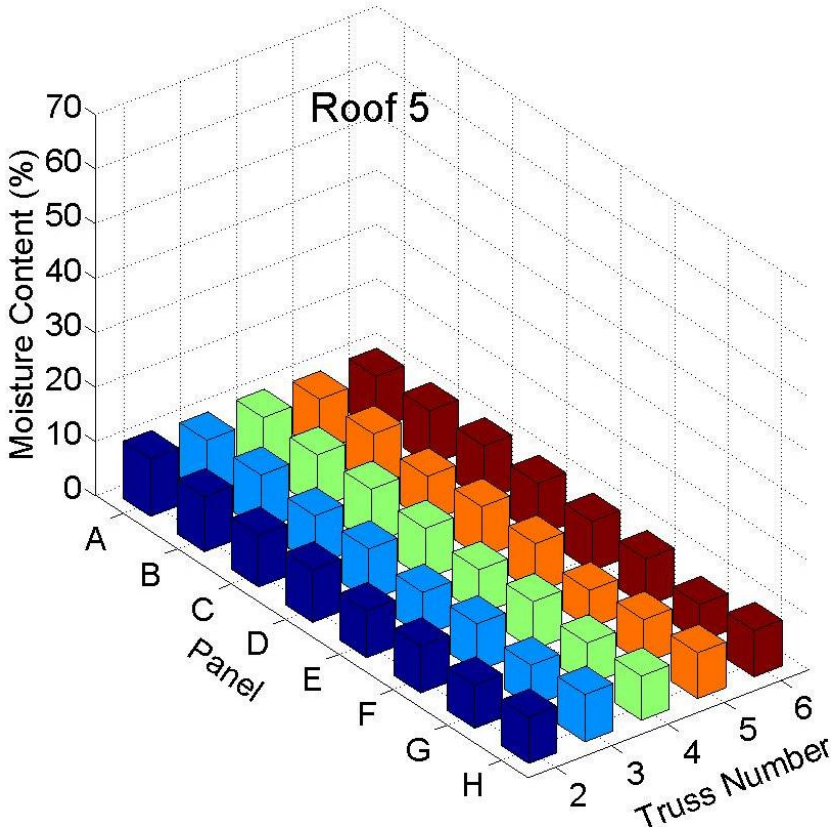


Figure 4-21. Roof 5 moisture contents (%) at time of structural testing

Table 4-7. Laboratory-built panel moisture contents (%) at time of structural testing

Panel							
	LII	A	13.4	11.8	12.4	12.0	12.0
		B	13.0	12.1	10.1	12.2	11.5
		C	9.2	9.1	9.8	10.4	9.8
		D	11.5	10.5	9.9	11.3	10.1
	LIII	A	10.1	11.3	12.3	12.0	11.5
		B	13.6	11.7	12.0	12.3	12.0
		C	11.3	11.1	9.8	11.3	11.8
		D	11.4	11.6	11.8	12.2	11.7
			2	3	4	5	6
			Truss Number				

In Roofs 2 and 4, samples were taken to gauge the in-service moisture contents of the roof sheathing. 3 in. by 6 in. samples were taken from each of the 1 ft. by 4 ft. sheathing sections located to the east of every roof test specimen shortly after roofing was removed. As with all other wood samples, the moisture contents were found per ASTM D 4442; the results are provided in Figure 4-22. These results corroborate other moisture content observations and measurements, where again greater levels of moisture were seen further downslope and in panels on the south side of the roofs. On the south faces, moisture contents approaching 100% were observed in these small sheathing specimens. Note that sheathing panels were not wetted uniformly across their areas, so the readings found cannot be extrapolated to accurately describe sheathing moisture contents in the full-scale specimens.

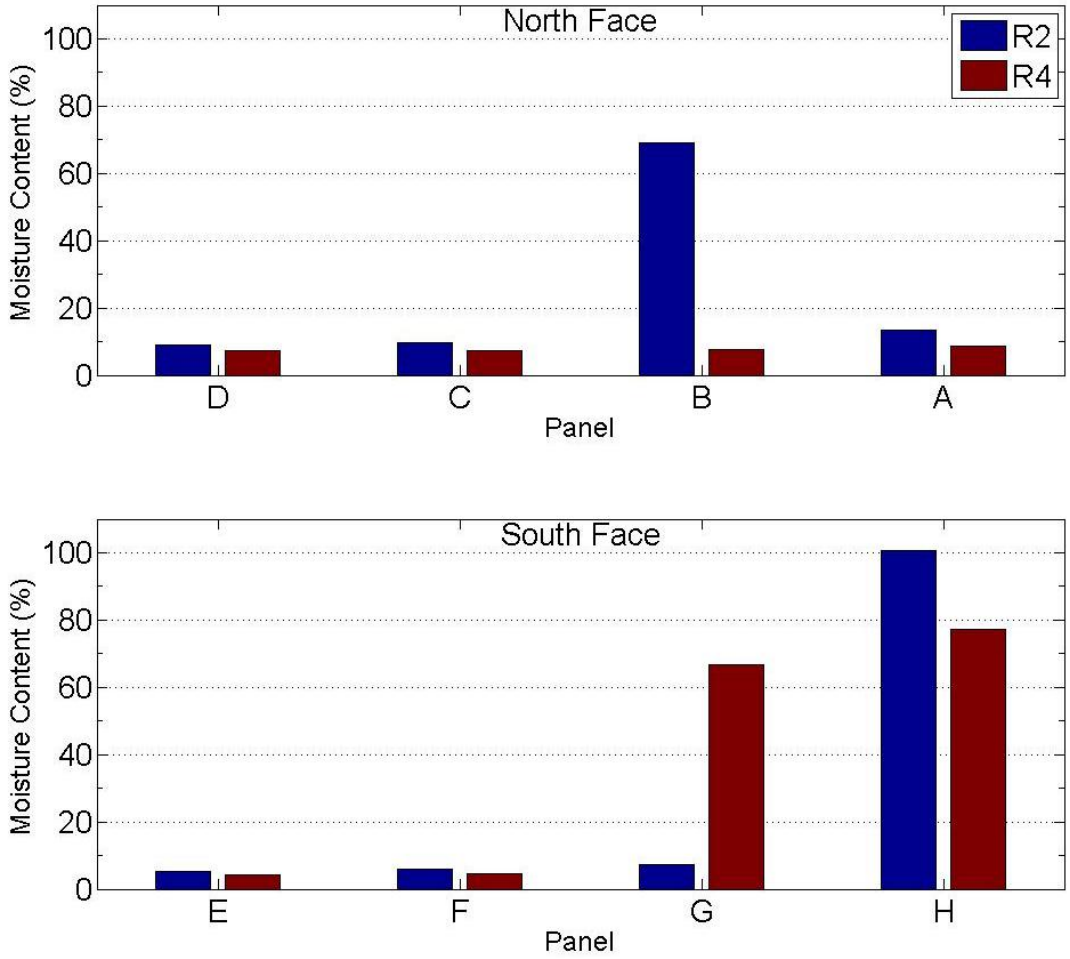


Figure 4-22. Moisture contents of sheathing samples taken after roofing removal per ASTM D 4442 Method B

Deflection and Pressure Measurements during Wind Uplift Testing

Deflection and pressure time-histories were recorded during panel testing with synchronized time steps. Time-histories of both readings are provided for panel R4-B in Figure 4-23. Pressure is shown in solid green with corresponding units on the right y-axis. The dashed blue line is the deflection time-history with units on the left y-axis. The graph indicates that early in the loading protocol, the relationship between pressure and deflection of the panel are nearly linear, but that under higher pressures, continued deflection was seen during pressure plateaus, indicating a non-linear relationship. Relatively large deflections were seen in this panel in the seconds leading up to failure.

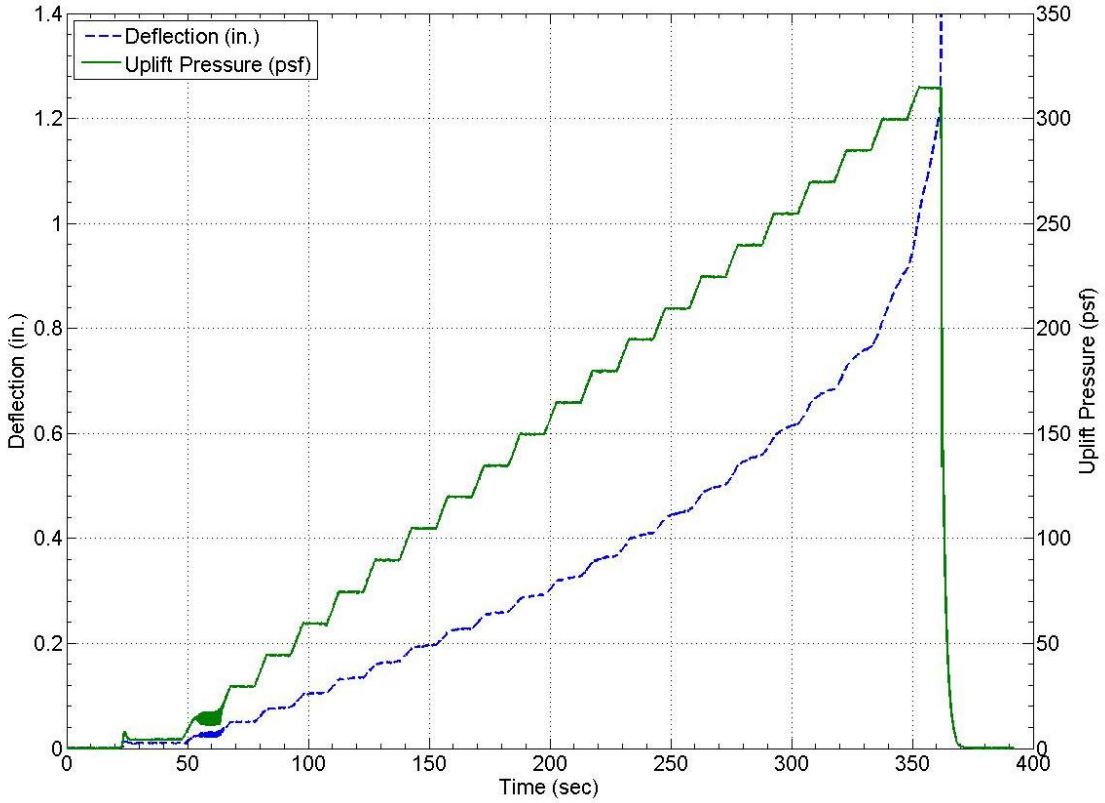


Figure 4-23. Uplift pressure and midspan deflection time-histories in panel R4-B (315.9 psf failure)

Panel Foam Depth Measurements

Foam depths were taken throughout the surface of every retrofitted sheathing panel after structural testing in two locations: at trusses (truss depth plus foam on top of the truss) and between trusses. All foam depths are provided in Appendix E. Means and standard deviations of the foam depths within roofs and laboratory sets are provided in Table 4-8. Although COV values within sample sets, curiously, were generally lower for the full-scale roofs than for the laboratory-built panels, the laboratory-built panels were closer in their average depths to the target depths for both retrofits. In sample sets with the Level III retrofit, Roof 4 contained a between-truss foam depth 0.71 in. greater than Roof 5 and 1.19 in. greater than LIII panels.

Table 4-8. Mean, standard deviation, and COV of foam depths in retrofitted panels

		Roof 2	Roof 3	Roof 4	Roof 5	LII	LIII
At Truss	Mean	4.36	4.47	4.92	4.66	3.93	3.84
	Std. Dev.	0.48	0.47	0.44	0.44	0.28	0.54
	COV	0.11	0.11	0.09	0.09	0.07	0.14
Between Truss	Mean	1.55	1.58	4.20	3.49	1.28	3.01
	Std. Dev.	0.37	0.39	0.46	0.44	0.39	0.36
	COV	0.24	0.24	0.11	0.12	0.31	0.12

Relationships between Measured Variables

Relationship between Framing Member Moisture Content and Failure Pressure of Panels

The effects of framing member moisture contents on the failure pressures of roof sheathing specimens were investigated. For each panel, the five framing member moisture contents (one from each framing member), were averaged together. Figure 4-24 shows a plot of the averaged framing member moisture content vs. the failure pressures for each roof sheathing panel. No visible trends were seen in Roof 1 (the leaking control roof) or in roofs 3 and 5 (the non-leaking ccSPF-retrofitted roofs), as their moisture contents were consistent. Linear regressions were performed for Roofs 2 and 4 (the leaking retrofitted roofs). Very small correlation coefficients were found, both well below the critical values for the coefficient of determination for 8-sample groups at the alpha = 0.05 level (Wheeler and Ganji 2004). Thus, no relationship was found between framing member moisture content and the ultimate wind uplift capacity of roof sheathing panels.

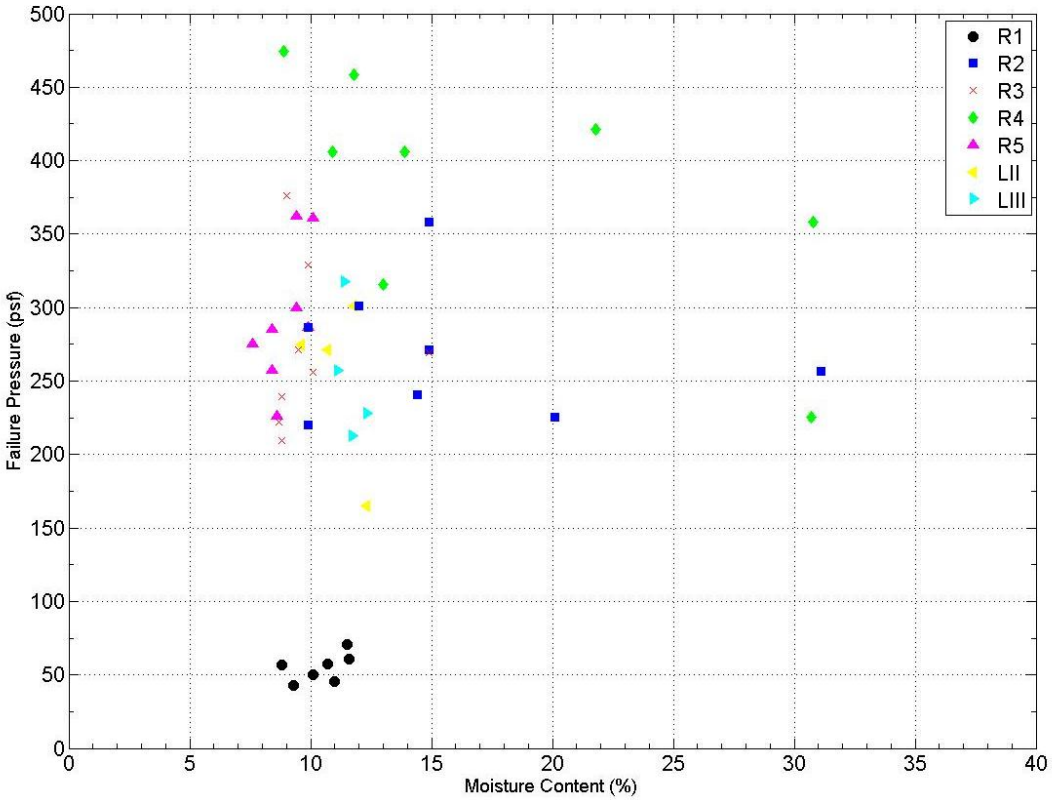


Figure 4-24. Framing moisture content vs. failure pressure of full-scale sheathing panels

Relationship between Foam Depth and Failure Pressure

Foam depths were averaged at both the at- and between-truss locations for every sheathing panel specimen. These averaged values of foam depth were plotted against the failure pressure of the panels. Figure 4-25 shows the relationship between foam depth at truss members and the failure pressure, while Figure 4-26 plots foam depth between truss members against the failure pressure. Although the impact of foam depth on failure pressure must be analyzed more thoroughly (e.g., with finite element analysis) to be truly understood, these relationships provide a baseline for understanding that increased foam depths (both at and between trusses) led to increased wind uplift capacity of ccSPF-retrofitted roof sheathing panels.

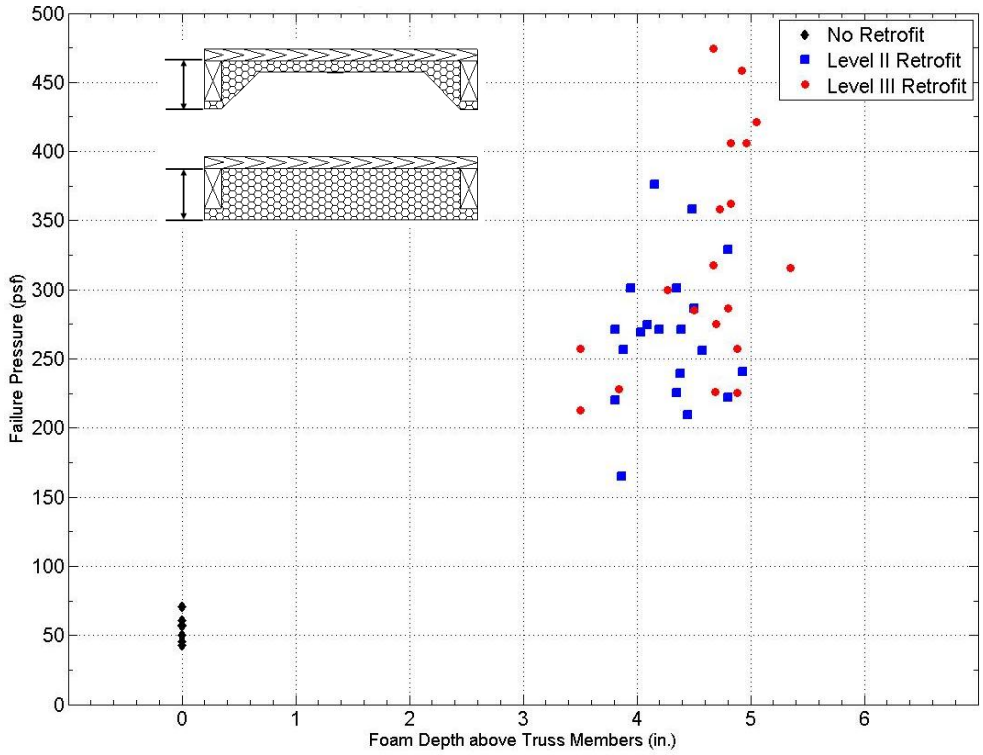


Figure 4-25. Foam depth at truss members vs. panel failure pressure

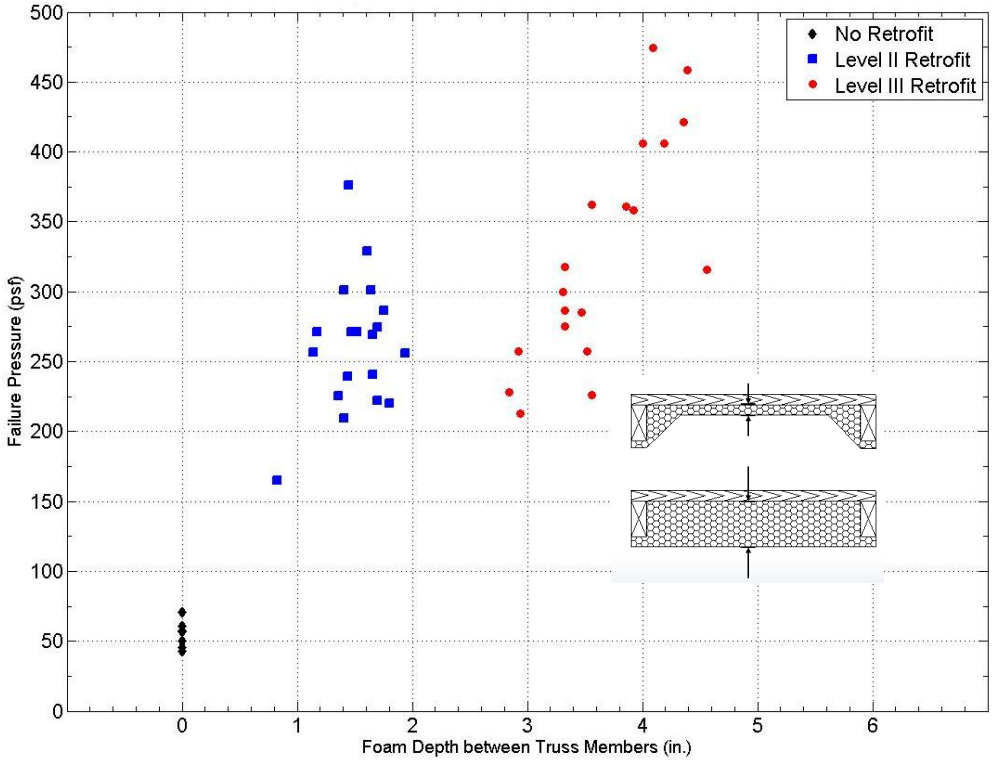


Figure 4-26. Foam depth between truss members vs. panel failure pressure

Relationship between Deflection and Applied Pressure

In panels where deflection measurements were taken, deflection vs. pressure relationships were investigated. Figure 4-27 shows the deflection vs. pressure plot for panel R4-B (all available deflection vs. pressure graphs are provided in Appendix F). As pressure increased, the rate of deflection per unit pressure also increased, showing a reduction in stiffness of the panel under greater loads. Also, during holds of constant pressure, the continued deflection is apparent by horizontal lines every 15 psf (equivalent to the pressure step during loading). The continued deflection under constant pressure suggests that the rate of loading may have an effect on the deflection behavior and ultimate failure pressure of panels. The nonlinear behavior of the panel suggests that ccSPF-retrofitted panels may exhibit stiffness degradation under cyclical loading. Loading rates and cyclic loading could be potential avenues for further study.

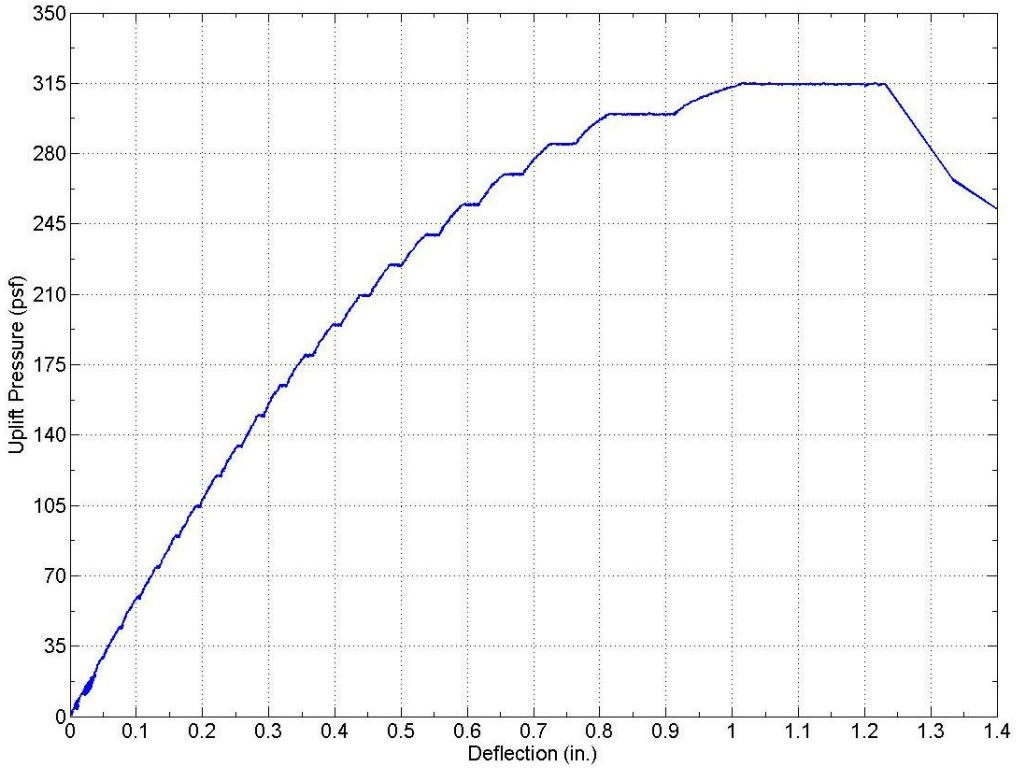


Figure 4-27. Deflection vs. pressure for Panel R4-B (315.9 psf failure)

Unconsidered Variables

Variables that were not measured may have influenced the results for wind uplift capacity of roof sheathing panels. Although retrofitted sheathing panel specimens often failed first at wood knots and metal truss plates connecting disparate members of the truss top chords, the presence of knots and truss plates was not indicated during structural testing. Examples of both types of failure are illustrated in Figure 4-28. Aside from eight samples taken outside of full sheathing specimens, moisture content of sheathing was not recorded. As with truss members, sheathing moisture contents varied greatly from panel to panel and again may have had influence on the failure pressures of full-scale specimens (note, however, that no correlation was found between truss member moisture content and panel failure pressure). Some foam inconsistencies (e.g., air pockets between passes of foam as in Figure 4-29) were observed, but again not quantified in any standard fashion. It is important to note the presence of these variables when considering COV values and relationships between other variables.

A

B

Figure 4-28. Framing member failure at A) a knot and B) a metal plate splice

Figure 4-29. Air pockets between foam passes

Statistical Significance

Analysis of Variance Tests Comparing Failure Pressure

A one-factor analysis of variance (ANOVA) test was performed in Excel to compare the mean failure pressures of sheathing panel specimens in the five roofs and two laboratory-built datasets. The experimental design for running an ANOVA between all roofs was as follows:

H_0: The mean panel failure pressures of all roofs are equivalent

H_a: At least one roof's mean failure pressure differs from any other roof's mean

Where the calculated test F statistic exceeds the critical F value, the null hypothesis is rejected and it is concluded that not all mean failure pressures are equivalent. If this is the case, post-hoc comparison procedures are used to determine which group means are statistically equivalent and which are statistically different.

Table 4-9 shows the result of the ANOVA test comparing the mean failure pressures of the different roofs. As would be expected from Roof 1 and Roof 4 average

values, a negligible P-value of 6 x 10^{-13} was calculated. As a result, it was concluded that not all mean panel failure pressures are equivalent between all roofs.

Table 4-9. Single-factor ANOVA for failure pressure group means

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	472311	6	78718	27.7	6E-13	2.33
Within Groups	116702	41	2846			
Total	589013	47				

To determine which sample group means of each roof were statistically equivalent or different, the Tukey-Kramer Honestly Significant Difference post-hoc comparison method was performed using built-in functions in MatLab (MathWorks 2009). Figure 4-30 displays the result of this analysis, which show that Roof 1 specimens failed at statistically lower pressures than the rest of the sample sets, while Roof 4 specimens failed at statistically higher pressures. Roofs 2, 3, and 5 all held statistically equivalent means.

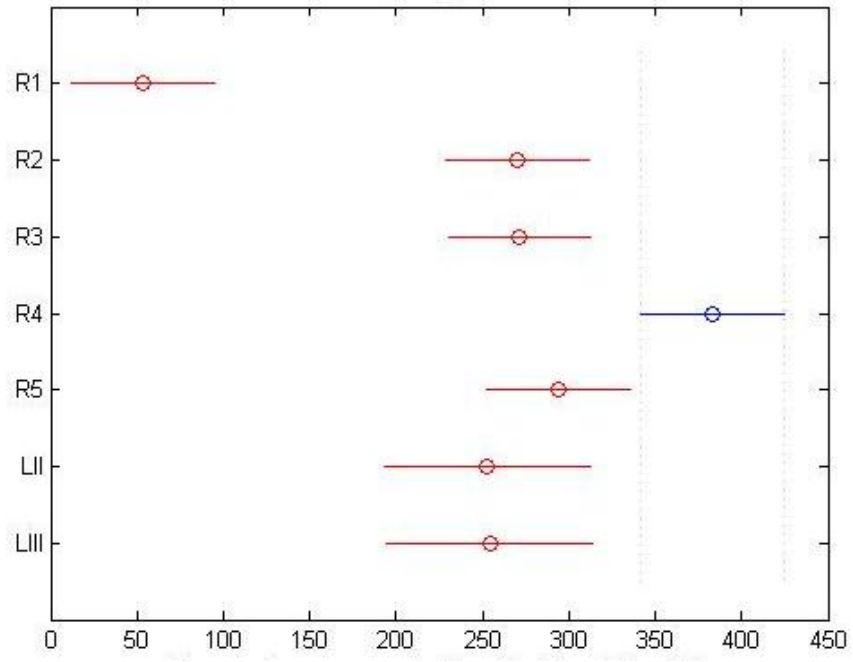


Figure 4-30. Tukey-Kramer comparison of mean failure pressures of panel groups

Comparisons between Roof Panels and Laboratory Panels

t-tests were used to compare failure pressures ofretrofitted roof panels with laboratory panels with the same foam configuration. Specifically, Roof 3 was compared to laboratory panels with Level II retrofits, while Roof 5 was compared with laboratory panels with Level III retrofits. The results are shown below in Table 4-10 and Table 4-11.

Table 4-10. Comparison between Roof 3 and LII failure pressures

	R3	LII
Mean	271.6	253.0
Variance	3120.1	3643.0
Observations	8	4
Hypothesized Mean Difference	0	
df	6	
t Stat	0.52	
P(T<=t) one-tail	0.31	
t Critical one-tail	1.94	
P(T<=t) two-tail	0.62	
t Critical two-tail	2.45	

Table 4-11. Comparison between Roof 5 and LIII failure pressures

	R5	LIII
Mean	294.1	254.3
Variance	2227.5	2150.4
Observations	8	4
Hypothesized Mean Difference	0	
df	6	
t Stat	1.40	
P(T<=t) one-tail	0.11	
t Critical one-tail	1.94	
P(T<=t) two-tail	0.21	
t Critical two-tail	2.45	

Both *t*-tests resulted in acceptance of the null hypothesis that the means of the sample sets were statistically equivalent. Thus, laboratory-level performance of the uplift capacity of roof sheathing panels was achieved in the full-scale roofs for both Level II and Level III retrofits.

Comparison to Design Wind Loads

"Worst-case" wind uplift pressures for roof sheathing panels were calculated using the Part 2: Low-rise Buildings (simplified) method for Components and Cladding in ASCE/SEI 7-10 (ASCE 2010). The building was residential (Risk and Occupancy Category 2) with 20 ft. mean roof height and 6 in 12 roof slope in suburban (Exposure C) conditions. The basic wind speed chosen was 180 mph, the maximum wind speed in the U.S. for Occupancy Category II. The topographic factor selected was 1.0. For the effective wind area of an individual sheathing panel of 32 ft^2, the net design wind pressure for roof corners in Exposure B at 30 ft. was found to be -133.74 psf. The adjustment factor for Exposure C at 20 ft. was 1.29, resulting in a "worst-case" design wind pressure of -172.5 psf.

All ccSPF-retrofitted panels in full-scale roofs, including wetted panels, failed above the worst-case design load. Only one laboratory-built panel with Level II protection failed below this level. Figure 4-26 on page 100 shows that this panel was the only panel with an average between-truss depth lower than the value prescribed for Level II retrofits. In general, however, nearly all ccSPF-retrofitted panels contained foam depths *above* the prescribed values; thus, these results may overstate the ability of Level II and Level II retrofits to withstand hurricane loads.

Discussion of Full-Scale Results

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

despite 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.

The moisture content in leaking ccSPF-retrofitted roof panels increased at a faster rate than in leaking non-retrofitted roof panels. 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, these elevated moisture contents may be a source of concern for longer-term exposures to these moisture contents. As evidenced by the in-service and final moisture contents of panels within leaking roofs, moisture does not have an outlet for quickly escaping wood structural members when ccSPF is applied to the underside of the deck, while sheathing roof framing exposed to open air on the underside of sheathing allows moisture to move away from the wood.

Within the leaking ccSPF-retrofitted roofs, greater levels of moisture (in sheathing, trusses, pictures, and roof interiors) were observed in the hotter south face of each roof. This result was surprising, as elevated temperatures alone should lead to faster evaporation. However, possible (speculative) explanations emerge from the temperature differences between the two sides of the roof. One such explanation is that the elevated temperature may have caused shingles to seal more efficiently on the south side, allowing less water to evaporate back up through shingles.

Higher moisture contents were observed toward the eaves than the ridges of leaking ccSPF-retrofitted roofs. This phenomenon occurred both on the north and south faces of the roofs. The highest moisture content during structural testing of 62% was observed at the eave. Truss moisture contents taken from the nearest specimens to the ridges were all below 14% during structural testing (only one measurement was above 11%). This suggests that moisture moved by gravity down the slope of the roof. With less sheathing area above panels positioned more toward the ridge, less water could potentially flow to these higher panels.

Although no tests were conducted for the presence of wood rot, no visible fungal decay was observed in wood structural members in any roofs. For this reason, it remains unknown whether the presence of decay fungus reduces the uplift capacity of ccSPF-retrofitted panels.

Wind uplift capacity is directly related to the depth of the ccSPF retrofit. This is evidenced by Roofs 4 and 5, which contained the Level III retrofit (Roof 4 with leaks and Roof 5 with no leaks). Roof 4 had statistically significantly greater average foam depth (4.92 in. at trusses and 4.20 in. between trusses) and failure pressure (383 psf) throughout the roofs than Roof 5 (4.66 in. at- and 3.49 in. between-truss foam depths and 294 psf failure pressure).

A majority of retrofitted panel failures appear to have initiated at the bond between roof sheathing and ccSPF near just outside of framing members. The scope of this thesis did not include an analysis of stress concentrations in the composite ccSPF-retrofitted roof sheathing panels. However, it seems that in the predominant failure pattern observed in both Level II and Level III retrofits, a crack between

sheathing and foam was initiated at the truss member. The crack may then have propagated along the sheathing surface to some distance and moving diagonally through the foam. If this is true, it suggests that tensile stress was concentrated near truss members, either from nearby nails connecting sheathing to truss members offering less stiffness than the foam, force transfer from ccSPF to truss members, or a combination of the two. Future research should investigate the transfer of stress created by applying uniform uplift pressure loading to sheathing in this composite system with both analytical models and physical experiments.

Sheathing panel specimens exhibited continued deflection during loading plateaus. As uplift pressures increased, midspan deflections continued to increase in many panels during the ten-second pressure plateaus. Thus, rate of loading and the number of loading cycles before failure may have an effect on the ultimate failure pressure of ccSPF-retrofitted roof sheathing panels.

CHAPTER 5
RESULTS FOR TENSILE TESTING OF SMALL SHEATHING SPECIMENS

Introduction to Tensile Testing Results

Testing utilizing a modified ASTM D 1623 Method C procedure investigated the tensile capacity of the ccSPF-to-sheathing bond subjected to moisture over time. ccSPF was sprayed on three surfaces: the smooth face of OSB, the textured face of OSB, and plywood. In total, 38 smooth OSB, 35 textured OSB, and 34 plywood samples were divided and tested for their tensile capacities after 1 week, 2 weeks, 4 weeks, 8 weeks, 12 weeks, and 16 weeks of water exposure in an enclosed chamber. Another 8 samples of each type were tested during the first four periods as non-wetted controls.

The results presented in this chapter do not include all of the samples tested. In total, 17 samples were removed after testing for one or more of the following reasons: failure away from the ccSPF-sprayed OSB surface during loading, unintentional failure before testing, or, in one case, moisture content vastly different from all other samples in the dataset. All results, including those removed, are provided in Appendix G.

Failure Stresses, Sheathing Moisture Contents, and Sheathing Specific Gravities

The following tables and graphs present individual failure stress results, sheathing moisture contents, and sheathing specific gravities for small specimen samples with foam sprayed on the smooth face of OSB, the textured face of OSB, and plywood, respectively. Failure stress data points considered outliers at the $\alpha = 0.01$ level by the Modified Thompson Tau Method (Wheeler and Ganji 2004) are indicated for sets with greater than four samples. As with full-scale data, outliers were not removed. Mean (shown as open circles to the left of each dataset), standard deviation (lines above and below the mean), and COV values are provided and displayed graphically.

Table 5-1. Failure stresses of specimens with foam sprayed on OSB smooth face

	Control	Week 1	Week 2	Week 4	Week 8	Week 12	Week 16
	23.9	4.5	18.3	21.1	17.9	12.5	16.6
	33.6	34.4	16.4	22.6	19.8	19.4*	10.6
	33.0	13.3	20.1	11.4	16.6	13.9	15.3
	26.4	6.6	11.9*	12.2	13.5	12.3	13.5
	20.3	26.7	18.0	14.2	14.1	13.2	12.0
	42.7	15.8	-	-	19.6	-	13.9
	15.8	7.7	-	-	-	-	-
	41.9	23.8	-	-	-	-	-
	-	26.3	-	-	-	-	-
	-	15.2	-	-	-	-	-
Mean	29.7	17.4	16.9**	16.3	16.9	14.3**	13.7
St. Dev	9.8	10.0	3.1**	5.2	2.7	2.9**	2.2
COV (%)	32.9	57.2	18.4**	31.9	15.9	20.6**	15.9

*Outlier
**Includes Outliers

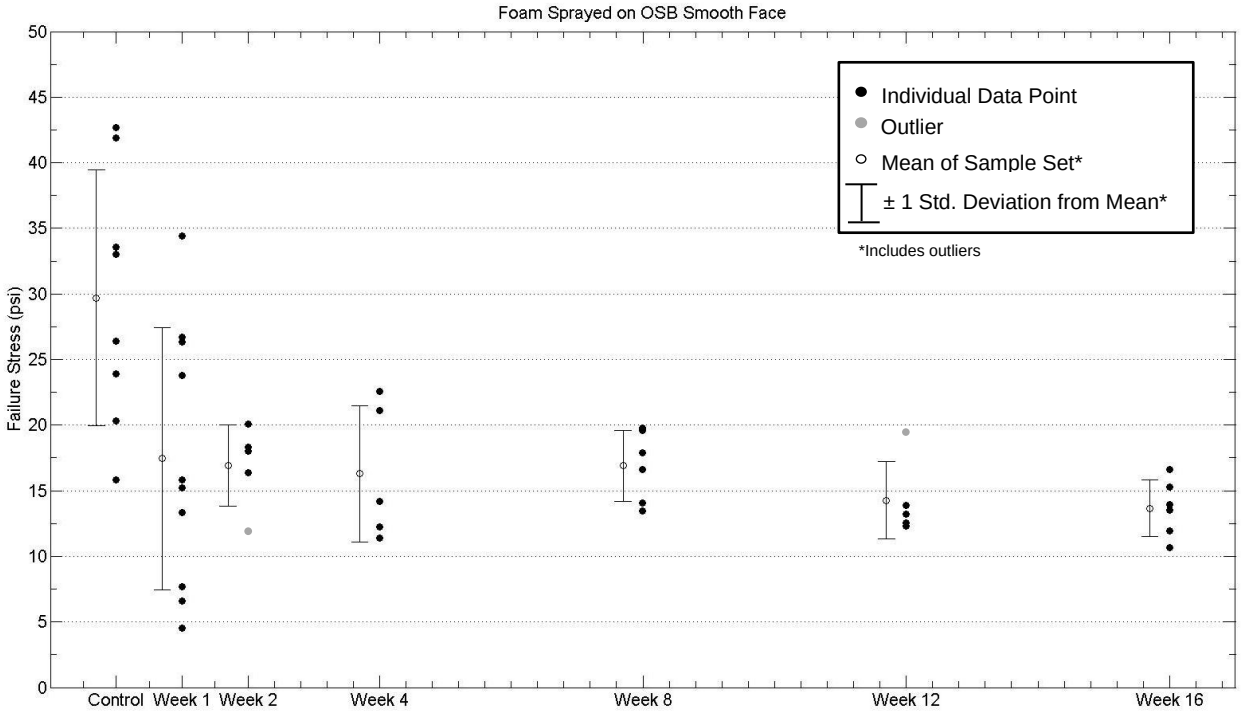


Figure 5-1. Failure stresses of specimens with foam sprayed on OSB smooth face

Table 5-2. Failure stresses of specimens with foam sprayed on OSB textured face

	Control	Week 1	Week 2	Week 4	Week 8	Week 12	Week 16
	9.5	18.4	6.9	23.2*	5.9	12.7	10.9
	23.2	12.0	11.8	5.4	9.2	9.2	14.8
	17.0	9.5	6.9	12.4	9.2	16.1	5.4
	17.2	19.2	15.2	10.2	10.8	9.1	7.4
	13.3	15.7	-	10.3	-	7.0	9.8
	10.6	-	-	8.0	-	4.6	-
	23.4	-	-	-	-	-	-
Mean	16.3	15.0	10.2	11.6	8.8	9.8	9.7
St. Dev	5.6	4.1	4.1	6.2	2.1	4.1	3.6
COV (%)	34.2	27.8	39.7	53.3	23.4	41.8	37.3

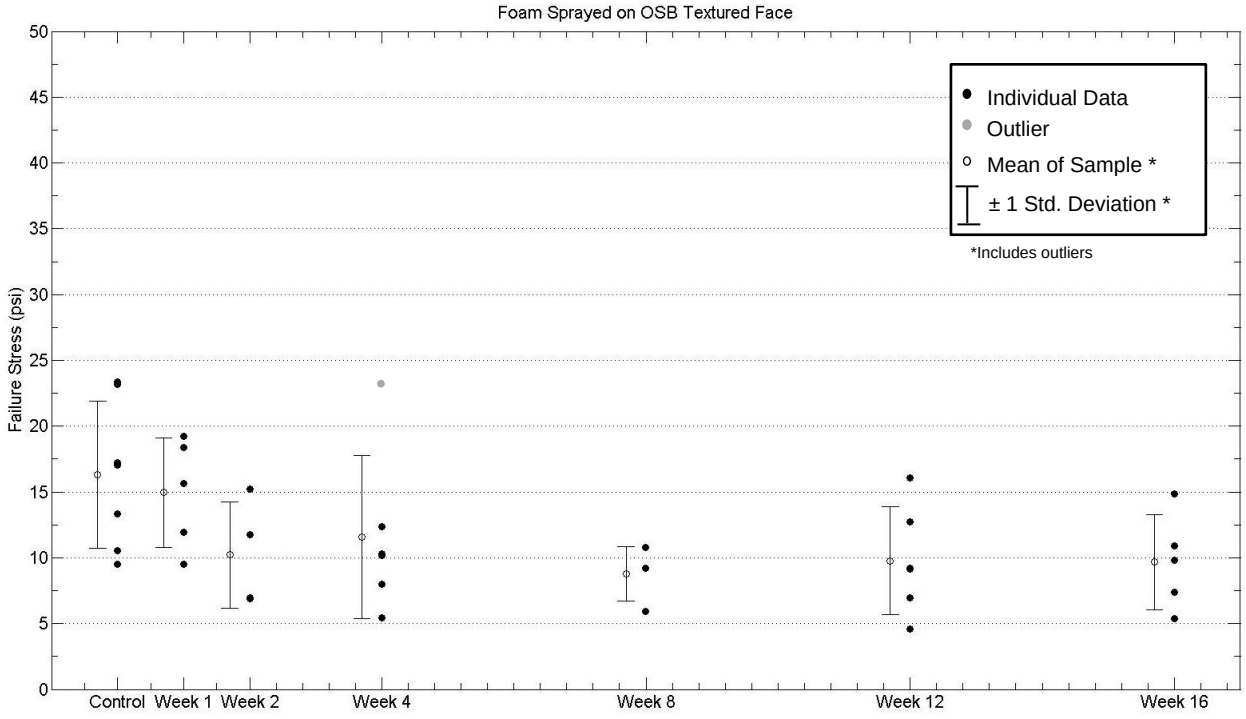


Figure 5-2. Failure stresses of specimens with foam sprayed on OSB textured face

Table 5-3. Failure stresses of specimens with foam sprayed on plywood

	Control	Week 1	Week 2	Week 4	Week 8	Week 12	Week 16
	14.6	25.1	19.0	30.0	21.0	12.4	16.2
	31.4	24.7	24.3	16.4	13.3	12.3	10.6
	18.8	13.6	14.6	21.7	13.5	17.5	13.0
	22.0	20.2	16.8	24.7	20.0	20.6	-
	31.6	-	-	17.8	-	15.9	-
	20.8	-	-	-	-	-	-
	27.8	-	-	-	-	-	-
Mean	23.9	20.9	18.7	22.1	17.0	15.7	13.3
St. Dev	6.5	5.3	4.1	5.5	4.2	3.5	2.8
COV (%)	27.4	25.5	22.2	24.8	24.5	22.4	21.3

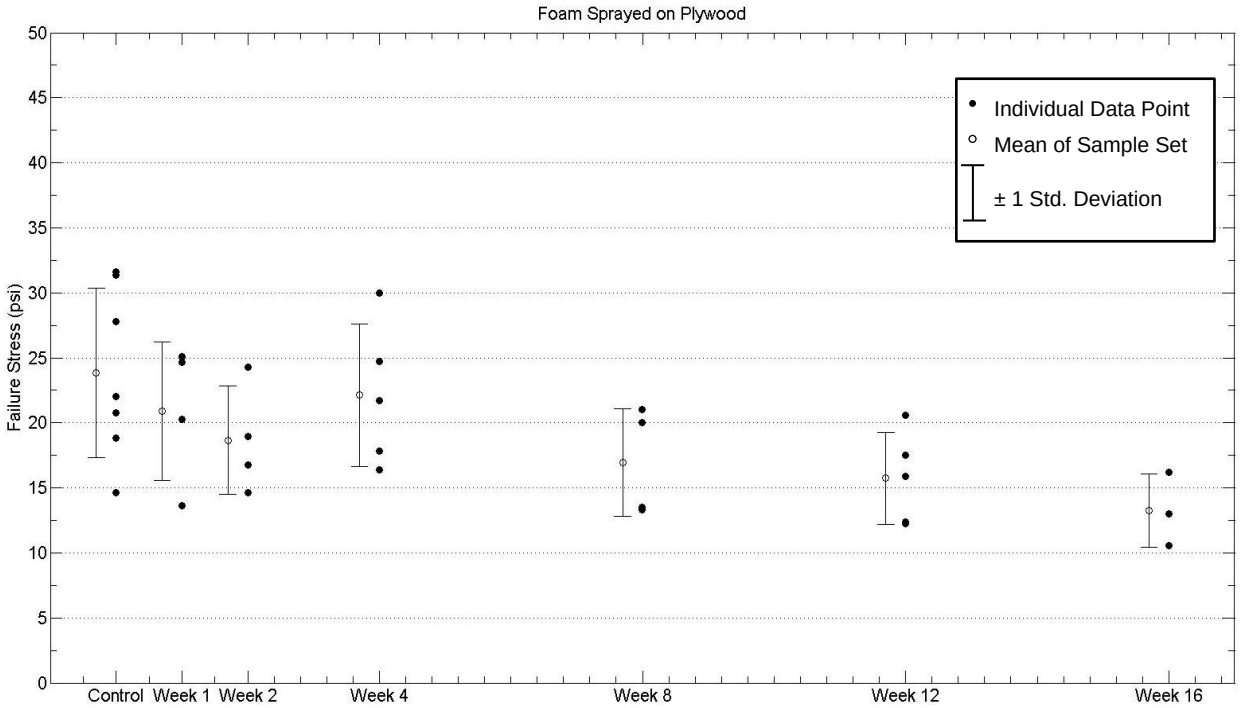


Figure 5-3. Failure stresses of specimens with foam sprayed on plywood

Table 5-4. Sheathing moisture content of specimens with foam sprayed on OSB smooth face

	Control	Week 1	Week 2	Week 4	Week 8	Week 12	Week 16
	9.6	116.0	66.3	66.1	67.2	34.4	121.5
	8.6	26.5	77.7	41.8	39.4	49.5	105.5
	7.5	43.0	38.4	92.5	73.9	72.8	119.5
	7.1	33.8	61.3	85.7	67.3	84.3	112.0
	-	31.6	30.6	100.5	43.3	90.7	117.6
	6.1	47.4	-	-	70.3	-	105.4
	8.4	40.4	-	-	-	-	-
	8.1	40.3	-	-	-	-	-
	-	51.6	-	-	-	-	-
	-	36.6	-	-	-	-	-
Mean	7.9	46.7	54.9	77.3	60.2	66.3	113.6
St. Dev	1.2	25.4	19.7	23.6	14.9	23.8	7.1
COV (%)	14.6	54.5	35.9	30.5	24.7	35.9	6.2

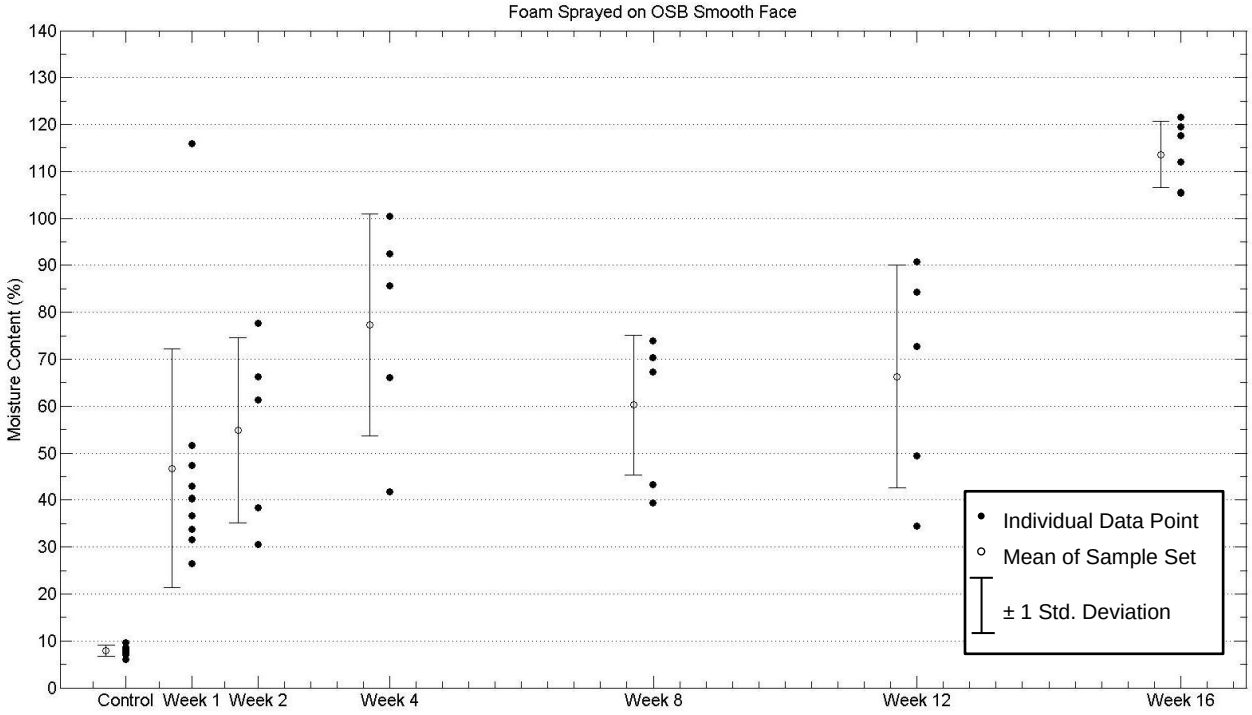


Figure 5-4. Sheathing moisture content of specimens with foam sprayed on OSB smooth face

Table 5-5. Sheathing moisture content of specimens with foam sprayed on OSB textured face

	Control	Week 1	Week 2	Week 4	Week 8	Week 12	Week 16
	9.4	98.4	84.5	25.0	99.3	109.5	-
	-	49.9	60.2	96.5	87.0	104.4	110.0
	7.0	75.9	73.0	79.3	82.9	116.7	121.1
	6.3	32.2	53.3	94.0	111.4	67.0	126.9
	7.5	37.9	-	57.6	-	119.9	107.3
	8.5	-	-	94.2	-	100.0	-
	8.6	-	-	-	-	-	-
Mean	7.9	58.9	67.8	74.4	95.2	102.9	116.3
St. Dev	1.2	27.8	13.9	28.3	12.9	19.1	9.3
COV (%)	14.7	47.2	20.5	38.0	13.5	18.6	8.0

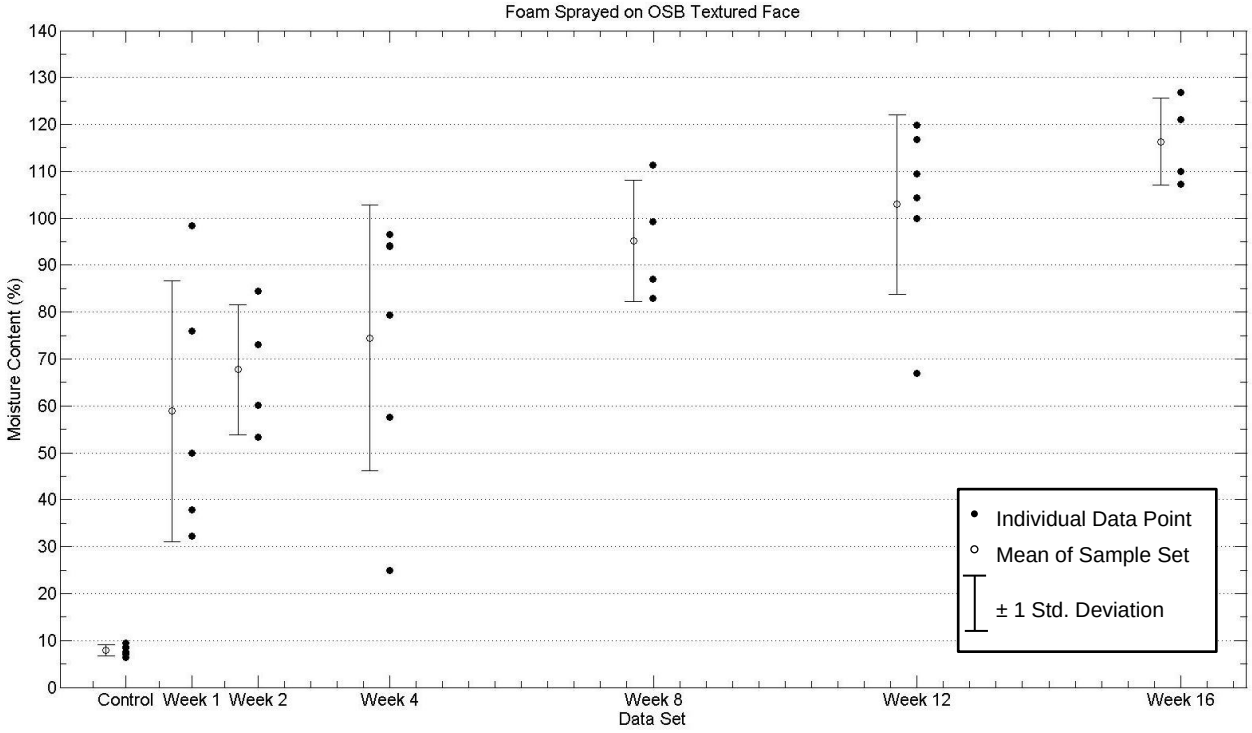


Figure 5-5. Sheathing moisture content of specimens with foam sprayed on OSB textured face

Table 5-6. Sheathing moisture content of specimens with foam sprayed on plywood

	Control	Week 1	Week 2	Week 4	Week 8	Week 12	Week 16
	9.9	105.4	94.2	36.0	93.0	101.8	100.6
	9.3	104.6	73.6	88.5	75.6	99.1	89.9
	9.1	58.3	77.5	48.8	45.7	99.4	40.6
	7.4	53.4	78.9	44.2	53.8	67.9	-
	6.0	-	-	50.4	-	73.7	-
	7.2	-	-	-	-	-	-
	8.2	-	-	-	-	-	-
Mean	8.1	80.4	81.0	53.6	67.0	88.4	77.0
St. Dev	1.4	28.4	9.1	20.3	21.5	16.2	32.0
COV (%)	17.0	35.4	11.2	37.9	32.0	18.3	41.5

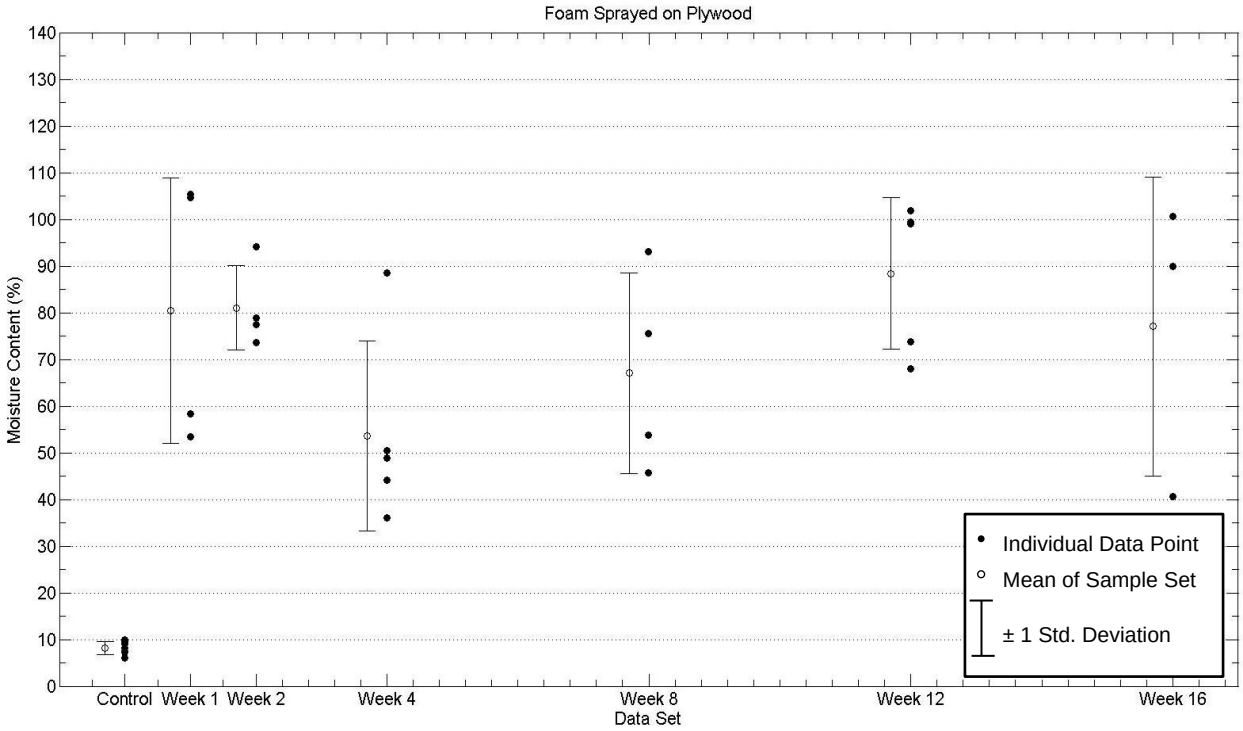


Figure 5-6. Sheathing moisture content of specimens with foam sprayed on plywood

Table 5-7. Sheathing specific gravity of specimens with foam sprayed on OSB smooth face

	Control	Week 1	Week 2	Week 4	Week 8	Week 12	Week 16
	0.64	0.34	0.66	0.64	0.46	0.54	0.41
	0.71	0.63	0.50	0.53	0.47	0.48	0.52
	0.69	0.52	0.51	0.50	0.46	0.59	0.37
	0.68	0.57	0.54	0.52	0.43	0.50	0.46
	0.43	0.51	0.53	0.50	0.48	0.49	0.48
	0.66	0.54	-	-	0.50	-	0.46
	0.66	0.50	-	-	-	-	-
	0.66	0.53	-	-	-	-	-
	-	0.50	-	-	-	-	-
	-	0.52	-	-	-	-	-
Mean	0.64	0.52	0.55	0.54	0.47	0.52	0.45
St. Dev	0.09	0.07	0.06	0.06	0.02	0.05	0.05
COV (%)	13.5	14.5	11.3	11.0	4.9	8.7	11.7

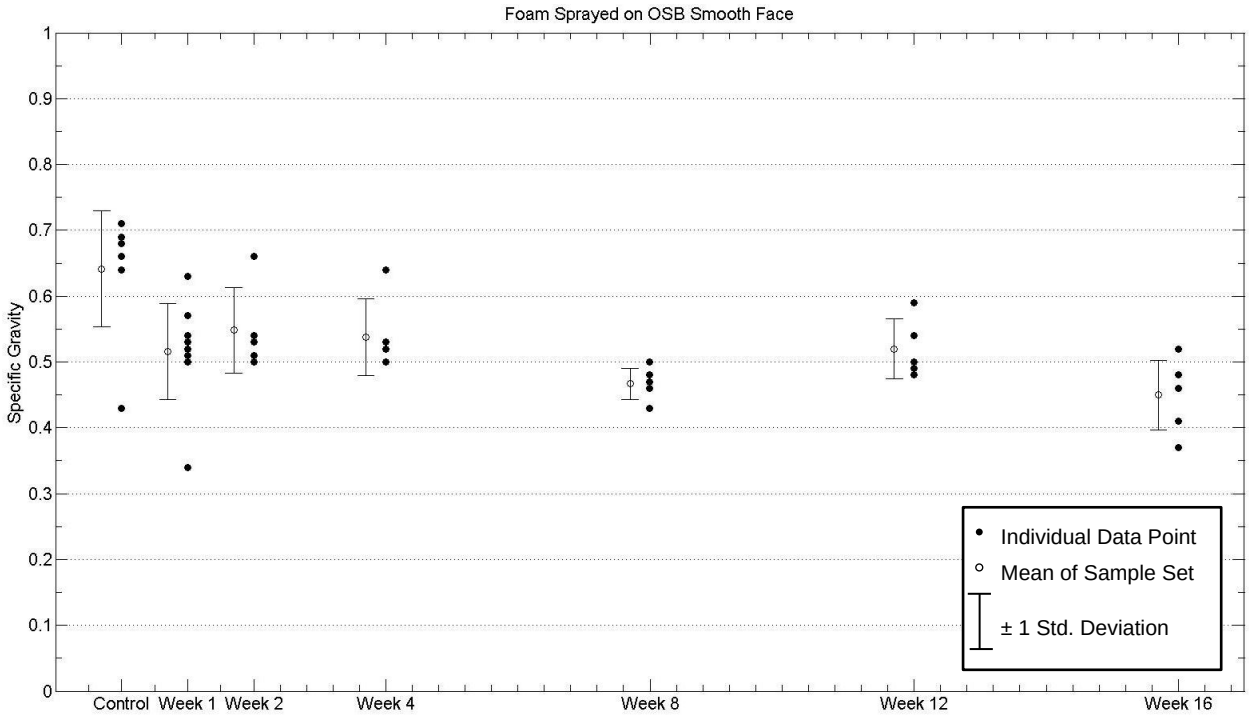


Figure 5-7. Sheathing specific gravity of specimens with foam sprayed on OSB smooth face

Table 5-8. Sheathing specific gravity of specimens with foam sprayed on OSB smooth face

	Control	Week 1	Week 2	Week 4	Week 8	Week 12	Week 16
	0.59	0.36	0.47	0.56	0.50	0.49	-
	0.58	0.39	0.53	0.57	0.45	0.50	0.52
	0.67	0.48	0.48	0.70	0.51	0.48	0.49
	0.65	0.53	0.51	0.45	0.43	0.48	0.47
	0.66	0.47	-	0.53	-	0.43	0.47
	0.58	-	-	0.5	-	0.5	-
	0.65	-	-	-	-	-	-
Mean	0.63	0.44	0.50	0.55	0.47	0.47	0.49
St. Dev	0.04	0.07	0.03	0.09	0.04	0.03	0.02
COV (%)	6.5	15.5	5.9	15.8	8.2	5.5	4.6

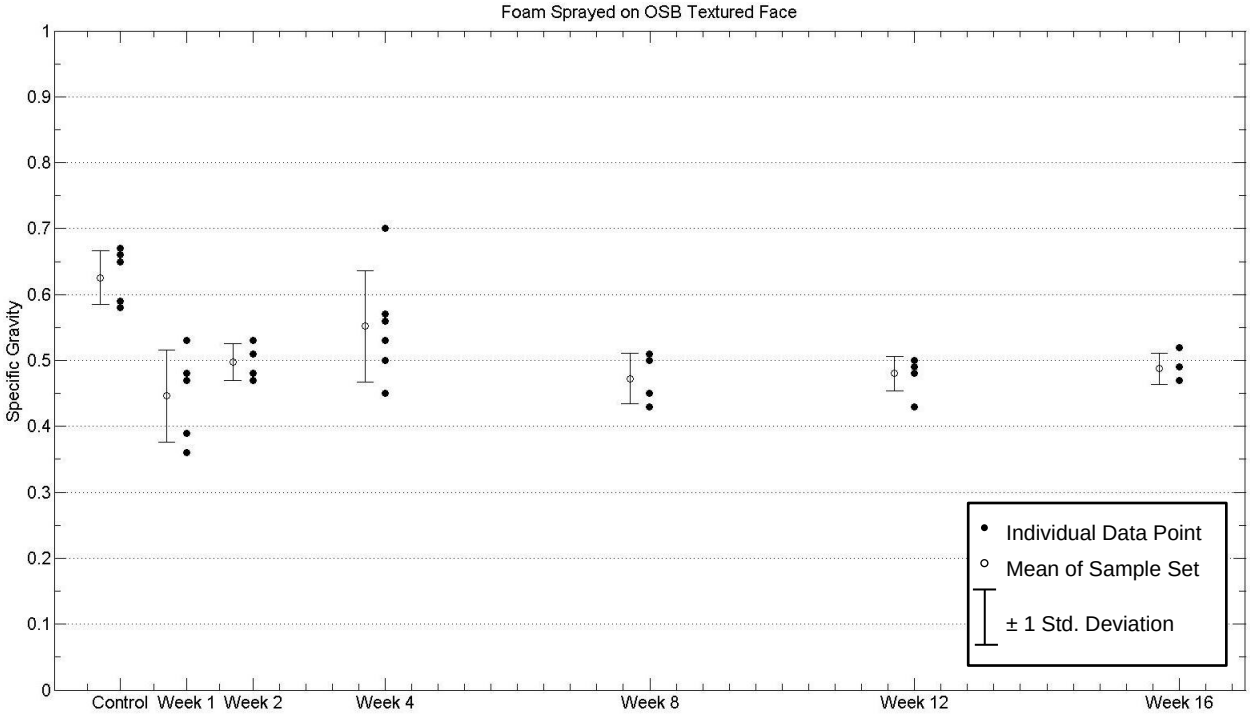


Figure 5-8. Sheathing specific gravity of specimens with foam sprayed on OSB textured face

Table 5-9. Sheathing specific gravity of specimens with foam sprayed on plywood

	Control	Week 1	Week 2	Week 4	Week 8	Week 12	Week 16
	0.51	0.51	0.38	0.62	0.44	0.45	0.50
	0.53	0.48	0.51	0.48	0.44	0.46	0.51
	0.53	0.51	0.48	0.45	0.46	0.46	0.45
	0.51	0.50	0.46	0.48	0.46	0.50	-
	0.43	-	-	0.62	-	0.53	-
	0.49	-	-	-	-	0.60	-
	0.51	-	-	-	-	-	-
Mean	0.50	0.50	0.46	0.53	0.45	0.50	0.49
St. Dev	0.03	0.02	0.06	0.08	0.01	0.06	0.03
COV (%)	6.6	3.2	12.4	15.6	2.5	11.5	6.3

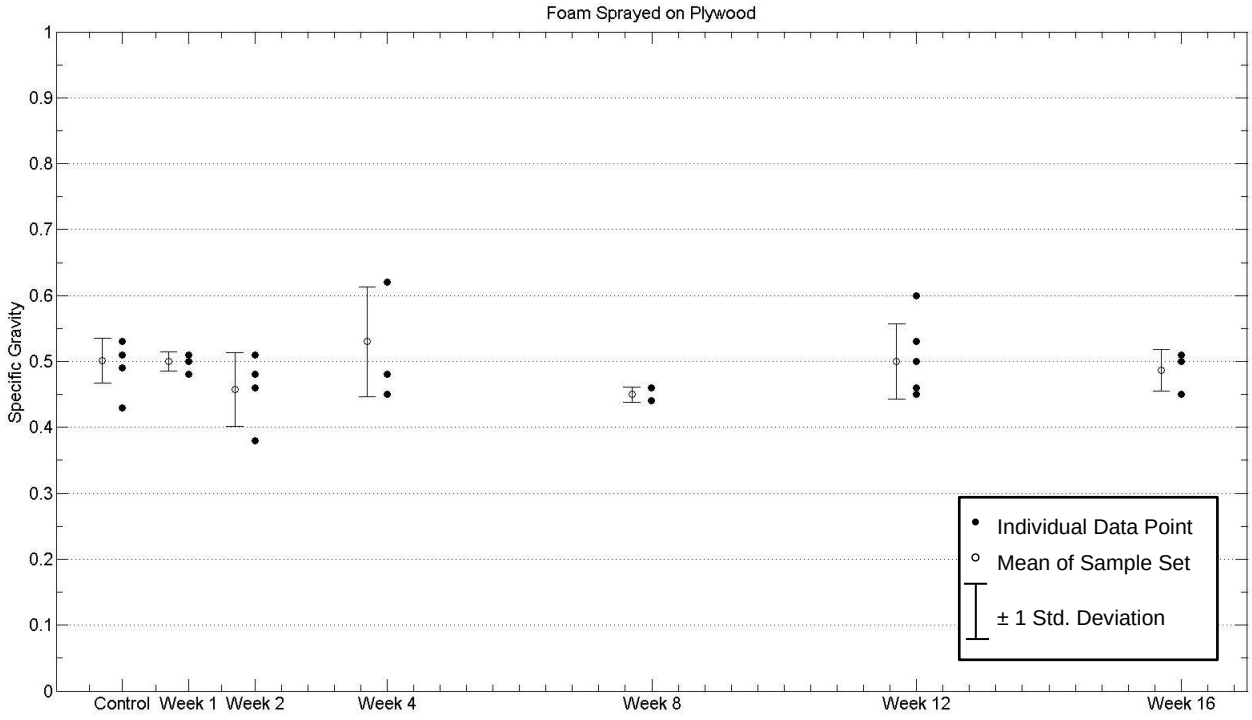


Figure 5-9. Sheathing specific gravity of specimens with foam sprayed on plywood

A wide range of COV values was observed throughout failure stress (15% to 60%) and moisture content (5% to 55%) results, creating difficulty for making conclusive remarks about trends. Nonetheless, some observations can be made about trends within the data. In specimens with ccSPF sprayed on the smooth OSB face, the control mean was 29.7 psi with a COV of 32.9%. Means of the water-exposed test series declined slightly over time from 17.4 psi to 13.7 psi, but COVs ranged from 15.9% to 57.2%. Mean moisture contents of the wetted test series steadily increased from 46.7% to 113.6%, suggesting that even drastic changes in moisture content had little effect on the adhesion between ccSPF and the smooth OSB face. Aside from slightly higher values in the control set, specific gravity values were consistent.

The control test series for foam sprayed on the textured OSB face failed at 16.3 psi on average with a 34.2% COV. From the Week 1 series to the Week 2 series, the mean failure stress dropped from 15.0 psi to 10.2 psi; after Week 2, the failure stresses leveled. COV values ranging from 23.4% to 53.3% were observed for failure stresses in the wetted test series. Moisture contents rose between each testing period in wetted samples, from 58.9% in Week 1 to 116.3% in Week 16. As with samples with ccSPF sprayed to the smooth surface, higher specific gravity values were measured in the control samples than the wetted samples.

In plywood samples, the failure stress of the control test series was 23.9 psi with a COV of 27.4%. The failure stresses of wetted plywood samples fluctuated over time, with sample set means ranging from 13.3 psi to 22.1 psi with COV values from 21.3% to 60.7%. In contrast to trends seen both OSB sample sets, plywood moisture contents

were unstable, reaching 80.4% by Week 1, decreasing in Week 4 measurements to 53.6%, and eventually climbing back to 77.0% in Week 16.

Relationships between Failure Stress, Moisture Content, and Specific Gravity

Sheathing moisture contents were plotted against bond failure stresses for all samples within each set. A slight reduction (note: this was not statistically significant) is seen in all sample sets with increasing moisture content up to approximately 70%, beyond which moisture contents leveled.

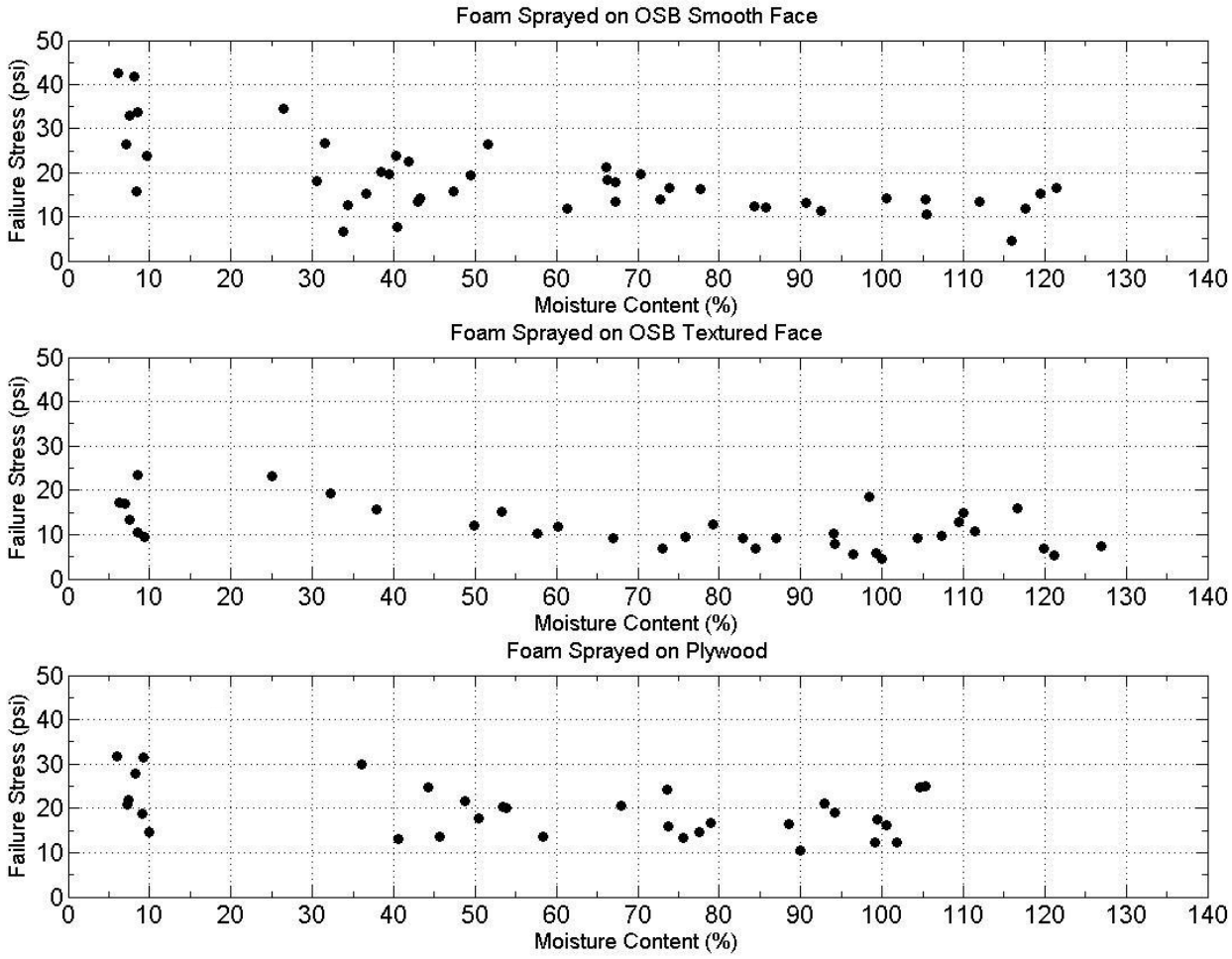


Figure 5-10. Moisture content vs. tensile failure stress of small specimens

Failure stresses were also plotted against calculated specific gravity values. No apparent trends are seen with the exception of the upper ranges of specific gravity

values in the OSB smooth face sample set. Note that these values are associated with the control samples; thus, the lower moisture content in these samples must also be considered when identifying trends with the specific gravity data.

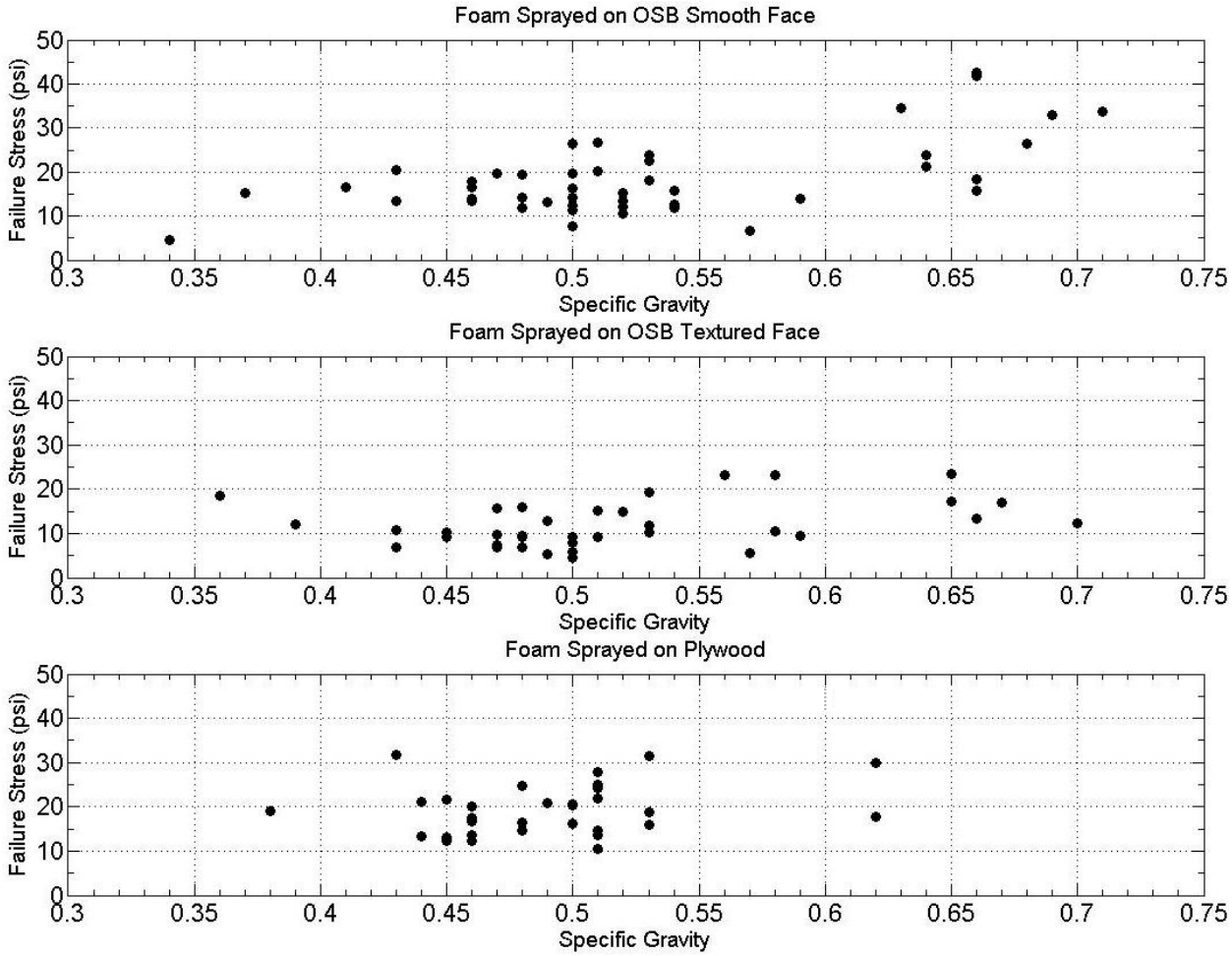


Figure 5-11. Specific gravity vs. tensile failure stress of small specimens

Statistical Significance of Small Specimen Results

As with full-scale failure pressure results, ANOVA tests were conducted on the failure stresses of each sample set for a 5% significance level. Where resultant p-values were less than 0.05, the Tukey-Kramer test was performed in Matlab to determine which sample sets were statistically different from others. The results are displayed in Table 5-10 through Table 5-12 and Figure 5-12.

Table 5-10. Single-factor ANOVA test for failure stress group means of small specimens with ccSPF sprayed on smooth OSB face

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1298.2	6	216.4	4.55	0.0014	2.35
Within Groups	1805.3	38	47.5			
Total	3103.5	44				

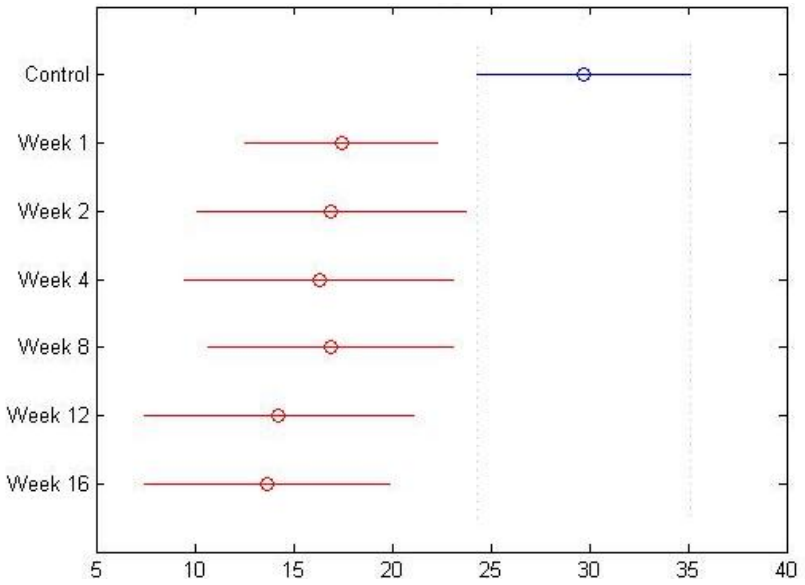


Figure 5-12. Tukey-Kramer comparison of mean failure pressures of panel groups

Table 5-11. Single-factor ANOVA test for failure stress group means of small specimens with ccSPF sprayed on textured OSB face

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	285.4	6	47.6	2.22	0.069	2.42
Within Groups	643.4	30	21.4			
Total	928.8	36				

Table 5-12. Single-factor ANOVA test for failure stress group means of small specimens with ccSPF sprayed on plywood

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	310.8	6	51.8	0.98	0.46	2.47
Within Groups	1368.8	26	52.6			
Total	1679.6	32				

Little statistical significance was found in the mean failure stresses between test series. Between ccSPF sprayed on the OSB smooth face, the OSB textured face, and plywood, the only statistical difference was seen between the control series and all wetted series in the OSB smooth face samples.

Finally, the coefficients of determination (R^2) were calculated for failure stresses plotted against time, moisture content, and specific gravity as shown in Table 5-13. Statistical significance of the R^2 values was determined by comparing the values against a minimum value for statistical significance as explained in Wheeler and Ganji (2004). R^2 values considered statistically significant for the number of coordinate pairs are indicated by bold lettering.

Table 5-13. Coefficients of determination for failure stress plotted against time, moisture content, and specific gravity (with number of coordinate pairs in parentheses and statistically significant results in bold type)

	Independent Variable		
Sample Set	Time	MC	SG
Smooth OSB	0.17 (45)	**0.39 (44)**	**0.38 (44)**
Textured OSB	0.18 (37)	0.30 (35)	0.14 (36)
Plywood	0.09 (33)	0.21 (33)	0.17 (33)

Once again, the only statistically significant values were seen for samples with ccSPF sprayed on the smooth OSB face. In these samples, failure stress was statistically correlated with both moisture content (inverse relationship) and specific gravity (direct relationship). No other statistical trends could be seen in the data. The overall absence of statistical significance may suggest that the presence of water does not degrade the ccSPF-to-sheathing bond over the 16-week period of time presented in

this thesis. However, once again, large COV values throughout the small specimen data contributed considerably to the lack of certainty in results.

Discussion of Small Specimen Results

The following observations were made for the laboratory testing results of the ccSPF-to-sheathing bond subjected to water exposure over time:

- The testing techniques used produced a high level of variability (COVs ranging from 5% to 60%) in the results for failure stress and moisture content.
- Little conclusive evidence was found showing the weakening of the ccSPF-to-sheathing bond.
- Mean tensile failure stresses for wetted small specimens ranged from 13.7 psi (1973 psf) to 17.4 psi (2506 psf) in smooth OSB specimens, 8.8 psi (1267 psf) to 15.0 psi (2160 psf) in textured OSB specimens, and 13.3 psi (1915 psf) to 22.1 psi (3182 psf) in plywood specimens. Of course, stress does not transfer uniformly in the composite roof system consisting of sheathing, trusses, and ccSPF. As discussed at the end of Chapter 4, it is believed that stress concentrations exist near truss members in full-scale ccSPF-retrofitted roof sheathing.
- Theoretically, if a maximum pressure of -172 psf (the calculated “worst-case” uplift in full-scale results) is applied to sheathing, the tributary width between sheathing panels (2 ft.) transfers a 172 psf * 2 ft. = 344 lb. per linear foot to the truss member. Assuming that all of the force is localized within the adhesive failure surface between ccSPF (for discussion, 3 in. wide on either side of the truss and excluding the space between sheathing and truss member) and

sheathing while transferring load to truss members in shear, the observed stress between foam and sheathing will be 344 lb/ft. divided by (3*2)/12 ft. = 688 psf, still well below the range of measured tensile stress capacities (above) in small specimen testing. Full-scale tests were conducted with ccSPF sprayed on the OSB smooth face. By the logic presented in this discussion point, the lower end of the wetted OSB smooth face failure stresses, 1973 psf, would translate to roughly 500 psf, which is in the vicinity of (albeit higher than) the failure pressures observed. These rough estimations provide a baseline for merging the results from Part I and Part II testing, but should not be interpreted as conclusive. Further study should focus on investigating the stress transfer in this system to fully place results from small specimen testing into the context of the full-scale system.

CHAPTER 6
CONCLUSIONS

This thesis evaluated the wind uplift capacity of ccSPF-retrofitted wood roof sheathing subjected to water leakage in two experimental studies. Part I determined the wind uplift capacity of full-scale ccSPF-retrofitted roof sheathing panels. Five full-scale roofs (a control, two with Level II ccSPF retrofits, and 2 with Level III ccSPF retrofits) were exposed to natural and simulated rainfall for 150 days. Sheathing panels were individually tested afterward to determine their wind uplift capacities following the UF-WRSUT test protocol. Part II laboratory testing of small specimens studied tensile capacity of the bond between ccSPF and OSB (both smooth and textured faces) and plywood after 1, 2, 4, 8, 12, and 16 weeks of water exposure. The following section summarizes the conclusions for Parts I and II.

Part I: Full-scale Wind Uplift Testing

The following conclusions were made based on results from full-scale testing:

- When exposed to water leakage, framing members and sheathing panels in ccSPF-retrofitted wood roofs accumulate higher moisture contents than those in conventional roof construction. Framing moisture contents increased to approximately 70% in ccSPF-retrofitted roofs, while the control roof maintained moisture contents between 10% and 20%. Sheathing was visibly saturated in ccSPF-retrofitted roofs, with measured moisture contents exceeding 100%. No visible moisture was identified in the control roof sheathing panels.
- Greater moisture contents were observed in roof framing and sheathing members in the south faces of ccSPF-retrofitted roofs than the north faces.

- Moisture accumulation occurred toward the eaves of ccSPF-retrofitted roofs exposed to leakage.
- High moisture contents in wood framing members were not associated with loss in wind uplift capacity of ccSPF-retrofitted roof sheathing specimens over 150-day exposure to leakage.

Part II: Small Specimen Tensile Testing

The following conclusions were made based on results from small specimen testing:

- The tensile stress capacity of wetted specimens was lower than control samples for every type of wood substrate. Reductions of 46% for OSB smooth faces, 33% for OSB textured faces, and 23% for plywood were measured.
- In wetted specimens of all types, no relationship was observed in the tensile stress capacity over the 16 weeks of water exposure.
- Wetted specimens showed no relationship between moisture content and failure stress.

Although a reduction in tensile capacity was observed between control specimens and wetted small specimens in Part II testing, there was no loss of tensile strength of wetted small specimens over the 16 weeks. Furthermore, the wind uplift capacity of ccSPF-retrofitted roof sheathing panels exposed to regular wetting over a 150-day period in Part I was no less than panels receiving no leakage. Thus, the results support the hypothesis of this study that water leakage in a wood roof does not affect its failure capacity within a season of wetting. However, ccSPF-retrofitted wood roofs exposed to the widespread leakage and regular wetting schemes used in this study accumulated high moisture contents over time in roofs with both the Level II and Level III ccSPF

retrofits, which does not support the secondary hypothesis that no accumulation will occur. If the observed moisture contents were sustained, fungal growth and loss in strength of the wood framing members would be inevitable over long periods.

Limitations

Several limitations were recognized for this research study. In Part I, the presence of wood knots and metal plate splices may have affected failure pressure. Although care was taken to install the string potentiometer correctly, screws used to install string potentiometers for displacement readings may not have always been attached to sheathing in retrofitted panels, as the sheathing surface was not visible in these panels. In Part II tests of small specimens, some splitting and premature failure of wood sheathing occurred due to high moisture contents, and some failures may have been initiated prematurely due to eccentric loading of specimens. There was also variable level of control of water spraying of the samples, with some specimens being wetted significantly more than others. Some specimens were temporarily left in standing water.

For both Part I and Part II of the research study, the exposure period to water (150 days and 16 weeks respectively) was very short in comparison to the expected service life of a residential roof of several decades. Furthermore, the wetting schemes in both Part I and Part II were highly exaggerated. For these reasons, conclusions made in this thesis cannot be applied directly to the expected in-service performance of actual ccSPF-retrofitted roofs.

Recommendations for Future Work

This research points to several opportunities for future work. It is recommended that studies be undertaken to develop and validate numerical models using finite element analysis to predict the capacity and stress distributions of ccSPF-retrofitted roof

sheathing subjected to uplift forces. It would be useful also to determine the likely failure mechanisms when ccSPF is adhered to moisture-saturated wood sheathing compared to dry panels. Further full-scale studies of longer-term exposure to rainfall and wind uplift tests are recommended to establish the likely performance of ccSPF-retrofitted wood roofs that are subjected to a realistic water leakage scenario. Investigation of the effects of the presence of wood rot on the ccSPF-to-wood bond may provide useful insight into the long-term performance of leaking retrofitted roofs. Finally, a cost-benefit analysis of applying a ccSPF retrofit to the underside of roof sheathing considering initial cost, maintenance, risk of failure/degradation, energy savings, etc. may demonstrate the overall utility of the ccSPF retrofit to wood roof sheathing.

APPENDIX A
PERCENTAGE POINTS OF THE STUDENTIZED RANGE (ALPHA = 0.05)

Table A-1. Percentage points of the Studentized range for α = 0.05

	t									
dfE	2	3	4	5	6	7	8	9	10	11
1	17.97	26.98	32.82	37.08	40.41	43.12	45.40	47.36	49.07	50.39
2	6.08	8.33	9.80	10.88	11.74	12.44	13.03	13.54	13.99	14.39
3	4.50	5.91	6.82	7.50	8.04	8.48	8.85	9.18	9.46	9.72
4	3.93	5.04	5.76	6.29	6.71	7.05	7.35	7.60	7.83	8.03
5	3.64	4.60	5.22	5.67	6.03	6.33	6.58	6.80	6.99	7.17
6	3.46	4.34	4.90	5.30	5.63	5.90	6.12	6.32	6.49	6.65
7	3.34	4.16	4.68	5.06	5.36	5.61	5.82	6.00	6.16	6.30
8	3.26	4.04	4.53	4.89	5.17	5.40	5.60	5.77	5.92	6.05
9	3.20	3.95	4.41	4.76	5.02	5.24	5.43	5.59	5.74	5.87
10	3.15	3.88	4.33	4.65	4.91	5.12	5.30	5.46	5.60	5.72
11	3.11	3.82	4.26	4.57	4.82	5.03	5.20	5.35	5.49	5.61
12	3.08	3.77	4.20	4.51	4.75	4.95	5.12	5.27	5.39	5.51
13	3.06	3.73	4.15	4.45	4.69	4.88	5.05	5.19	5.32	5.43
14	3.03	3.70	4.11	4.41	4.64	4.83	4.99	5.13	5.25	5.36
15	3.01	3.67	4.08	4.37	4.60	4.78	4.94	5.08	5.20	5.31
16	3.00	3.65	4.05	4.33	4.56	4.74	4.90	5.03	5.15	5.26
17	2.98	3.63	4.02	4.30	4.52	4.70	4.86	4.99	5.11	5.21
18	2.97	3.61	4.00	4.28	4.49	4.67	4.82	4.96	5.07	5.17
19	2.96	3.59	3.98	4.25	4.47	4.65	4.79	4.92	5.04	5.14
20	2.95	3.58	3.96	4.23	4.45	4.62	4.77	4.90	5.01	5.11
24	2.92	3.53	3.90	4.17	4.37	4.54	4.68	4.81	4.92	5.01
30	2.89	3.49	3.85	4.10	4.30	4.46	4.60	4.72	4.82	4.92
40	2.86	3.44	3.79	4.04	4.23	4.39	4.52	4.63	4.73	4.82
60	2.83	3.40	3.74	3.98	4.16	4.31	4.44	4.55	4.65	4.73
120	2.80	3.36	3.68	3.92	4.10	4.24	4.36	4.47	4.56	4.64
∞	2.77	3.31	3.63	3.86	4.03	4.17	4.29	4.39	4.47	4.50

APPENDIX B
HOURLY RAINFALL AT GAINESVILLE REGIONAL AIRPORT DURING FULL-SCALE EXPOSURE

Table B-1. August 2010 measured hourly rainfall (in.) at Gainesville Regional Airport

D/HR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Sum
1														0.11	0.04										0.15
2																									0
3																									0
4																									0
5																									0
6													0.41	0.04											0.45
7											T	T	T	T	T				0.67	0.18	0.09				0.94
8																									0
9														T		T									0
10										0.01	0.06	0.01													0.08
11																			T	T					0
12											0.35			T	T		0.06								0.41
13									0.16		T	0.14	T	0.37	0.11	T	0.06	T	T						0.84
14												0.01				0.09	T								0.1
15												0.04	0.01		T	T									0.05
16																									0
17																			T	0.02	T	0.02	0.02		0.06
18																									0
19																									0
20												0.08	0.03	T											0.11
21						0.02				T	T	T	T									T			0.02
22																		0.34		T					0.34
23															T						0.01	T			0.01
24										0.01	0.06	0.09	0.03	T							T				0.19
25				T	T	T																			0
26					0.18	T							T	0.22	0.27	0.28	0.02	T	T	T	0.01	0.03	T	T	1.01
27	T	0.01	0.04	T	T	T											0.09	T				T			0.14
28									T		T	T							T	T					0
29											T					T									0
30																									0
31																									0

Start Date

NCDC. (2011). "Quality Controlled Local Climatological Data." NOAA National Climatic Data Center, Asheville, NC.

Table B-2. September 2010 measured hourly rainfall (in.) at Gainesville Regional Airport

D/HR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Sum
1																									0
2																									0
3																									0
4																									0
5																0.07									0.07
6																	T	0.27	T						0.27
7												T	T												0
8																									0
9																									0
10																									0
11																									0
12																0.02	0.3	0.01							0.33
13																									0
14																									0
15																									0
16																									0
17																									0
18																									0
19																									0
20																									0
21																									0
22																									0
23												T	T		0.02	0.02									0.04
24													T					T	T						0
25	T					T	T												T						0
26				T	0.06	0.01																T	0.08	0.04	0.19
27												T	0.23	0.17	0.02	0.01	T								0.43
28																T	T							0.01	0.01
29	T												T				T	T	T	T	0.01	T			0.01
30								T	T	T															0

NCDC. (2011). "Quality Controlled Local Climatological Data." NOAA National Climatic Data Center, Asheville, NC.

Table B-3. October 2010 measured hourly rainfall (in.) at Gainesville Regional Airport

D/HR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Sum
1																									0
2																									0
3																									0
4																									0
5																									0
6																									0
7																									0
8																									0
9																									0
10																									0
11																									0
12																									0
13																									0
14																									0
15																									0
16																									0
17																									0
18																									0
19																									0
20																									0
21																									0
22																									0
23																									0
24																									0
25																									0
26																									0
27																									0
28																		T							0
29																									0
30																									0
31																									0

NCDC. (2011). "Quality Controlled Local Climatological Data." NOAA National Climatic Data Center, Asheville, NC.

Table B-4. November 2010 measured hourly rainfall (in.) at Gainesville Regional Airport

D/HR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Sum
1																									0
2									T			T					T	0.01	T	0.05	0.09	0.03	0.01	T	0.19
3	0.04	0.03																							0.07
4			T	T	T			T						T	0.09	0.02									0.11
5																									0
6																									0
7																									0
8																									0
9																									0
10																									0
11																									0
12																									0
13																									0
14																									0
15																									0
16										T	T	T		0.03	0.04	T					T	T	T		0.07
17																									0
18																									0
19																									0
20																									0
21																									0
22																									0
23																									0
24																									0
25																									0
26													T		T		T						T	0.09	0.09
27																									0
28																									0
29																					T	0.01	T	0.01	0.02
30	T	T	T														0.01	T							0.01

NCDC. (2011). "Quality Controlled Local Climatological Data." NOAA National Climatic Data Center, Asheville, NC.

Table B-5. December 2010 measured hourly rainfall (in.) at Gainesville Regional Airport

D/HR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Sum
1		T	T	T	0.01	0.01																			0.02
2																									0
3																									0
4																									0
5					0.02	T																			0.02
6																									0
7																									0
8																									0
9																									0
10										T	T														0
11																									0
12										0.04	0.02	0.07	T												0.13
13																									0
14																									0
15																									0
16											T	T	T		T										0
17																									0
18										T														T	0
19	T																								0
20																									0
21																									0
22																									0
23																									0
24																									0
25																		T	0.14	0.18	0.1	0.09	T		0.51
26	T			0.01				T	T																0.01
27																									0
28																									0
29																									0
30																									0
31																									0

NCDC. (2011). "Quality Controlled Local Climatological Data." NOAA National Climatic Data Center, Asheville, NC.

Table B-6. January 2011 measured hourly rainfall (in.) at Gainesville Regional Airport

D/HR	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Sum
1																									0
2									T			T					T	0.01	T	0.05	0.09	0.03	0.01	T	0.19
3	0.04	0.03																							0.07
4			T	T	T			T						T	0.09	0.02									0.11
5																									0
6																	**All Panels Removed**								0
7																									0
8																									0
9																									0
10																									0
11																									0
12																									0
13																									0
14																									0
15																									0
16										T	T	T		0.03	0.04	T					T	T	T		0.07
17																									0
18																									0
19																									0
20																									0
21																									0
22																									0
23																									0
24																									0
25																									0
26													T		T		T						T	0.09	0.09
27																									0
28																									0
29																					T	0.01	T	0.01	0.02
30	T	T	T														0.01	T							0.01
31																									0

NCDC. (2011). "Quality Controlled Local Climatological Data." NOAA National Climatic Data Center, Asheville, NC.

APPENDIX C
FULL-SCALE WIND UPLIFT TESTING SUMMARY

Code	Date Harvested	Test Date	Days Between*	Roof Number	Sheathing Letter	Retrofit Type	Treatment	Clamped?	Failure Pressure (psf)	Truss Code	Original Mass, A (g)	Oven-dry Mass, B (g)	MC (%)	Specimen Dimensions L (in)	w (in)	t (in)	SG
R1-E	1.8.11	1.13.11	5	1	E	-	wet	no	56.6	2	62.5	57.6	8.5	3.45	1.50	1.00	0.68
										3	42.7	39.2	8.9	3.43	1.50	0.98	0.48
										4	53.1	48.6	9.3	3.45	1.53	1.00	0.56
										5	47.5	43.8	8.4	3.38	1.45	1.08	0.51
										6	37.9	34.8	8.9	3.35	1.48	1.00	0.43
R2-H	1.11.11	1.14.11	3	2	H	II	wet	no	256.5	2	61.1	54.9	11.3	3.43	1.48	1.10	0.60
										3	62.2	48.9	27.2	3.5	1.525	1.075	0.52
										4	52.4	38.0	37.9	3.55	1.525	1.075	0.40
										5	67.2	45.3	48.3	3.525	1.525	1.05	0.49
										6	56.6	43.2	31.0	3.5	1.475	1.125	0.45
R1-A	1.8.11	1.17.11	9	1	A	-	wet	no	60.7	2	45.8	40.8	12.3	3.43	1.48	1.03	0.48
										3	49.9	44.7	11.6	3.38	1.48	1.05	0.52
										4	49.9	44.8	11.4	3.43	1.50	1.03	0.52
										5	63.5	57.2	11.0	3.40	1.50	1.13	0.61
										6	48.2	43.1	11.8	3.40	1.45	1.05	0.51
R4-F	1.14.11	1.17.11	3	4	F	III	wet	no	406.1	2	48.0	41.6	15.4	3.48	1.50	1.05	0.46
										3	63.5	55.1	15.2	3.45	1.50	1.00	0.65
										4	46.1	42.1	9.5	3.43	1.48	0.95	0.54
										5	50.0	46.0	8.7	3.40	1.45	1.05	0.54
										6	51.9	43.0	20.7	3.48	1.55	1.08	0.45
R3-D	1.13.11	1.17.11	4	3	D	II	dry	no	271.2	2	49.7	45.5	9.2	3.45	1.48	1.05	0.52
										3	55.2	50.2	10.0	3.35	1.45	1.25	0.50
										4	43.5	39.9	9.0	3.45	1.48	1.00	0.48
										5	47.3	43.0	10.0	3.38	1.48	0.95	0.55
										6	59.4	54.3	9.4	3.35	1.48	1.15	0.58
R2-G	1.11.11	1.18.11	7	2	G	II	wet	no	225.1	2	60.2	52.4	14.9	3.45	1.50	1.10	0.56
										3	54.1	46.7	15.8	3.48	1.50	1.05	0.52
										4	46.7	39.4	18.5	3.55	1.53	1.10	0.40
										5	59.5	44.9	32.5	3.55	1.58	1.00	0.49
										6	44.6	37.6	18.6	3.53	1.48	0.95	0.46
R3-C	1.13.11	1.18.11	5	3	C	II	dry	no	329.2	2	50.9	46.4	9.7	3.45	1.50	0.95	0.58
										3	44.7	40.5	10.4	3.35	1.48	1.00	0.50
										4	44.1	40.1	10.0	3.48	1.50	1.03	0.46
										5	48.5	44.3	9.5	3.40	1.48	1.00	0.54
										6	44.7	40.6	10.1	3.40	1.48	1.00	0.49
R1-B	1.8.11	1.18.11	10	1	B	-	wet	no	50.0	2	43.0	38.5	11.7	3.40	1.50	0.98	0.47
										3	47.8	42.9	11.4	3.40	1.48	1.00	0.52
										4	46.7	41.9	11.5	3.40	1.50	0.94	0.53
										5	49.0	43.8	11.9	3.40	1.50	1.00	0.52
										6	50.0	44.9	11.4	3.43	1.48	1.06	0.51

*Number of days between harvesting and testing

R2-F	1.11.11	1.18.11	7	2	F	II	wet	no	358.4	2	57.3	52.6	8.9	3.35	1.48	0.95	0.68
										3	33.8	30.6	10.5	3.45	1.53	0.90	0.39
										4	70.5	57.5	22.6	3.50	1.58	0.93	0.69
										5	67.0	59.1	13.4	3.40	1.50	1.10	0.64
										6	47.0	39.5	19.0	3.48	1.50	0.95	0.49
R3-B	1.13.11	1.18.11	5	3	B	II	dry	no	256.0	2	47.7	43.4	9.9	3.45	1.50	1.08	0.48
										3	46.1	42.0	9.8	3.45	1.48	1.03	0.49
										4	55.5	50.3	10.3	3.43	1.48	1.00	0.61
										5	55.6	50.4	10.3	3.45	1.53	1.13	0.52
										6	58.0	52.7	10.1	3.40	1.48	1.03	0.63
R1-C	1.8.11	1.18.11	10	1	C	-	wet	no	45.4	2	49.6	44.5	11.5	3.35	1.45	1.10	0.51
										3	55.7	50.0	11.4	3.48	1.50	1.03	0.57
										4	63.7	58.1	9.6	3.43	1.45	1.10	0.65
										5	36.3	32.7	11.0	3.45	1.48	0.98	0.40
										6	50.2	45.1	11.3	3.45	1.48	1.05	0.51
R2-E	1.11.11	1.18.11	7	2	E	II	wet	no	220.4	2	54.3	49.7	9.3	3.35	1.53	1.03	0.58
										3	52.6	48.8	7.8	3.43	1.45	1.08	0.56
										4	56.9	52.4	8.6	3.43	1.48	1.10	0.58
										5	50.1	46.0	8.9	3.30	1.45	0.93	0.63
										6	53.8	46.7	15.2	3.43	1.53	1.08	0.51
R3-A	1.13.11	1.18.11	5	3	A	II	dry	no	269.1	2	42.6	38.4	10.9	3.43	1.48	0.98	0.48
										3	47.8	43.3	10.4	3.45	1.50	1.00	0.51
										4	63.9	-	-	3.45	1.50	1.05	-
										5	54.6	49.3	10.8	3.45	1.48	1.03	0.58
										6	63.0	57.4	9.8	3.53	1.50	1.08	0.62
R2-A	1.11.11	1.19.11	8	2	A	II	wet	no	271.2	2	60.4	54.0	11.9	3.45	1.49	1.07	0.60
										3	49.8	41.2	20.9	3.47	1.51	0.92	0.52
										4	58.2	49.9	16.6	3.47	1.48	1.06	0.56
										5	56.2	50.3	11.7	3.40	1.49	1.02	0.59
										6	63.6	56.0	13.6	3.48	1.50	1.02	0.65
R4-G	1.14.11	1.19.11	5	4	G	III	wet	no	225.1	2	69.3	53.8	28.8	3.54	1.54	1.12	0.54
										3	48.3	41.9	15.3	1.50	1.51	1.01	1.11
										4	54.9	38.1	44.1	3.53	1.53	0.95	0.45
										5	61.9	50.3	23.1	3.54	1.55	1.01	0.55
										6	73.6	51.8	42.1	3.55	1.54	1.09	0.53
R3-E	1.13.11	1.19.11	6	3	E	II	dry	no	209.6	2	42.0	38.6	8.8	3.50	1.54	1.08	0.41
										3	48.9	45.1	8.4	3.46	1.45	1.33	0.41
										4	46.9	43.2	8.6	3.42	1.49	0.95	0.54
										5	41.0	37.6	9.0	3.41	1.49	1.35	0.33
										6	57.3	52.6	8.9	3.48	1.54	1.09	0.55
L II-A	-	1.19.11	-	L II	A	II	lab	no	164.7	2	32.1	28.3	13.4	3.5	1.50	0.97	0.34
										3	36.9	33.0	11.8	3.5	1.49	1.05	0.37
										4	40.9	36.4	12.4	3.5	1.50	1.05	0.40
										5	43.0	38.4	12.0	3.5	1.44	1.03	0.45
										6	42.0	37.5	12.0	3.5	1.47	0.99	0.45

R4-H	1.14.11	1.19.11	5	4	H	III	wet	no	358.5	2	73.3	54.8	33.8	3.54	1.53	1.57	0.39
										3	62.1	55.7	11.5	3.49	1.50	1.03	0.63
										4	66.3	40.7	62.9	3.55	1.54	1.05	0.43
										5	48.2	43.7	10.3	3.44	1.49	0.95	0.55
										6	66.2	48.8	35.7	3.52	1.54	1.11	0.50
R1-H	1.8.11	1.19.11	11	1	H	-	wet	no	70.6	2	40.5	36.2	11.9	3.46	1.55	0.98	0.42
										3	53.8	48.4	11.2	3.43	1.48	1.01	0.58
										4	56.6	50.9	11.2	3.40	1.49	1.02	0.61
										5	55.9	50.4	10.9	3.51	1.50	1.07	0.55
										6	70.1	62.5	12.2	3.40	1.48	1.06	0.72
LIII-A	-	1.20.11	-	L III	A	III	lab	yes	318.0	2	60.1	54.6	10.1	3.50	1.51	1.11	0.57
										3	44.3	39.8	11.3	3.50	1.49	0.97	0.48
										4	39.4	35.1	12.3	3.41	1.50	0.96	0.43
										5	49.3	44.0	12.0	3.50	1.51	1.03	0.49
										6	55.3	49.6	11.5	3.68	1.51	1.03	0.53
R1-G	1.8.11	1.20.11	12	1	G	-	wet	yes	57.5	2	47.5	42.6	11.5	3.49	1.50	1.03	0.48
										3	64.3	58.0	10.9	3.43	1.47	1.07	0.65
										4	55.2	49.9	10.6	3.39	1.46	1.02	0.61
										5	49.4	44.9	10.0	3.52	1.50	1.02	0.51
										6	53.8	48.8	10.2	3.43	1.47	1.08	0.55
R2-B	1.11.11	1.20.11	9	2	B	II	wet	yes	240.9	2	70.7	65.1	8.6	3.47	1.49	1.03	0.75
										3	56.4	50.9	10.8	3.43	1.48	1.11	0.55
										4	76.1	67.0	13.6	3.48	1.49	1.08	0.73
										5	61.3	49.6	23.6	3.50	1.51	0.96	0.60
										6	55.8	48.4	15.3	3.48	1.49	0.98	0.58
R3-F	1.13.11	1.20.11	7	3	F	II	dry	yes	239.2	2	39.4	36.1	9.1	3.45	1.50	0.97	0.44
										3	54.1	49.9	8.4	3.38	1.48	0.93	0.65
										4	41.0	37.8	8.5	3.43	1.49	0.93	0.49
										5	42.6	39.3	8.4	3.40	1.49	1.11	0.43
										6	58.0	53.0	9.4	3.34	1.50	1.05	0.61
R4-D	1.14.11	1.20.11	6	4	D	III	wet	yes	406.2	2	54.4	49.8	9.2	3.41	1.47	1.02	0.59
										3	38.8	34.1	13.8	3.44	1.42	1.10	0.39
										4	58.8	53.2	10.5	3.40	1.50	1.07	0.60
										5	44.0	39.8	10.6	3.35	1.47	0.97	0.51
										6	40.6	36.8	10.3	3.43	1.48	1.09	0.41
LIII-B	-	1.20.11	-	L III	B	III	lab	yes	228.4	2	73.7	64.9	13.6	3.43	1.53	1.03	0.73
										3	46.0	41.2	11.7	3.52	1.53	0.93	0.50
										4	52.2	46.6	12.0	3.48	1.55	0.99	0.53
										5	56.6	50.4	12.3	3.50	1.54	1.04	0.55
										6	46.5	41.5	12.0	3.51	1.53	1.00	0.47
R5-C	1.18.11	1.20.11	2	5	C	III	dry	yes	362.2	2	35.8	32.7	9.5	3.40	1.48	0.95	0.42
										3	52.6	48.2	9.1	3.46	1.48	0.97	0.59
										4	43.9	39.9	10.0	3.33	1.48	0.92	0.53
										5	52.9	48.8	8.4	3.44	1.49	0.92	0.63
										6	56.0	50.9	10.0	3.38	1.47	0.98	0.64

R5-G	1.18.11	1.20.11	2	5	G	III	dry	yes	275.5	2	35.6	33.0	7.9	3.43	1.45	0.94	0.43
										3	56.6	52.6	7.6	3.43	1.47	0.96	0.66
										4	35.0	32.5	7.7	3.43	1.46	0.86	0.46
										5	40.5	37.5	8.0	3.39	1.48	0.97	0.47
										6	68.7	64.3	6.8	3.46	1.51	0.99	0.77
R5-A	1.18.11	1.21.11	3	5	A	III	dry	yes	361.1	2	40.7	36.8	10.6	3.40	1.48	0.99	0.45
										3	55.9	50.8	10.0	3.37	1.17	0.95	0.83
										4	57.4	52.1	10.2	3.43	1.50	1.07	0.58
										5	44.5	40.6	9.6	3.44	1.48	1.04	0.47
										6	63.6	57.9	9.8	3.44	1.51	1.12	0.61
R4-C	1.14.11	1.21.11	7	4	C	III	wet	no	421.5	2	48.8	31.4	55.4	3.47	1.52	1.02	0.35
										3	53.2	48.1	10.6	3.40	1.47	1.01	0.58
										4	49.3	44.7	10.3	3.43	1.49	0.98	0.54
										5	50.7	42.4	19.6	3.42	1.52	0.93	0.54
										6	39.4	34.8	13.2	3.46	1.49	1.00	0.41
LII-B	-	1.21.11	-	L II	B	II	lab	yes	301.2	2	46.8	41.4	13.0	3.47	1.53	1.04	0.46
										3	49.9	44.5	12.1	3.48	1.54	1.07	0.48
										4	38.1	34.6	10.1	3.50	1.56	1.07	0.36
										5	54.1	48.2	12.2	3.48	1.52	1.03	0.54
										6	45.4	40.7	11.5	3.50	1.55	1.04	0.44
R1-F	1.8.11	1.21.11	13	1	F	-	wet	no	45.6	2	54.4	49.1	10.8	3.46	1.49	1.00	0.58
										3	41.2	37.0	11.4	3.40	1.48	1.00	0.45
										4	47.9	43.4	10.4	3.45	1.50	1.00	0.51
										5	43.4	39.1	11.0	3.40	1.48	1.05	0.45
										6	45.9	41.2	11.4	3.40	1.46	1.06	0.48
R5-B	1.18.11	1.21.11	3	5	B	III	dry	yes	286.2	2	46.7	42.4	10.1	3.38	1.49	1.04	0.49
										3	49.2	44.7	10.1	3.38	1.48	0.93	0.59
										4	50.4	45.9	9.8	3.42	1.89	0.89	0.49
										5	42.9	39.1	9.7	3.44	1.49	1.01	0.46
										6	45.3	41.2	10.0	3.42	1.49	0.99	0.50
R2-C	1.11.11	1.22.11	11	2	C	II	wet	yes	301.0	2	58.7	53.3	10.1	3.77	1.89	0.94	0.49
										3	59.8	54.7	9.3	3.32	1.40	1.00	0.72
										4	53.7	45.8	17.2	3.40	1.44	1.10	0.52
										5	57.2	51.1	11.9	3.39	1.41	1.12	0.58
										6	55.2	49.6	11.3	3.46	1.49	1.05	0.56
R3-G	1.13.11	1.22.11	9	3	G	II	dry	yes	222.4	2	54.0	49.7	8.7	3.41	1.50	1.09	0.54
										3	52.5	48.4	8.5	3.37	1.50	0.98	0.59
										4	62.9	57.9	8.6	3.42	1.51	1.01	0.68
										5	41.0	37.7	8.8	3.38	1.44	0.98	0.48
										6	62.9	57.7	9.0	3.42	1.51	1.08	0.63
LII-C	-	1.22.11	-	L II	C	II	lab	yes	274.9	2	46.5	42.6	9.2	3.52	1.55	1.02	0.47
										3	63.6	58.3	9.1	3.48	1.57	1.01	0.65
										4	60.6	55.2	9.8	3.50	1.55	1.06	0.59
										5	43.5	39.4	10.4	3.50	1.54	1.07	0.42
										6	56.0	51.0	9.8	3.51	1.54	1.07	0.54

R4-A	1.14.11	1.22.11	8	4	A	III	wet	yes	458.8	2	39.1	34.8	12.4	3.45	1.48	0.99	0.42
										3	54.6	49.3	10.8	3.43	1.52	0.99	0.58
										4	40.2	34.7	15.9	3.49	1.50	1.04	0.39
										5	46.4	42.2	10.0	3.39	1.49	0.98	0.52
										6	60.7	55.1	10.2	3.40	1.47	1.17	0.58
R2-D	1.11.11	1.22.11	11	2	D	II	wet	yes	286.3	2	53.4	48.5	10.1	3.37	1.46	1.11	0.54
										3	46.4	41.9	10.7	3.39	1.47	1.01	0.51
										4	42.3	38.7	9.3	3.48	1.51	1.00	0.45
										5	50.1	45.6	9.9	3.46	1.48	1.02	0.53
										6	51.2	46.7	9.6	3.43	1.49	1.02	0.55
R4-B	1.14.11	1.24.11	10	4	B	III	wet	yes	315.9	2	45.7	41.0	11.5	3.43	1.50	1.00	0.48
										3	61.4	55.7	10.2	3.43	1.51	1.03	0.64
										4	42.5	36.0	18.1	3.48	1.49	0.96	0.44
										5	53.2	47.1	13.0	3.43	1.52	1.55	0.35
										6	50.2	44.7	12.3	3.43	1.47	1.00	0.54
R1-D	1.8.11	1.24.11	16	1	D	-	wet	yes	42.8	2	41.3	37.9	9.0	3.38	1.46	1.00	0.47
										3	54.9	50.2	9.4	3.48	1.52	1.00	0.58
										4	49.1	44.8	9.6	3.34	1.44	1.02	0.56
										5	44.7	41.0	9.0	3.43	1.45	1.01	0.50
										6	48.3	44.0	9.8	3.42	1.52	0.94	0.55
R3-H	1.13.11	1.24.11	11	3	H	II	dry	yes	376.3	2	51.6	47.4	8.9	3.39	1.47	1.05	0.55
										3	49.8	45.8	8.7	3.37	1.49	1.00	0.56
										4	41.2	37.8	9.0	3.40	1.47	1.00	0.46
										5	48.1	44.0	9.3	3.36	1.46	1.06	0.52
										6	53.6	49.1	9.2	3.40	1.46	0.97	0.63
LII-D	-	1.24.11	-	L II	D	II	lab	yes	271.2	2	54.3	48.7	11.5	3.48	1.53	1.03	0.54
										3	49.5	44.8	10.5	3.51	1.55	1.05	0.48
										4	55.3	50.3	9.9	3.49	1.57	1.01	0.55
										5	48.3	43.4	11.3	3.50	1.52	0.86	0.58
										6	41.3	37.5	10.1	3.47	1.49	0.97	0.46
R5-D	1.18.11	1.24.11	6	5	D	III	dry	yes	299.7	2	41.2	37.6	9.6	3.40	1.50	1.04	0.43
										3	50.8	46.4	9.5	3.35	1.45	1.00	0.59
										4	60.2	55.1	9.3	3.38	1.49	1.01	0.66
										5	46.0	42.1	9.3	3.43	1.48	0.97	0.52
										6	59.3	54.1	9.6	3.34	1.46	1.11	0.61
R5-H	1.18.11	1.25.11	7	5	H	III	dry	no	285.0	2	46.2	42.6	8.5	3.41	1.47	1.02	0.51
										3	60.2	55.4	8.7	3.44	1.50	0.93	0.71
										4	43.8	40.5	8.1	3.44	1.48	1.03	0.47
										5	45.1	41.6	8.4	3.37	1.48	1.04	0.49
										6	58.7	54.1	8.5	3.44	1.46	1.02	0.64
LIII-C	-	1.25.11	-	L III	C	III	lab	yes	257.6	2	43.4	39.0	11.3	3.50	1.55	0.98	0.45
										3	58.2	52.4	11.1	3.47	1.53	0.95	0.63
										4	38.1	34.7	9.8	3.45	1.55	0.95	0.42
										5	54.2	48.7	11.3	3.46	1.52	0.98	0.58
										6	40.6	36.3	11.8	3.47	1.57	0.97	0.42

R5-F	1.18.11	1.25.11	7	5	F	III	dry	no	257.6	2	49.1	45.2	8.6	3.4	1.49	1.04	0.53
										3	56	51.5	8.7	3.4	1.49	1.10	0.56
										4	47.1	43.3	8.8	3.46	1.51	1.01	0.50
										5	61.6	57.6	6.9	3.42	1.46	1.05	0.67
										6	41.2	37.9	8.7	3.35	1.47	1.05	0.45
R5-E	1.18.11	1.25.11	7	5	E	III	dry	yes	226.1	2	48.2	44.4	8.6	3.33	1.48	1.03	0.53
										3	54.1	50.1	8.0	3.38	1.47	1.05	0.59
										4	47.6	44.0	8.2	3.44	1.48	0.99	0.53
										5	42.2	38.7	9.0	3.35	1.47	1.04	0.46
										6	43.3	39.7	9.1	3.34	1.47	1.09	0.46
LIII-D	-	1.25.11	-	L III	D	III	lab	yes	213.0	2	41.9	37.6	11.4	3.50	1.54	1.04	0.41
										3	57.6	51.6	11.6	3.46	1.54	1.09	0.54
										4	48.5	43.4	11.8	3.48	1.53	1.00	0.50
										5	53.3	47.5	12.2	3.43	1.51	0.99	0.56
										6	45.8	41.0	11.7	3.47	1.54	1.00	0.47
R4-E	1.14.11	1.25.11	11	4	E	III	wet	yes	474.5	2	43.1	39.5	9.1	3.359	1.479	0.99	0.49
										3	65.1	59.8	8.9	3.427	1.486	1.051	0.68
										4	51.3	46.9	9.4	3.415	1.508	1.034	0.54
										5	49.2	45.7	7.7	3.377	1.459	1.055	0.54
										6	48.7	44.5	9.4	3.355	1.449	1.015	0.55

Retrofit Types: C - Control; II - Level II Retrofit; III - Level III Retrofit
Treatments: W - Wet (Leakage Introduced); D - Dry (No Leakage Introduced)
Failure Mode: TBD (See Prevatt 2007)

APPENDIX D
FULL-SCALE TRUSS SPECIFIC GRAVITIES

Table D-1. Roof 1 specific gravities at time of structural testing

Panel	2	3	4	5	6
A	0.5	0.5	0.5	0.6	0.5
B	0.5	0.5	0.5	0.5	0.5
C	0.5	0.6	0.7	0.4	0.5
D	0.5	0.6	0.6	0.5	0.6
E	0.7	0.5	0.6	0.5	0.4
F	0.6	0.5	0.5	0.5	0.5
G	0.5	0.7	0.6	0.5	0.6
H	0.4	0.6	0.6	0.6	0.7
	Truss Number				

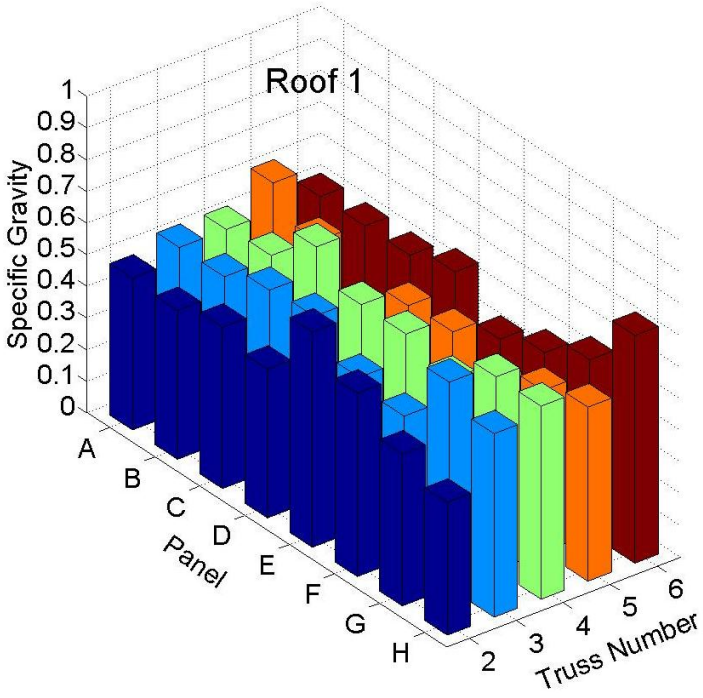


Figure D-1. Roof 1 specific gravities at time of structural testing

Table D-2. Roof 2 specific gravities at time of structural testing

Panel	2	3	4	5	6
A	0.6	0.5	0.6	0.6	0.7
B	0.8	0.6	0.7	0.6	0.6
C	0.5	0.7	0.5	0.6	0.6
D	0.5	0.5	0.5	0.5	0.6
E	0.6	0.6	0.6	0.6	0.5
F	0.7	0.4	0.7	0.6	0.5
G	0.6	0.5	0.4	0.5	0.5
H	0.6	0.5	0.4	0.5	0.5
	Truss Number				

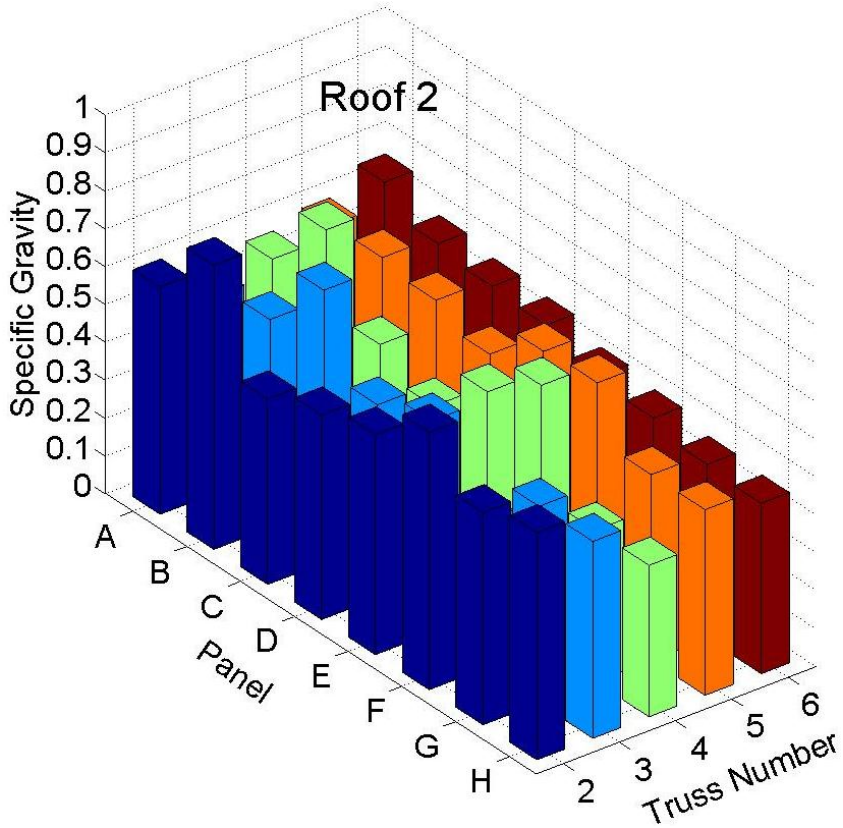


Figure D-2. Roof 2 specific gravities at time of structural testing

Table D-3. Roof 3 specific gravities at time of structural testing

Panel						
	A	0.5	0.5	-	0.6	0.6
	B	0.5	0.5	0.6	0.5	0.6
	C	0.6	0.5	0.5	0.5	0.5
	D	0.5	0.5	0.5	0.6	0.6
	E	0.4	0.4	0.5	0.3	0.6
	F	0.4	0.7	0.5	0.4	0.6
	G	0.5	0.6	0.7	0.5	0.6
	H	0.6	0.6	0.5	0.5	0.6
		2	**3**	**4**	**5**	**6**
		Truss Number				

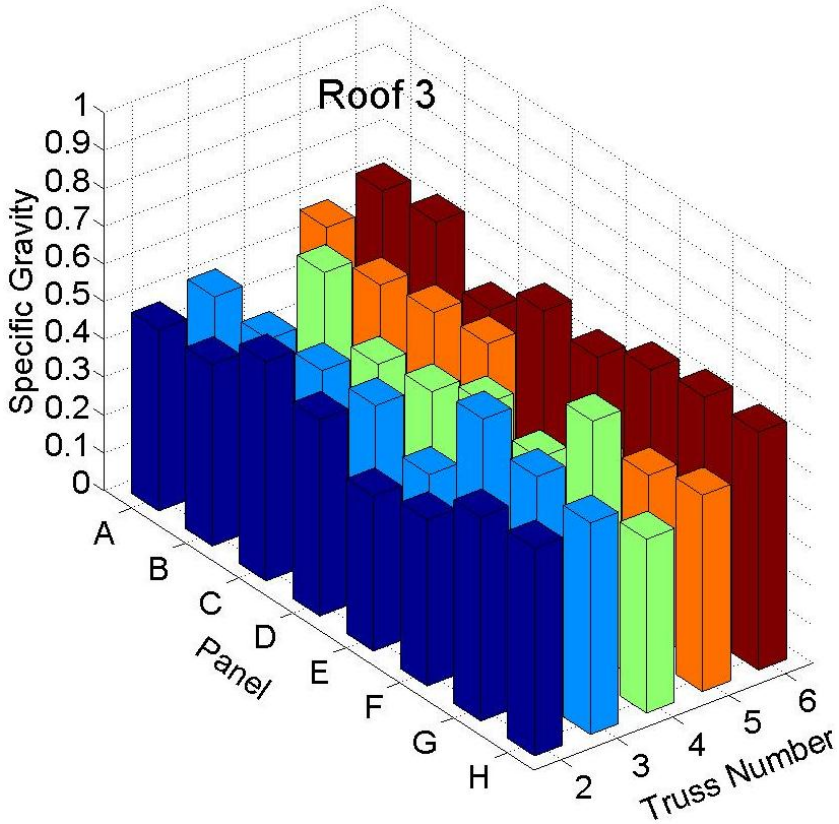


Figure D-3. Roof 3 specific gravities at time of structural testing

Table D-4. Roof 4 specific gravities at time of structural testing

Panel	2	3	4	5	6
A	0.4	0.6	0.4	0.5	0.6
B	0.5	0.6	0.4	0.4	0.5
C	0.4	0.6	0.5	0.5	0.4
D	0.6	0.4	0.6	0.5	0.4
E	0.5	0.7	0.5	0.5	0.6
F	0.5	0.7	0.5	0.5	0.5
G	0.5	1.1	0.5	0.6	0.5
H	0.4	0.6	0.4	0.6	0.5
	Truss Number				

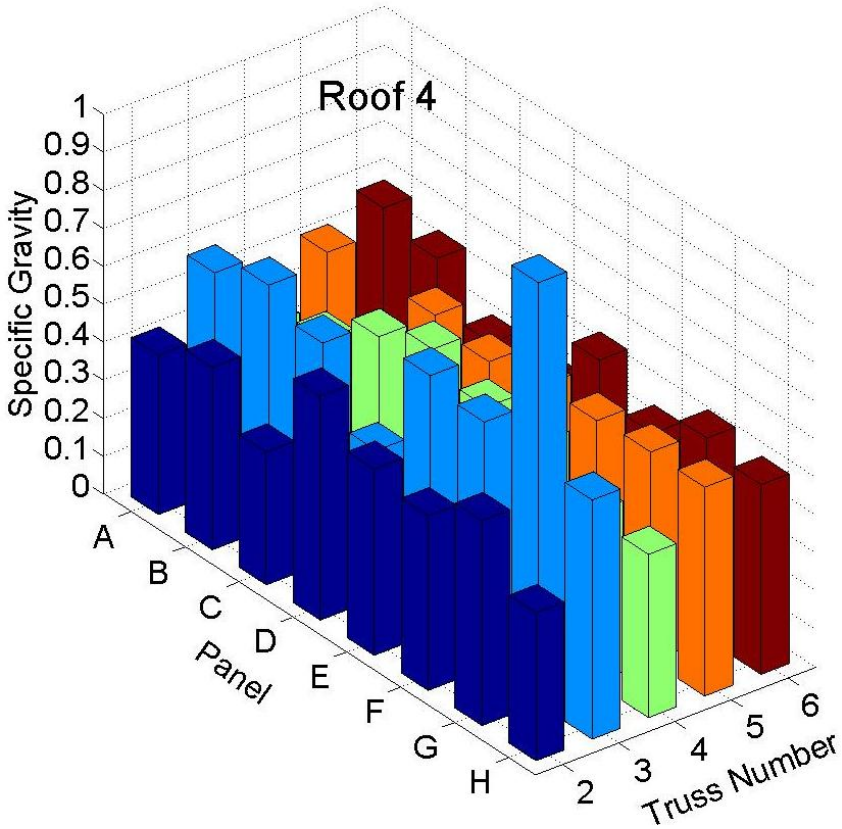


Figure D-4. Roof 4 specific gravities at time of structural testing

Table D-5. Roof 5 specific gravities at time of structural testing

Panel	2	3	4	5	6
A	0.5	0.8	0.6	0.5	0.6
B	0.5	0.6	0.5	0.5	0.5
C	0.4	0.6	0.5	0.6	0.6
D	0.4	0.6	0.7	0.5	0.6
E	0.5	0.6	0.5	0.5	0.5
F	0.5	0.6	0.5	0.7	0.5
G	0.4	0.7	0.5	0.5	0.8
H	0.5	0.7	0.5	0.5	0.6
	Truss Number				

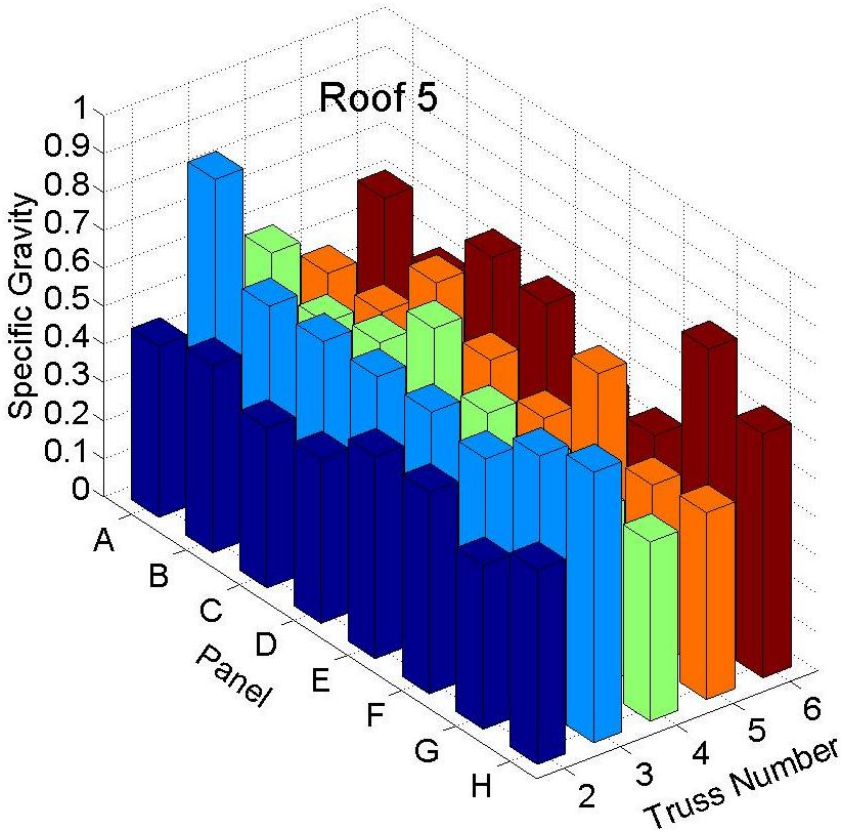


Figure D-5. Roof 5 specific gravities at time of structural testing

Table D-6. Laboratory-built specific gravities at time of structural testing

Panel							
	LII	A	0.3	0.4	0.4	0.5	0.4
		B	0.5	0.5	0.4	0.5	0.4
		C	0.5	0.6	0.6	0.4	0.5
		D	0.5	0.5	0.6	0.6	0.5
	LIII	A	0.6	0.5	0.4	0.5	0.5
		B	0.7	0.5	0.5	0.6	0.5
		C	0.4	0.6	0.4	0.6	0.4
		D	0.4	0.5	0.5	0.6	0.5
			2	**3**	**4**	**5**	**6**
			Truss Number				

APPENDIX E
FULL-SCALE FOAM DEPTH MEASUREMENTS

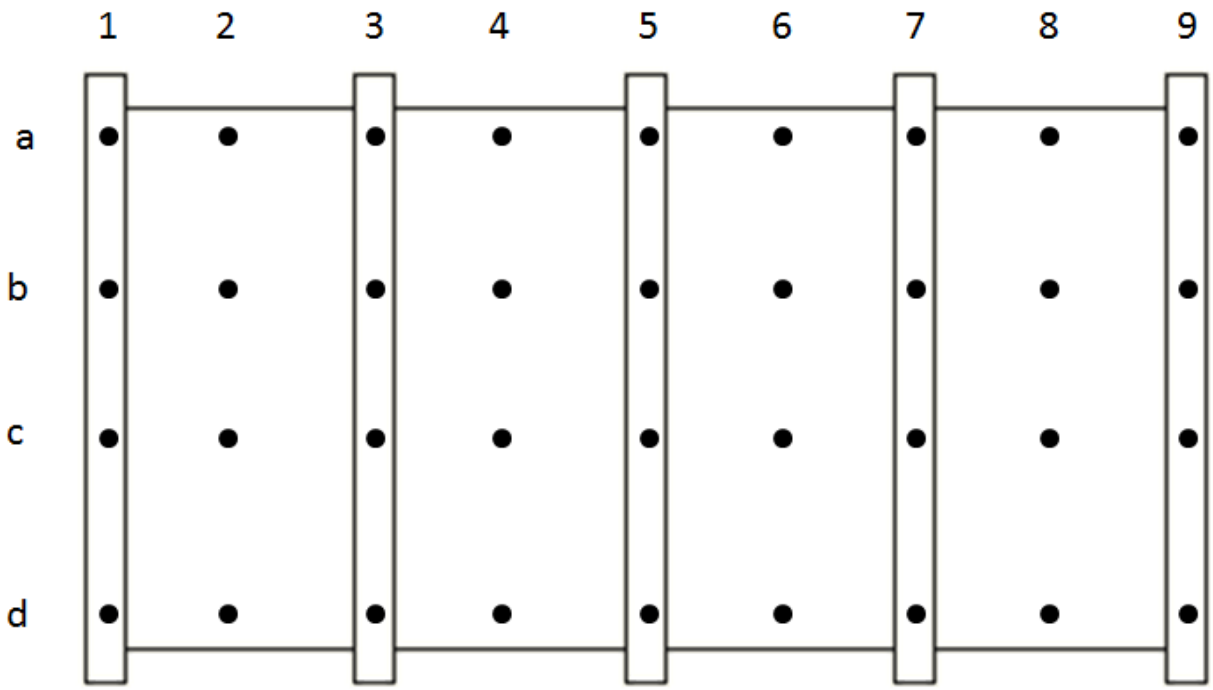


Figure E-1. Location of foam measurements on ccSPF-retrofitted sheathing panels

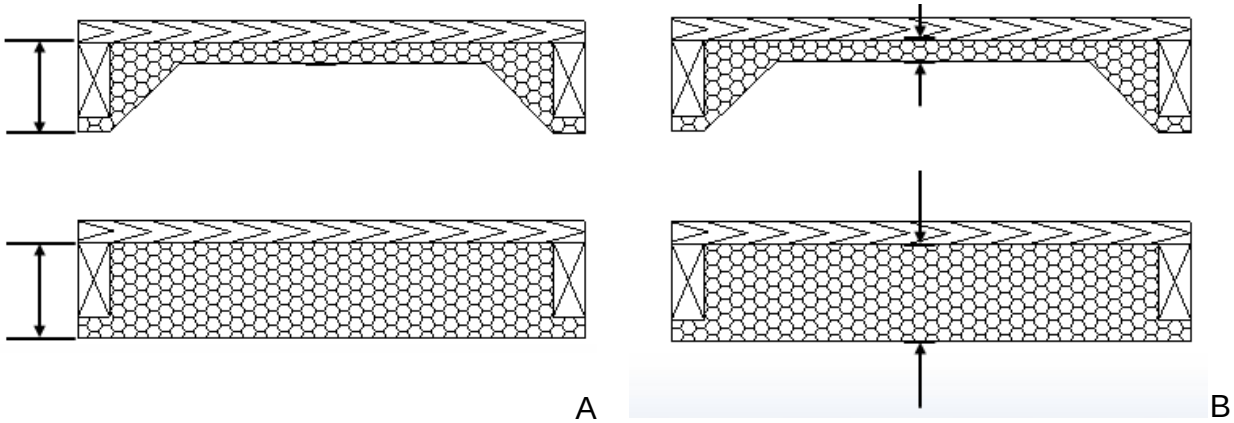


Figure E-2. Cross-section of foam depth measurement cross-section A) at trusses and B) between trusses

Table E-1. Foam Depth Measurements, Roof 2 (in.)

Panel	Position	1	2	3	4	5	6	7	8	9
A	a	4	1.25	4	1.25	4.25	1.5	3.75	1.5	4.25
	b	4	1.25	4.25	1.5	4.25	1.75	4	1.25	5
	c	4.25	1.5	4.5	1.75	4.25	1.75	4	1.75	4.25
	d	4.25	1.25	4.25	2	4.25	1.5	4.25	1.5	4
B	a	5.75	2	6	2.25	5	2	5.5	2	5.5
	b	5	1.5	5.5	2	4.75	1.5	5	1.75	5
	c	4.25	1.25	4.75	1.5	4.75	1.5	4.5	1.5	4.75
	d	3.75	1.25	-	1.5	4.75	1.5	4.5	1.5	4.75
C	a	4.25	2.25	4.5	2.5	4	2	4.5	1.5	4.25
	b	4	2	5.25	1.5	4	2	4.5	1.5	4
	c	4	1.25	5.25	1.75	4	1.5	4.5	1.25	4
	d	4.25	1	4.75	1.5	4.5	1.5	4.5	1.25	4
D	a	4.5	1.5	4.75	1.5	4	1.25	4.5	1.25	4.25
	b	4.5	2	4.5	1.5	4	1.75	4.25	1.25	4.5
	c	4.5	1.5	4.5	2.75	-	1.75	4	1.75	5
	d	4.5	2	4.25	2.5	-	2	5	1.75	5.5
E	a	-	1.5	-	2	-	2.25	-	1.5	3.75
	b	-	2	-	1.5	-	1.75	-	1.25	3.5
	c	-	2	-	2	-	1.5	-	1.75	3.75
	d	-	2	-	2	-	1.25	-	2.5	4.25
F	a	5.5	-	-	-	4.5	-	4.5	-	4.5
	b	5	-	4.25	-	4.5	-	4.25	-	5
	c	5	-	4.25	-	4.25	-	4	-	4.75
	d	4.25	-	4	-	4	-	4	-	4.75
G	a	4.5	1.5	4.5	1.25	5	1.25	4.75	1.5	4.5
	b	4.75	1	4.5	1.25	4.25	1.25	4.5	1.5	4
	c	4.5	1.25	4	1.5	4	1.5	4	1.5	4
	d	5	1.5	4	1.25	4	1.25	4	1.5	4.25
H	a	4.5	1	4	1	3.75	1.25	3.75	1.25	3.75
	b	4.5	1	3.75	1.25	3.75	1.25	3.75	1.25	3.75
	c	3.75	1	4	1.25	3.75	1.25	3.75	0.75	4
	d	3.75	1	4	1.25	3.75	1.25	3.75	1.25	3.75

Table E-2. Foam Depth Measurements, Roof 3 (in.)

Panel	Position	1	2	3	4	5	6	7	8	9
A	a	4.25	2	4	1.75	3.75	1.75	3.75	1.5	4
	b	4.25	1.75	4	2.25	3.75	1.5	3.75	1.75	4
	c	4.5	1.75	4	1.5	4	1.5	3.75	1.5	4
	d	4.75	0.5	4.25	2	4	2	3.75	1.5	4.25
B	a	4.5	2	5.25	2.75	5	2.5	5.75	1.25	5
	b	3.75	1.75	4.75	2	4.5	2.25	5.5	1.25	5
	c	3.75	2	5	1.75	4.25	2	4.75	1.5	4.5
	d	4	2.5	4.5	2.25	3.75	2	3.75	1.25	4.25
C	a	4.5	1.25	5.25	1.75	4.75	1.5	4.5	1.5	4.5
	b	4.5	1.25	5.25	1.75	4.75	1.5	4.75	1.5	5
	c	4.75	1.5	5.5	2	4.5	2	4.5	1.75	5.25
	d	4.75	1.75	5	1.5	4.25	1.75	4.5	1.5	5.25
D	a	4.5	1.5	4.75	1.75	4.5	1.25	4	0.75	4.5
	b	4.25	1.25	4.254	2	4.5	1.25	4.25	1	4.5
	c	4.5	1.5	4.5	1.75	4.25	1.25	4	1.75	4.75
	d	4.5	1.5		1.75	4	2	4	1.25	5
E	a	4.5	1.75	4.75	1.25	4.5	1.5	4.5	1.25	4.5
	b	4.25	2	4.75	1.25	4.5	1.25	4	1.25	4.5
	c	4.5	1.5	4.75	1	4.5	1.75	4	1	4
	d	4.5	1.25	4.75	1.5	4.5	1.75	4	1.25	4.75
F	a	4.5	1	-	1	-	1.75	4.25	1.5	-
	b	5.25	1.25	-	1.5	-	1.75	4.25	1.25	-
	c	4.5	1.75	-	1.5	-	1.5	4	1.25	-
	d	4.5	1.5	-	1.75	-	1.25	3.75	1.5	-
G	a	5	1.5	5	1.25	5	2.25	5	1.75	5.75
	b	5.5	1.5	5	2	4.75	2.5	5.25	1.75	5.5
	c	5	1.5	4.5	1.5	4.75	1.5	5.25	1.25	4
	d	4.25	2.25	4.5	2.25	4.25	1.5	3.75	1	4
H	a	4	1	3.75	1	4	2	4	1	4.5
	b	4.25	1.5	4	1	-	1.5	4	1.5	-
	c	4.25	2	4	1.25	-	1.5	4.5	1.5	-
	d	4.5	1.5	4.5	1	-	2	4	2	-

Table E-3. Foam Depth Measurements, Roof 4 (in.)

Panel	Position	1	2	3	4	5	6	7	8	9
A	a	-	4.5	4.5	4.5	4.5	4.5	4	4.75	5.5
	b	5.5	4.5	5	4.75	4.75	4.5	4.5	4.5	5
	c	5.25	4	5.25	4	-	4	4.75	5	5
	d	-	3.5	-	3.5	-	5	5.25	4.75	5
B	a	4.5	5	5.5	4.5	5.5	5	5.75	4.5	5
	b	5	4.5	6	4.75	5.75	5	6	4.5	5
	c	6	4.75	5.75	4	5	4.75	5.75	4	4.5
	d	5.5	4.75	4.75	4	-	4.5	-	4.5	5
C	a	-	4	-	4.25	-	4.25	5	4.5	5.25
	b	-	4.25	-	4.5	-	4.5	5	4.25	5
	c	-	4.75	-	4	-	4.75	5	4	-
	d	-	5	-	4	-	4.75	-	4	-
D	a	-	3.75	4.5	3.5	4.75	3.5	5.25	4	-
	b	4.75	4	5.25	3.5	4.25	4.25	5	4	-
	c	5	4	4.75	5	4.5	3.5	4.75	4	-
	d	5	4.25	4.5	-	4.75	4.25	5.5	4.5	-
E	a	4.5	3.5	4.125	4.5	5	5	5	4.25	4.75
	b	5	3.25	4.25	4	4	4.75	5.5	4.25	4.5
	c	-	3.5	-	4.625	-	3.75	4.5	3.75	4.75
	d	-	4.5	-	4.375	-	3.75	4.5	3.75	5
F	a	5	4.5	4.5	4.5	4.75	4.25	4.5	3.25	4.75
	b	5	4.25	5	3.5	5.5	4.5	4.5	3.75	4.5
	c	5	4.5	4.5	4.5	5.5	4.25	4.75	3.75	5.25
	d	4.75	4	4.5	4.5	5.75	4.5	5.5	4.5	5.75
G	a	5	3.5	5	3.75	5.25	4	-	5	5.5
	b	4.5	3.5	5	4.25	5	4.5	-	4	5.5
	c	4.5	3.75	4.75	4	4.25	4.5	-	4.25	5
	d	4.75	3.75	4.5	3.75	4.75	4.5	-	3.75	4.75
H	a	5	4	4.25	4.75	4.75	3.75	4.5	3.5	4.75
	b	5	3.5	4.25	4.5	5	4.5	4.75	3.25	4.75
	c	4.75	3.5	4.75	4	4	4.5	5	3.5	5
	d	4.5	4.25	5.25	3.75	4.25	4	5.25	3.5	4.75

Table E-4. Foam Depth Measurements, Roof 5 (in.)

Panel	Position	1	2	3	4	5	6	7	8	9
A	a	-	3.5	-	4.75	-	3.75	-	3.75	-
	b	-	3.5	-	4	-	3.5	-	4.5	-
	c	-	3.25	-	3.5	-	4.5	-	4.5	-
	d	-	3	-	3.75	-	4	-	4	-
B	a	5	3	5	4	5.25	2.75	5	3	4.5
	b	4.75	3	5.25	4.25	5	3	4.5	3.5	4.75
	c	4	2.75	5.25	3.5	5	3.5	4.5	3.5	4.75
	d	4	2.75	5.25	3	4.75	4.25	4.75	3.5	4.75
C	a	4	4	4.75	3.75	4.5	3.75	5	4	6
	b	5	4.25	5	4	4.5	3.25	5	3.5	5
	c	5.5	3	4.75	3.75	4.75	4	4.5	3.5	4.75
	d	5	3	4.5	3	5	3	4.5	3.25	4.5
D	a	3.5	2.5	4.75	3.75	5	4.25	4	3	4.75
	b	3.5	3	4.5	3.5	5.25	3.75	3.625	3.5	4.75
	c	3.5	3	4.25	3	4.5	3	3.75	3.5	4.75
	d	3.5	3	4.25	3.5	4.25	2.75	4	4	5
E	a	4.75	3.75	5.5	4	4.75	3.5	4.5	3.25	4.75
	b	4.5	3.5	5.25	3.75	4.75	3.5	4.5	3.25	4.5
	c	4.5	3.5	5	3.5	4.5	3.5	4.5	3.5	4.25
	d	4.75	3.75	4.75	3.75	4.75	3.5	4.5	3.5	4.5
F	a	5.5	4	5.25	4	-	3	4.5	3.25	5
	b	4.5	4	5	3.75	-	3.5	4.5	3.5	5.5
	c	5.25	4	-	4	-	3.25	4.5	3	5
	d	-	3.5	-	3.25	5	3.25	4.25	3	4.5
G	a	5	3.75	4.75	3.5	4.75	3.5	4.75	3	4.5
	b	5	3.5	4.5	3.5	5	3.25	4.5	2.5	5
	c	4.5	3.25	4.75	3.75	4.5	3.5	4	3	5
	d	4.75	3	4.75	3.25	4.5	3.5	4	3.5	5.5
H	a	4.5	3.75	4.5	3.5	4.75	3.5	4.25	3	4.25
	b	4.75	4	4.25	3	4.25	3	4	3.5	4.5
	c	4.5	4	4.75	3.5	4.5	3	4.25	3.5	4.75
	d	5.25	4	4.75	3.75	4.25	3.5	-	3	-

Table E-5. Foam Depth Measurements, LII (in.)

Panel	Position	1	2	3	4	5	6	7	8	9
A	a	3.5	0.75	4.25	0.75	4	0.75	4.25	0.75	3.5
	b	3.5	0.75	4.205	0.75	4	0.75	4.25	0.75	3.5
	c	3.5	1	4	0.75	4.25	0.75	4	1.25	3.5
	d	3.5	0.75	3.75	0.75	4	1	4.25	1	3.75
B	a	3.5	1.5	4	1.5	3.75	1.25	4.25	1.5	4
	b	3.5	1	4	1.75	4	1.5	3.75	1	4
	c	3.5	1.25	4.25	1.5	4	1.5	4	1	4.25
	d	3.75	1.75	4.25	2	4	1.5	4	1	4.25
C	a	3.625	2	4.25	1.5	4.25	2	4.5	1.5	4
	b	3.625	1.75	4.25	1.75	4.25	1.5	4.25	1.75	3.75
	c	3.625	1.5	4	1.75	4.25	2	4.25	2	4
	d	3.625	1.5	3.75	1.75	4.25	1.25	4.75	1.75	4.5
D	a	3.75	1.25	3.75	1.25	3.75	1.25	4	1.25	3.75
	b	3.75	1	4	1.25	4	1.5	4	1	3.75
	c	3.75	1	3.75	0.75	4	1.5	3.75	1	3.75
	d	3.75	1.25	3.75	1	3.75	1.25	3.75	1.25	3.75

Table E-6. Foam Depth Measurements, LIII (in.)

Panel	Position	1	2	3	4	5	6	7	8	9
A	a	4	3	-	2.75	5.25	2.75	5	3.5	4
	b	4.25	3	-	3	5.25	3.25	5.25	3.5	4.25
	c	4.5	3.5	-	3.5	5.25	3.5	5.5	3.5	4
	d	4.25	3.5	-	3.75	5.25	3.5	4.75	3.75	4
B	a	3.5	2.5	3.75	3	4	2.75	4.25	3	3.75
	b	3.5	2.25	3.75	3.25	4	2.75	4.25	3	3.5
	c	3.5	2.5	3.75	3.5	4	2.5	4.25	3	3.75
	d	3.5	2.5	3.75	3.5	4	2.5	4.25	3	3.75
C	a	3.5	3	3.5	3.25	3.5	2.5	3.5	3	3.5
	b	3.5	3.25	3.5	2.75	3.5	2.75	3.5	3	3.5
	c	3.5	2.75	3.5	2.75	3.5	2.75	3.5	3.25	3.5
	d	3.5	2.25	3.5	3	3.5	3	3.5	3.5	3.5
D	a	3.5	3	3.5	2.75	3.5	2.5	3.5	2.75	3.5
	b	3.5	3.25	3.5	3.25	3.5	3	3.5	3	3.5
	c	3.5	2.75	3.5	3.25	3.5	3	3.5	3	3.5
	d	3.5	2.75	3.5	3	3.5	3.25	3.5	2.5	3.5

APPENDIX F
PRESSURE VS DEFLECTION IN FULL-SCALE WIND UPLIFT TESTING

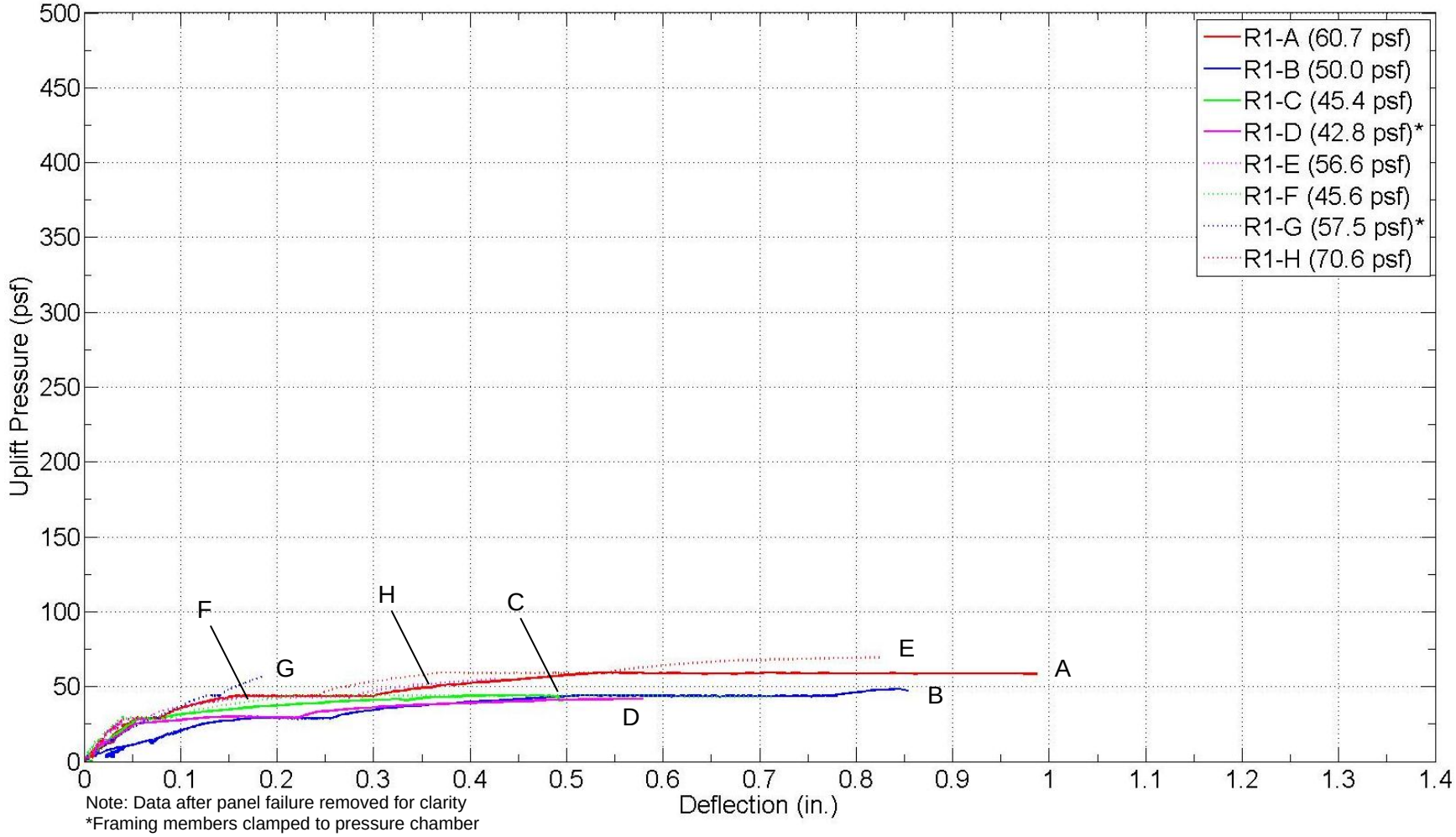


Figure F-1. Pressure vs. midspan deflection of sheathing panels in Roof 1

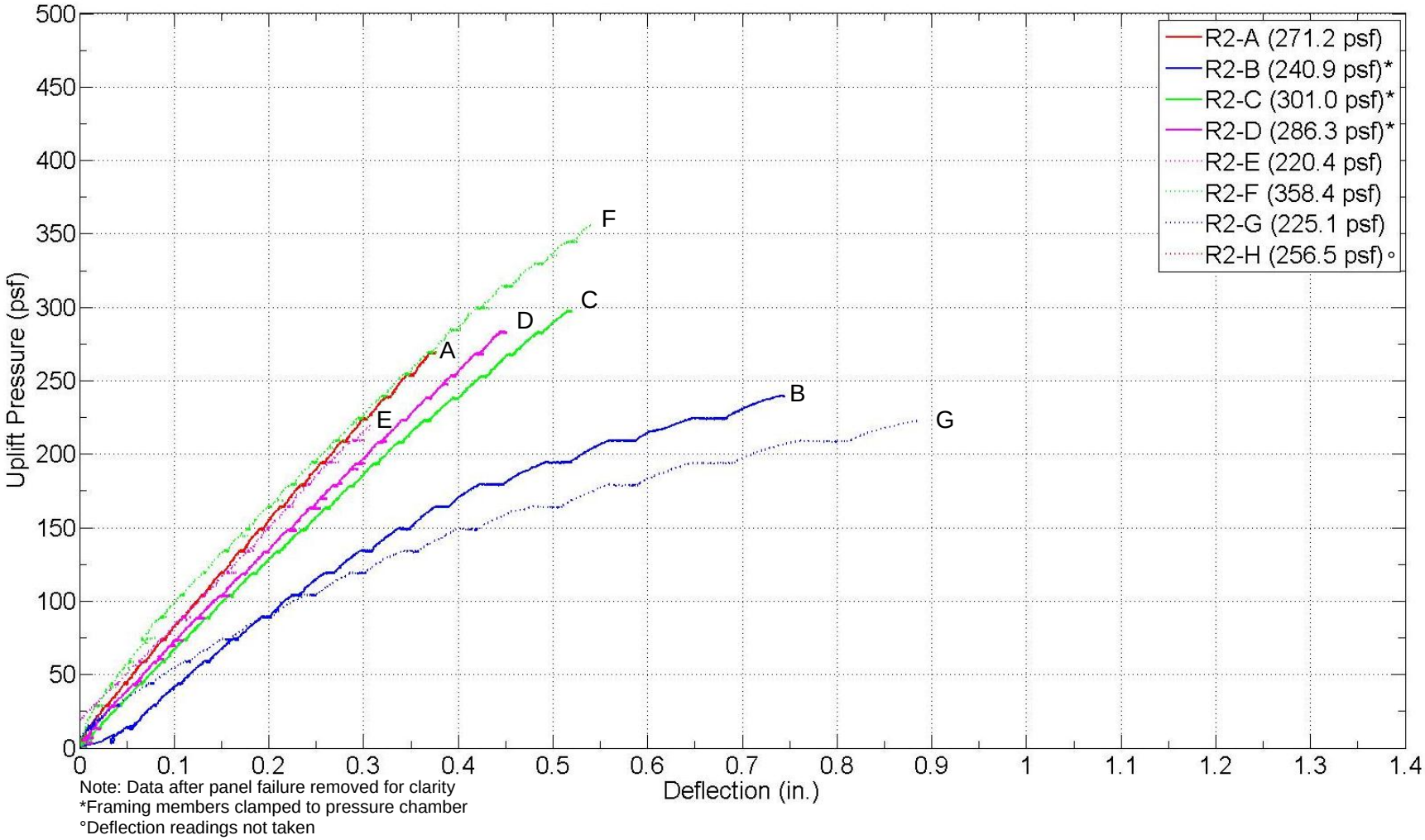


Figure F-2. Pressure vs. midspan deflection of sheathing panels in Roof 2

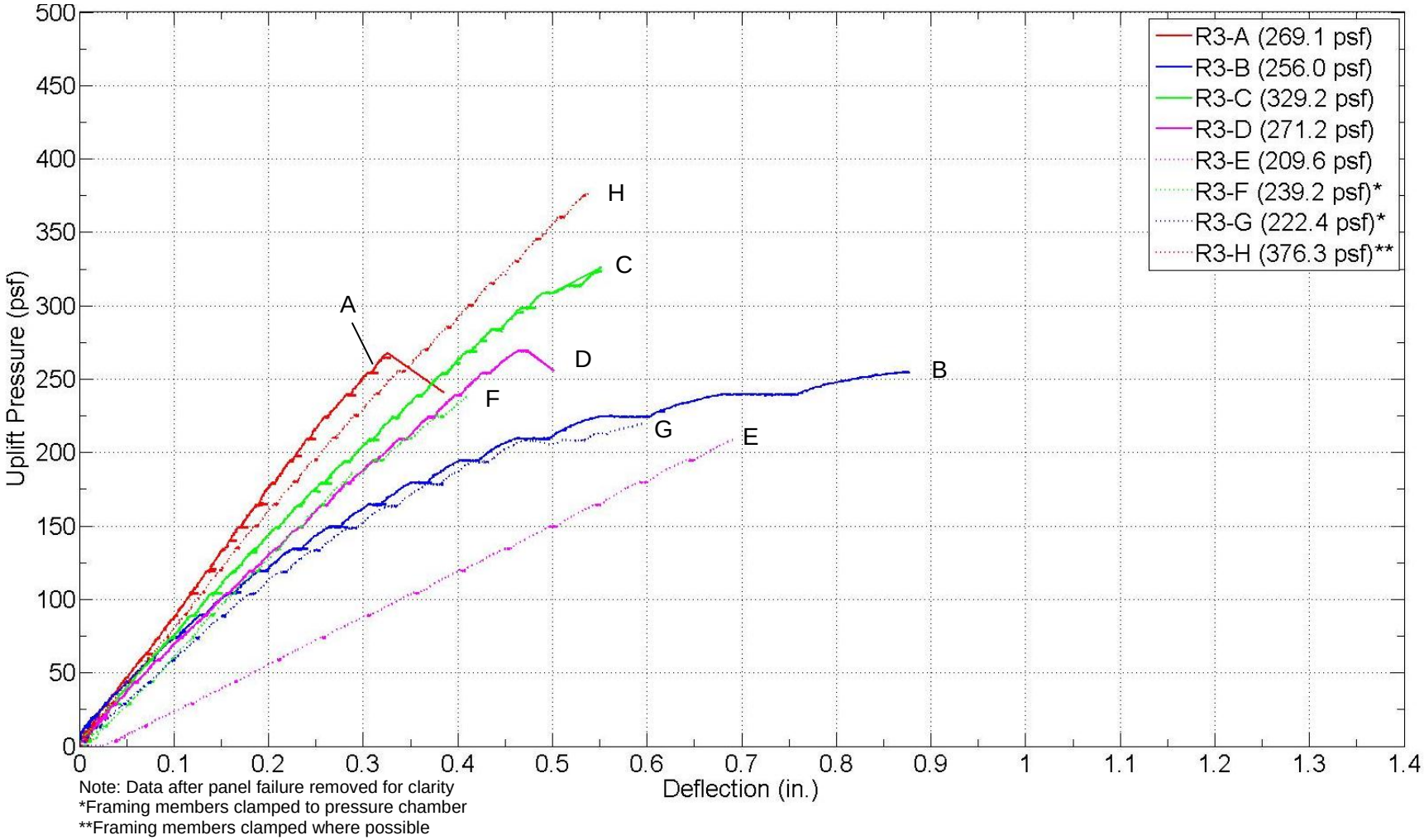


Figure F-3. Pressure vs. midspan deflection of sheathing panels in Roof 3

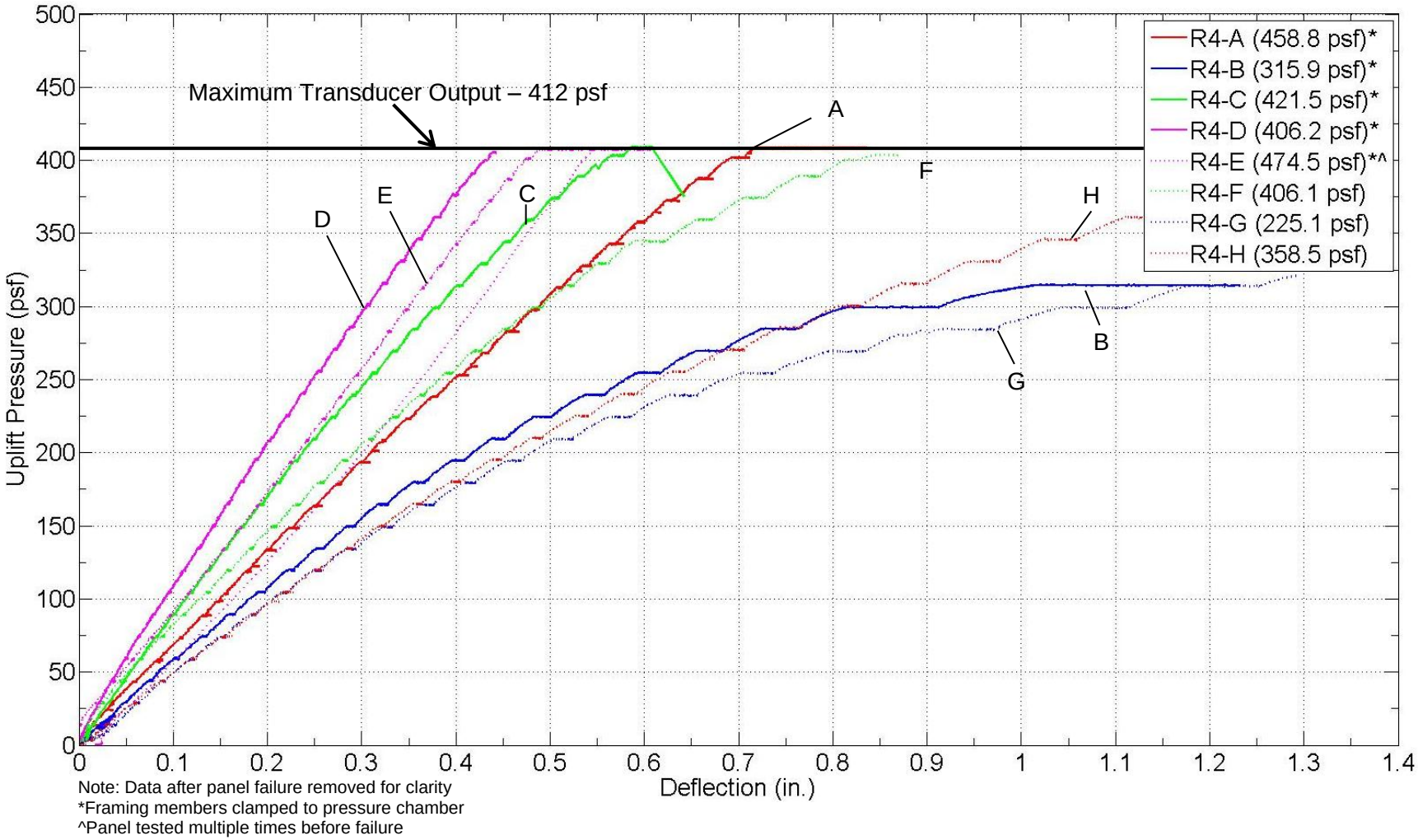
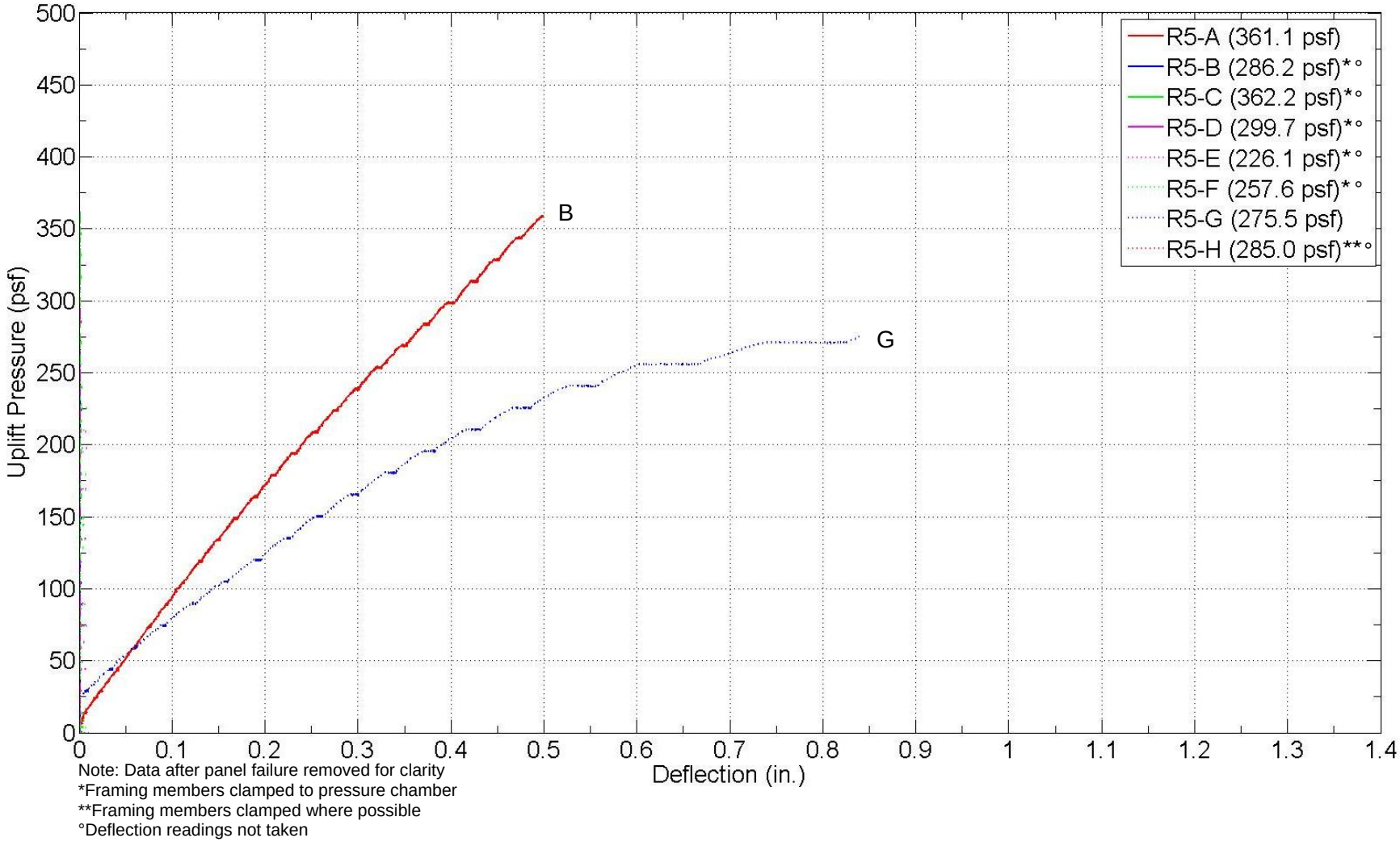


Figure F-4. Pressure vs. midspan deflection of sheathing panels in Roof 4



Note: Data after panel failure removed for clarity
*Framing members clamped to pressure chamber
**Framing members clamped where possible
°Deflection readings not taken

Figure F-5. Pressure vs. midspan deflection of sheathing panels in Roof 5

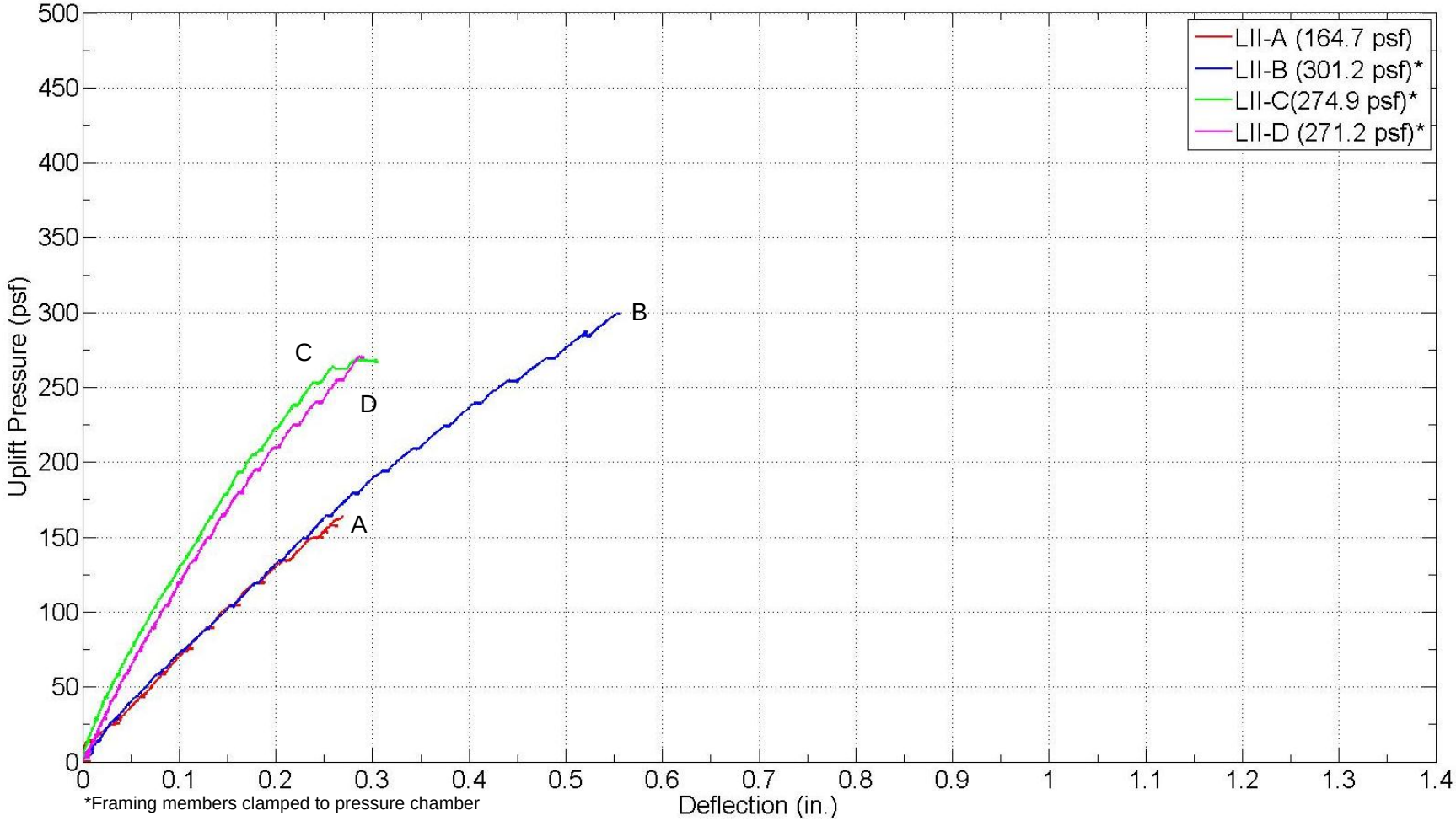


Figure F-6. Pressure vs. midspan deflection of sheathing panels in LII

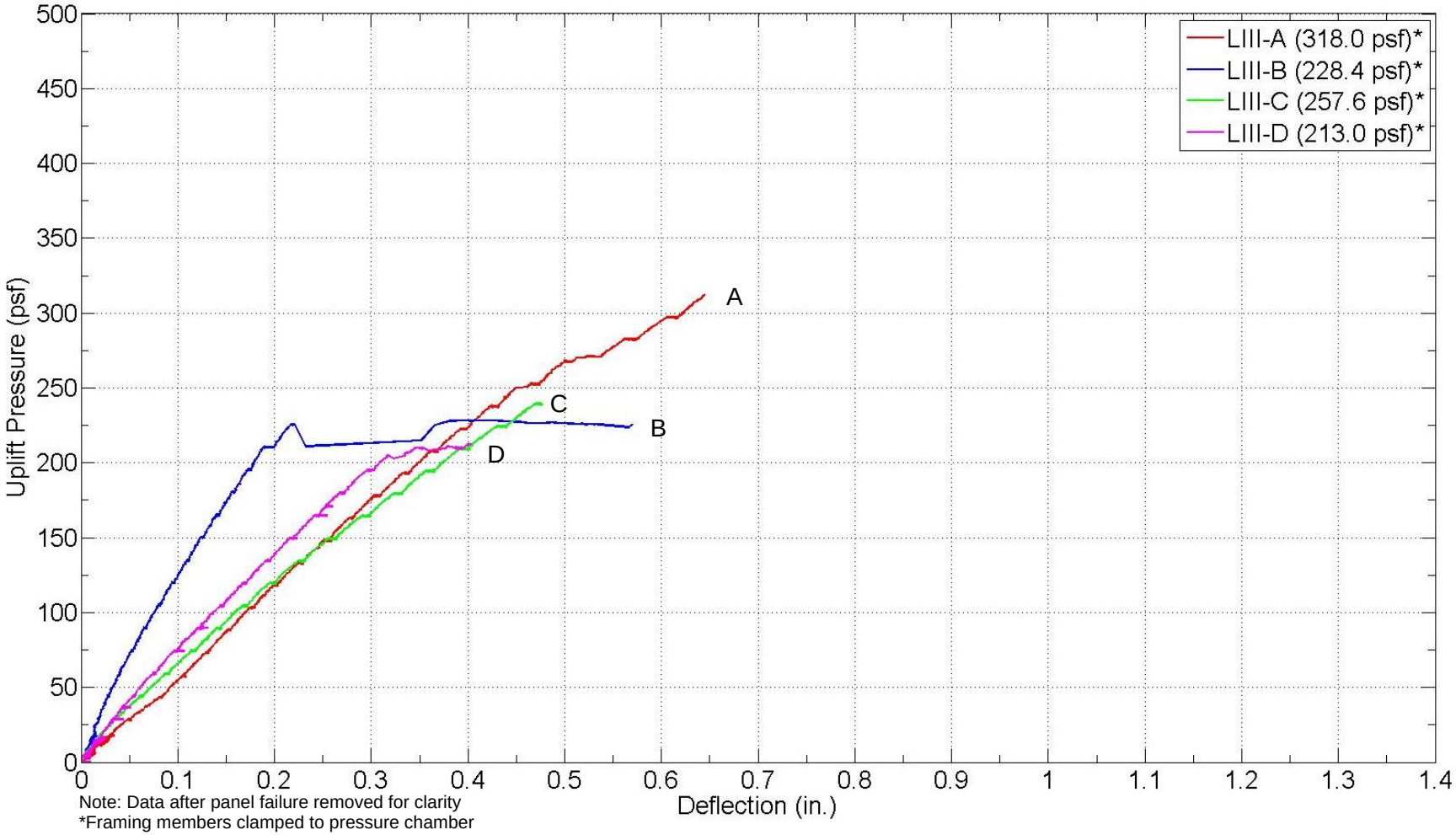


Figure F-7. Pressure vs. midspan deflection of sheathing panels in LIII

APPENDIX G
SMALL SPECIMEN TENSILE TESTING SUMMARY OF RESULTS

Table G-1. Test sheet for Week 1 small specimen tensile testing

Week 1 Testing - 11.15.10

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
						5*6		**8/7**			$\frac{10-11}{11}\times 100$				$\frac{0.061*11}{13*14*15}$
Code	Test Order	Sheathing Type	Treatment	Foam Dimensions		L x B (sq. in)	Failure Load (psi)	Tensile Stress (psi)	Original Mass, A (g)	Oven-dry Mass, B (g)	MC	Sheathing Dimensions			SG
				L (in)	B (in)							L (in)	w (in)	t (in)	
1-1-P-C	1	P	C	2.82	2.87	8.1	118.2	14.6	61.2	55.7	9.9	4.8	3.0	0.47	0.51
1-2-OT-W	2	OT	W	2.92	2.82	8.2	151.6	18.4	110.5	55.7	98.4	5.1	3.2	0.59	0.36
1-3-OS-W	3	OS	W	2.96	2.84	8.4	37.9	4.5	120.3	55.7	116.0	5.5	2.9	0.64	0.34
1-4-OT-W	4	OT	W	2.86	2.94	8.4	100.5	12.0	83.5	55.7	49.9	5.5	2.9	0.55	0.39
1-5-OT-W	5	OT	W	2.82	3.05	8.6	82.0	9.5	98.0	55.7	75.9	4.6	3.0	0.53	0.48
1-6-OS-W	6	OS	W	2.91	2.97	8.6	297.3	34.4	88.9	70.3	26.5	4.6	3.0	0.50	0.63
1-7-OS-W	7	OS	W	3.04	2.83	8.6	114.5	13.3	119.3	83.4	43.0	5.1	3.0	0.63	0.52
1-8-P-W	8	P	W	2.63	3.02	7.9	199.2	25.1	126.3	61.5	105.4	5.0	3.1	0.48	0.51
1-9-P-W	9	P	W	2.82	2.75	7.8	191.4	24.7	106.6	52.1	104.6	4.8	2.9	0.48	0.48
1-10-OS-W	10	OS	W	3.02	2.76	8.3	55.1	6.6	94.6	70.7	33.8	4.9	2.7	0.56	0.57
1-11-OT-C*	11	OT	C	2.82	3.11	8.8	190.5	21.7	81.8	74.3	10.1	5.2	3.0	0.55	0.53
1-12-P-C	12	P	C	2.82	2.88	8.1	254.7	31.4	62.5	57.2	9.3	4.8	2.9	0.47	0.53
1-13-OT-W	13	OT	W	2.72	2.9	7.9	151.5	19.2	95.6	72.3	32.2	4.9	3.0	0.56	0.53
1-14-P-W	14	P	W	2.9	3.11	9.0	122.6	13.6	93.7	59.2	58.3	4.8	3.2	0.47	0.51
1-15-OS-C	15	OS	C	2.79	2.75	7.7	183.2	23.9	71.8	65.5	9.6	4.8	2.9	0.45	0.64
1-16-OT-W	16	OT	W	3.01	2.8	8.4	132.0	15.7	97.9	71.0	37.9	5.2	2.9	0.62	0.47
1-17-OS-C	17	OS	C	2.74	2.79	7.6	256.8	33.6	81.9	75.4	8.6	4.8	3.1	0.44	0.71
1-18-P-W	18	P	W	2.68	2.9	7.8	157.3	20.2	74.4	48.5	53.4	4.4	3.0	0.46	0.50
1-19-OT-C	19	OT	C	2.74	2.89	7.9	75.2	9.5	67.3	61.5	9.4	4.7	2.9	0.46	0.59
1-20-OS-W	20	OS	W	2.78	2.96	8.2	219.7	26.7	93.7	71.2	31.6	4.6	3.1	0.60	0.51
1-21-P-W*	21	P	W	2.8	3.45	9.7	66.6	6.9	133.3	67.6	97.2	4.9	3.1	0.70	0.39

*Failed on bottom flange

Sheathing Types: P - Plywood; OT - OSB with Foam on Textured Face; OS - OSB with Foam on Smooth Face
Treatments: C - Control Specimens (not wetted); W - Wetted Test Specimens
Failure Type: S - Slow Failure; R - Rapid Failure; F - Failed Test

Table G-2. Test sheet for Week 2 small specimen tensile testing

Week 2 Testing - 12.09.10 (samples placed in chamber 11.25.10)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
						5*6		**8/7**			$\frac{10-11}{11}\times 100$				$\frac{0.061*11}{13*14*15}$
Code	Test Order	Sheathing Type	Treatment	Foam Dimensions		L x B (sq. in)	Failure Load (psi)	Tensile Stress (psi)	Original Mass, A (g)	Oven-dry Mass, B (g)	MC	Sheathing Dimensions			SG
				L (in)	B (in)							L (in)	w (in)	t (in)	
2-1-OS-W	1	OS	W	2.84	2.85	8.1	148.1	18.3	102.1	61.4	66.3	4.6	2.9	0.43	0.66
2-2-OT-W	2	OT	W	3.24	2.9	9.4	64.9	6.9	126.6	68.6	84.5	4.6	3.3	0.58	0.47
2-3-P-C	3	P	C	2.85	2.74	7.8	147.1	18.8	61.2	56.1	9.1	4.8	2.9	0.46	0.53
2-4-OT-W	4	OT	W	2.93	3.01	8.8	103.8	11.8	110.7	69.1	60.2	4.8	3.0	0.56	0.53
2-5-OT-C	5	OT	C	2.75	2.66	7.3	169.5	23.2	66.0	67.1	-1.6***	4.5	2.9	0.55	0.58
2-6-OS-W	6	OS	W	2.93	2.66	7.8	127.6	16.4	137.0	77.1	77.7	4.9	3.1	0.62	0.50
2-7-P-W	7	P	W	3.01	2.67	8.0	152.5	19.0	94.2	48.5	94.2	4.3	3.9	0.47	0.38
2-8-OS-W	8	OS	W	2.93	2.88	8.4	169.2	20.1	93.4	67.5	38.4	4.5	3.0	0.60	0.51
2-9-P-W*	9	P	W	2.91	2.72	7.9	97.7	12.3	80.4	45.6	76.3	4.0	3.0	0.47	0.49
2-10-OS-C	10	OS	C	2.87	3	8.6	284.1	33.0	74.8	69.6	7.5	4.8	2.9	0.44	0.69
2-11-P-W	11	P	W	2.93	3.01	8.8	214.1	24.3	92.9	53.5	73.6	4.5	3.0	0.47	0.51
2-12-OT-W	12	OT	W	2.73	2.79	7.6	52.8	6.9	96.2	55.6	73.0	4.8	2.7	0.55	0.48
2-13-P-W	13	P	W	3.09	2.92	9.0	132.0	14.6	86.6	48.8	77.5	4.4	3.1	0.46	0.48
2-14-OT-W**	14	OT	W	3.6	2.83	10.2	10.0	1.0	116.3	65.4	77.8	4.8	2.8	0.55	0.53
2-15-OT-C	15	OT	C	2.84	3.66	10.4	177.0	17.0	65.9	61.6	7.0	4.5	2.8	0.44	0.67
2-16-OS-W	16	OS	W	3.12	2.42	7.6	89.6	11.9	126.0	78.1	61.3	5.1	3.1	0.55	0.54
2-17-P-W	17	P	W	2.87	2.85	8.2	137.2	16.8	78.7	44.0	78.9	4.3	2.9	0.47	0.46
2-18-P-C	18	P	C	2.83	2.7	7.6	168.2	22.0	55.2	51.4	7.4	4.8	2.8	0.45	0.51
2-19-OS-C	19	OS	C	2.76	3.03	8.4	220.9	26.4	75.8	70.8	7.1	5.0	2.8	0.46	0.68
2-20-OS-W	20	OS	W	2.81	2.86	8.0	144.7	18.0	91.3	69.9	30.6	5.0	2.9	0.55	0.53
2-21-OT-W	21	OT	W	3.23	2.6	8.4	127.9	15.2	114.5	74.7	53.3	4.9	3.3	0.56	0.51

*Failed on bottom flange
**Failed before loading
***Abnormal result

Sheathing Types: P - Plywood; OT - OSB with Foam on Textured Face; OS - OSB with Foam on Smooth Face
Treatments: C - Control Specimens (not wetted); W - Wetted Test Specimens
Failure Type: S - Slow Failure; R - Rapid Failure; F - Failed Test

Table G-3. Test sheet for Week 4 small specimen tensile testing

Week 4 Testing – 12.08.10

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
						5*6		**8/7**			$\frac{10-11}{11}\times 100$				$\frac{0.061*11}{13*14*15}$
Code	Test Order	Sheathing Type	Treatment	Foam Dimensions		L x B (sq. in)	Failure Load (psi)	Tensile Stress (psi)	Original Mass, A (g)	Oven-dry Mass, B (g)	MC	Sheathing Dimensions			SG
				L (in)	B (in)							L (in)	3.1	0.44	
4-1-OT-W	1	OT	W	2.81	2.92	8.2	190.7	23.2	84.4	67.5	25.0	4.9	2.9	0.52	0.56
4-2-OT-C	2	OT	C	3	2.44	7.3	125.9	17.2	69.4	65.3	6.3	4.5	3.1	0.44	0.65
4-3-OT-C	3	OT	C	2.753	2.86	7.9	104.9	13.3	74.1	68.9	7.5	4.8	2.8	0.47	0.66
4-4-P-W	4	P	W	2.95	2.72	8.0	240.4	30.0	83.5	61.4	36.0	4.3	3.0	0.46	0.62
4-5-P-W	5	P	W	2.83	2.95	8.3	136.8	16.4	98.4	52.2	88.5	4.8	2.9	0.47	0.48
4-6-P-W	6	P	W	2.9	2.78	8.1	175.3	21.7	79.6	53.5	48.8	4.6	3.0	0.53	0.45
4-7-OT-2	7	OT	W	3.02	2.94	8.9	48.4	5.4	133.6	68.0	96.5	4.9	3.1	0.47	0.57
4-8-P-C	8	P	C	2.93	2.93	8.6	271.5	31.6	56.9	53.7	6.0	4.4	2.9	0.58	0.43
4-9-OT-W	9	OT	W	2.8	2.82	7.9	97.7	12.4	122.3	68.2	79.3	4.6	2.8	0.46	0.70
4-10-OS-C	10	OS	C	2.91	2.76	8.0	163.4	20.3	73.9	53.9	37.1***	4.8	3.0	0.53	0.43
4-11-OS-W	11	OS	W	2.87	2.93	8.4	177.6	21.1	99.8	60.1	66.1	4.6	2.9	0.43	0.64
4-12-OS-C	12	OS	C	2.76	2.6	7.2	306.3	42.7	63.0	59.4	6.1	4.6	2.8	0.43	0.66
4-13-P-W*	13	P	W	2.74	3.05	8.4	37.1	4.4	71.3	47.7	49.5	4.6	2.9	0.69	0.32
4-14-OT-W	14	OT	W	2.78	2.96	8.2	83.6	10.2	125.9	64.9	94.0	4.5	2.8	0.68	0.45
4-15-OS-W	15	OS	W	2.59	3.04	7.9	177.7	22.6	84.4	59.5	41.8	4.4	2.7	0.57	0.53
4-16-OS-W	16	OS	W	2.95	2.78	8.2	93.2	11.4	127.6	66.3	92.5	4.8	3.0	0.56	0.50
4-17-P-C	17	P	C	2.95	2.82	8.3	172.8	20.8	53.8	50.2	7.2	4.5	3.0	0.47	0.49
4-18-OS-W	18	OS	W	2.87	2.92	8.4	102.5	12.2	119.6	64.4	85.7	4.7	2.9	0.55	0.52
4-19-OS-W	19	OS	W	2.85	2.74	7.8	110.8	14.2	121.7	60.7	100.5	4.5	2.9	0.57	0.50
4-20-P-W	20	P	W	2.98	2.97	8.9	218.6	24.7	72.1	50.0	44.2	4.4	3.0	0.48	0.48
4-21-OT-W	21	OT	W	2.98	2.83	8.4	86.9	10.3	105.9	67.2	57.6	4.7	3.1	0.53	0.53
4-22-P-W	22	P	W	3.06	2.67	8.2	145.1	17.8	103.8	69.0	50.4	4.5	3.2	0.47	0.62
4-23-OT-W**	23	OT	W	2.88	2.82	8.1	10.9	1.3	128.0	59.5	115.1	4.4	3.0	0.55	0.51
4-24-OT-W	24	OT	W	3	2.71	8.1	64.8	8.0	126.2	65.0	94.2	4.8	3.1	0.56	0.48

*Failed on bottom flange
**Failed before loading
***Abnormal result

Sheathing Types: P - Plywood; OT - OSB with Foam on Textured Face; OS - OSB with Foam on Smooth Face
Treatments: C - Control Specimens (not wetted); W - Wetted Test Specimens
Failure Type: S - Slow Failure; R - Rapid Failure; F - Failed Test

Table G-4. Test sheet for Week 8 small specimen tensile testing

Week 8 Testing - 01.03.11

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
						5*6		**8/7**			$\frac{10-11}{11}\times 100$				$\frac{0.061*11}{13*14*15}$
Code	Test Order	Sheathing Type	Treatment	Foam Dimensions		L x B (sq. in)	Failure Load (psi)	Tensile Stress (psi)	Original Mass, A (g)	Oven-dry Mass, B (g)	MC	Sheathing Dimensions			SG
				L (in)	B (in)							L (in)	w (in)	t (in)	
8-1-OT-W*	1	OT	W	2.74	3.03	8.3	119.0	14.3	-	-	-	-	-	-	-
8-2-P-C*	2	P	C	2.77	2.78	7.7	133.7	17.4	-	-	-	-	-	-	-
8-3-OT-W**	3	OT	W	3	2.91	8.7	0.7	0.1	-	-	-	-	-	-	-
8-4-P-W*	4	P	W	2.97	3.05	9.1	144.3	15.9	-	-	-	-	-	-	-
8-5-OT-W	5	OT	W	2.85	3.06	8.7	51.4	5.9	140.5	70.5	99.3	4.7	3.1	0.59	0.50
8-6-P-W*	6	P	W	2.89	2.94	8.5	166.1	19.5	-	-	-	-	-	-	-
8-7-OS-C	7	OS	C	2.69	2.94	7.9	125.2	15.8	78.9	72.8	8.4	5.0	3.0	0.45	0.66
8-8-OS-W	8	OS	W	2.92	2.7	7.9	141.1	17.9	105.0	62.8	67.2	4.9	2.8	0.62	0.46
8-9-P-W	9	P	W	2.62	3.12	8.2	171.9	21.0	105.4	54.6	93.0	4.7	3.2	0.51	0.44
8-10-P-W	10	P	W	2.83	2.96	8.4	111.2	13.3	88.5	50.4	75.6	4.6	3.1	0.50	0.44
8-11-OS-W	11	OS	W	2.75	2.97	8.2	161.6	19.8	95.5	68.5	39.4	5.1	3.0	0.57	0.47
8-12-OS-W	12	OS	W	3.02	2.9	8.8	145.7	16.6	118.6	68.2	73.9	4.9	3.0	0.61	0.46
8-13-OT-W	13	OT	W	2.78	3.22	9.0	82.4	9.2	132.4	70.8	87.0	4.5	3.2	0.67	0.45
8-14-OS-W	14	OS	W	2.85	3.06	8.7	117.4	13.5	110.4	66.0	67.3	4.9	3.2	0.60	0.43
8-15-OT-W	15	OT	W	2.85	3.04	8.7	79.9	9.2	130.8	71.5	82.9	4.8	3.1	0.57	0.51
8-16-P-C	16	P	C	3.09	2.99	9.2	256.6	27.8	57.8	53.4	8.2	4.5	3.0	0.48	0.51
8-17-OS-W	17	OS	W	3.04	2.83	8.6	121.2	14.1	101.2	70.6	43.3	5.0	2.9	0.62	0.48
8-18-P-W	18	P	W	2.92	2.9	8.5	114.1	13.5	80.7	55.4	45.7	4.9	3.0	0.50	0.46
8-19-OT-C	19	OT	C	2.82	3.04	8.6	90.5	10.6	71.5	65.9	8.5	4.8	3.1	0.47	0.58
8-20-OT-C	20	OT	C	2.61	2.92	7.6	178.0	23.4	73.4	67.6	8.6	4.5	3.0	0.47	0.65
8-21-P-W	21	P	W	2.87	2.78	8.0	159.9	20.0	82.9	53.9	53.8	4.6	2.9	0.53	0.46
8-22-OS-W	22	OS	W	2.9	2.97	8.6	168.8	19.6	120.2	70.6	70.3	4.9	3.0	0.58	0.50
8-23-OT-W	23	OT	W	3.05	2.94	9.0	96.6	10.8	135.1	63.9	111.4	4.6	3.0	0.64	0.43
8-24-OS-C	24	OS	C	2.66	2.85	7.6	317.5	41.9	57.5	53.2	8.1	3.8	2.8	0.46	0.66

*Failed on bottom flange
**Failed before loading

Sheathing Types: P - Plywood; OT - OSB with Foam on Textured Face; OS - OSB with Foam on Smooth Face
Treatments: C - Control Specimens (not wetted); W - Wetted Test Specimens
Failure Type: S - Slow Failure; R - Rapid Failure; F - Failed Test

Table G-5. Test sheet for Week 12 small specimen tensile testing

Week 12 Testing - 01.31.11

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
						5*6		**8/7**			$\frac{10-11}{11} \times 100$				$\frac{0.061 * 11}{13 * 14 * 15}$
Code	Test Order	Sheathing Type	Treatment	Foam Dimensions		L x B (sq. in)	Failure Load (psi)	Tensile Stress (psi)	Original Mass, A (g)	Oven-dry Mass, B (g)	MC	Sheathing Dimensions			SG
				L (in)	B (in)							L (in)	w (in)	t (in)	
12-1-OS-W	1	OS	W	2.91	2.86	8.3	104.3	12.5	91.5	68.1	34.4	5.0	2.86	0.54	0.54
12-2-P-W	2	P	W	2.73	2.89	7.9	97.8	12.4	103.7	51.4	101.8	4.7	2.89	0.507	0.45
12-3-OS-W	3	OS	W	3.03	3.04	9.2	178.7	19.4	93.3	62.4	49.5	4.3	3.04	0.61	0.48
12-4-OT-W	4	OT	W	2.94	2.95	8.7	110.2	12.7	134.3	64.1	109.5	4.3	2.95	0.63	0.49
12-5-P-W	5	P	W	2.84	2.92	8.3	101.8	12.3	88.8	44.6	99.1	4.1	2.92	0.49	0.46
12-6-P-W	6	P	W	2.7	2.77	7.5	131.2	17.5	97.7	49.0	99.4	4.6	2.77	0.503	0.46
12-7-P-W	7	P	W	2.67	3.13	8.4	171.8	20.6	110.8	66.0	67.9	5.1	3.13	0.509	0.50
12-8-OS-W	8	OS	W	2.99	2.68	8.0	111.2	13.9	105.9	61.3	72.8	3.9	2.7	0.608	0.59
12-9-P-W	9	P	W	3.09	3.02	9.3	148.2	15.9	100.4	57.8	73.7	4.4	3.0	0.501	0.53
12-10-OT-W	10	OT	W	2.71	2.71	7.3	67.7	9.2	128.8	63.0	104.4	4.6	2.7	0.61	0.50
12-11-OT-W	11	OT	W	2.8	2.77	7.8	124.5	16.1	133.9	61.8	116.7	4.5	2.8	0.64	0.48
12-12-OT-W	12	OT	W	2.77	2.95	8.2	74.6	9.1	116.7	69.9	67.0	4.9	3.0	0.62	0.48
12-13-OT-W	13	OT	W	2.85	2.96	8.4	58.9	7.0	130.6	59.4	119.9	5.0	3.0	0.57	0.43
12-14-OS-W*	14	OS	W	2.84	2.89	8.2	4.0	0.5	139.9	71.4	95.9	4.9	2.9	0.6	0.51
12-15-OT-W	15	OT	W	2.75	3.03	8.3	38.2	4.6	131.6	65.8	100.0	4.6	3.0	0.62	0.46
12-16-OS-W	16	OS	W	2.85	2.95	8.4	103.4	12.3	127.9	69.4	84.3	4.8	2.9	0.6	0.50
12-17-P-W**	17	P	W	2.8	2.62	7.3	333.8	45.5	64.5	54.6	18.1	4.3	2.6	0.486	0.60
12-18-OS-W	18	OS	W	2.88	2.87	8.3	109.0	13.2	126.8	66.5	90.7	4.8	2.8	0.6	0.49

*Failed before loading

**Abnormal moisture content for a wetted sample

Sheathing Types: P - Plywood; OT - OSB with Foam on Textured Face; OS - OSB with Foam on Smooth Face

Treatments: C - Control Specimens (not wetted); W - Wetted Test Specimens

Failure Type: S - Slow Failure; R - Rapid Failure; F - Failed Test

Table G-6. Test sheet for Week 16 small specimen tensile testing

Week 16 Testing - 02.28.11

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
						5*6		**8/7**			$\frac{10-11}{11}\times 100$				$\frac{0.061*11}{13*14*15}$
Code	Test Order	Sheathing Type	Treatment	Foam Dimensions		L x B (sq. in)	Failure Load (psi)	Tensile Stress (psi)	Original Mass, A (g)	Oven-dry Mass, B (g)	MC	Sheathing Dimensions			SG
				L (in)	B (in)							L (in)	w (in)	t (in)	
16-1-OT-W	1	OT	W	3.04	2.86	8.7	94.7	10.9	-	-	-	5.0	3.0	0.57	-
16-2-P-W*	2	P	W	2.83	2.89	8.2	129.8	15.9	-	-	-	5.1	3.0	0.44	-
16-3-P-W*	3	P	W	2.7	2.93	7.9	122.9	15.5	-	-	-	5.5	3.1	0.44	-
16-4-OT-W	4	OT	W	2.78	2.73	7.6	112.6	14.8	143.0	68.1	110.0	4.7	2.9	0.59	0.52
16-5-OS-W	5	OS	W	2.9	2.85	8.3	137.5	16.6	133.8	60.4	121.5	4.6	2.9	0.67	0.41
16-6-P-W	6	P	W	2.77	3.14	8.7	141.0	16.2	132.6	66.1	100.6	5.0	3.3	0.50	0.50
16-7-OS-W	7	OS	W	2.76	2.89	8.0	84.8	10.6	139.1	67.7	105.5	4.6	2.9	0.59	0.52
16-8-OT-W	8	OT	W	2.77	2.87	7.9	42.6	5.4	144.4	65.3	121.1	4.7	3.0	0.59	0.49
16-9-OT-W	9	OT	W	3.04	2.92	8.7	64.4	7.4	164.5	72.5	126.9	5.0	3.0	0.64	0.47
16-10-OS-W	10	OS	W	2.95	3.18	9.4	143.1	15.3	156.7	71.4	119.5	5.1	3.2	0.72	0.37
16-11-P-W	11	P	W	2.76	2.8	7.7	81.7	10.6	106.9	56.3	89.9	5.0	2.8	0.47	0.51
16-12-P-W*	12	P	W	2.85	3.13	8.9	169.4	19.0	-	-	-	5.2	3.3	0.47	-
16-13-OS-W	13	OS	W	2.85	3.13	8.9	120.6	13.5	168.3	79.4	112.0	5.0	3.2	0.66	0.46
16-14-OS-W	14	OS	W	2.94	3.02	8.9	106.2	12.0	156.9	72.1	117.6	5.1	3.1	0.58	0.48
16-15-OT-W	15	OT	W	2.86	2.83	8.1	79.5	9.8	142.2	68.6	107.3	4.8	2.8	0.66	0.47
16-16-OT-W*	16	OT	W	2.39	3	7.2	41.4	5.8	-	-	-	5.1	3.0	0.44	-
16-17-OS-W	17	OS	W	2.97	2.93	8.9	123.6	13.9	136.0	66.2	105.4	4.5	3.0	0.65	0.46
16-18-P-W	18	P	W	2.8	2.87	8.0	104.7	13.0	67.5	48.0	40.6	4.6	2.9	0.48	0.45

*Failed on bottom flange
- No readings taken

Sheathing Types: P - Plywood; OT - OSB with Foam on Textured Face; OS - OSB with Foam on Smooth Face
Treatments: C - Control Specimens (not wetted); W - Wetted Test Specimens
Failure Type: S - Slow Failure; R - Rapid Failure; F - Failed Test

Table G-7. Test sheet for Week 1 supplemental small specimen tensile testing

Week 1 Supplemental Testing

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
						5*6		**8/7**			$\frac{10-11}{11} \times 100$				$\frac{0.061 * 11}{13 * 14 * 15}$
Code	Test Order	Sheathing Type	Treatment	Foam Dimensions		L x B (sq. in)	Failure Load (psi)	Tensile Stress (psi)	Original Mass, A (g)	Oven-dry Mass, B (g)	MC	Sheathing Dimensions			SG
				L (in)	B (in)							L (in)	w (in)	t (in)	
1-22-OS-W	22	OS	W	3.04	2.86	8.7	137.788	15.8	103.0	69.9	47.4	4.9	2.9	0.56	0.54
1-23-OS-W	23	OS	W	3.06	2.92	8.9	68.7628	7.7	98.4	70.1	40.4	4.8	3.0	0.60	0.50
1-24-OS-W	24	OS	W	2.92	2.91	8.5	201.981	23.8	97.5	69.5	40.3	4.7	3.0	0.57	0.53
1-25-OS-W	25	OS	W	2.99	2.82	8.4	222.155	26.3	107.2	70.7	51.6	5.0	3.0	0.58	0.50
1-26-OS-W	26	OS	W	2.98	2.76	8.2	124.952	15.2	98.9	72.4	36.6	4.9	2.8	0.61	0.52

Sheathing Types: P - Plywood; OT - OSB with Foam on Textured Face; OS - OSB with Foam on Smooth Face
Treatments: C - Control Specimens (not wetted); W - Wetted Test Specimens
Failure Type: S - Slow Failure; R - Rapid Failure; F - Failed Test

LIST OF REFERENCES

AFPA. (2005). *National Design Specification for Wood Construction (NDS)*, American Forest and Paper Association, Washington, D.C.

ARMA. (2006). "Asphalt Roofing Residential Manual." The Asphalt Roofing Manufacturers Association, Washington, DC.

ASCE. (2010). *Minimum Design Loads for Buildings and Other Structures (ASCE/SEI 7-10)*, American Society of Civil Engineers, Reston, VA.

ASTM. (2002). "E330 - Structural Performance of Exterior Windows, Doors, Skylights and Curtain Walls by Uniform Static Air Pressure Difference."

ASTM. (2003). "D1623 - Standard Test Method for Tensile and Tensile Adhesion Properties of Rigid Cellular Plastics." American Society of Testing and Materials.

ASTM. (2004). "E 330-02 Standard Test Method for Structural Performance of Exterior Windows, Doors, Skylights and Curtain Walls by Uniform Static Air Pressure Difference." Annual Book of ASTM Standards, American Society for Testing and Materials.

ASTM. (2006a). "ASTM D 2395-02 Standard Test Methods for Specific Gravity of Wood and Wood-base Materials." ASTM International, West Conshohocken, PA.

ASTM. (2006b). "ASTM D 4933-99: Standard Guide for Moisture Conditioning of Wood and Wood-base Materials." ASTM International, West Conshohocken, PA.

ASTM. (2006c). "D 4442-92 (Reapproved 2003) - Standard Test Methods for Direct Moisture Content Measurement of Wood and Wood-base Materials."

Berdahl, P., Akbari, H., Levinson, R., and Miller, W. A. (2008). "Weathering of roofing materials - An overview." *Construction and Building Materials*(22), 423-433.

Blake, E. S., Rappaport, E. N., Landsea, C. W., and NHC Miami. (2007). "The Deadliest, Costliest, and Most Intense United States Tropical Cyclones from 1851 to 2006 (and Other Frequently Requested Hurricane Facts)." National Hurricane Center, Miami, FL.

Bomberg, M., and Lstiburek, J. (1998). *Spray polyurethane foam in external envelopes of buildings*, CRC.

Breyer, D., Fridley, K., Cobeen, K., and Pollock, D. (2007). "Design of Wood Structures." McGraw-Hill, Inc., New York, New York.

Briscoe, C. R., Mantell, S. C., Davidson, J. H., and Okazaki, T. (2010). "Design Procedure for Web Core Sandwich Panels for Residential Roofs." *Journal of Sandwich Structures and Materials*.

Carll, C., and Wiedenhoeft, A. C. (2009). "Moisture-Related Properties of Wood and the Effects of Moisture on Wood and Wood Products." Moisture Control in Buildings: The Key Factor in Mold Prevention, H. R. Trechsel and M. T. Bomberg, eds., ASTM International, West Conshohocken, PA, 54-79.

Ching, F. (1991). *Building Construction Illustrated*, Van Nostrand Reinhold.

Chow, P., McNatt, J. D., Lambrechts, S. J., and Gertner, G. Z. (1988). "Direct withdrawal and head pull-through performance of nails and staples in structural wood-based panel materials." *Forest Products Journal*, 38(6).

Crowley, J., Dentz, J., Morse-Fortier, L., and Parent, M. (1993). "Reinventing Wood Frame Construction: Development of an Innovative Roof Component System." *Forest Products Journal*, 43(7/8).

Cunningham, T. P., Jr. (1993). "Evaluation of Roof Sheathing Fastening Schedules for High Wind Uplift Pressures." Hurricanes of 1992, Cook and Soltani, eds., ASCE, Miami, FL, 330-339.

Datin, P., Prevatt, D.O., and Pang, W. (2010). "Wind Uplift Capacity of Residential Wood Roof Sheathing Panels Retrofitted with Insulating Foam Adhesive." *Journal of Architectural Engineering*.

Datin, P. L. (2010). "Structural Load Paths in Low-rise, Wood-framed Structures," PhD Dissertation, University of Florida, Gainesville, FL.

Dedecker, K. (2002). "Introduction to Rigid Foams." The Polyurethanes Book, D. Randall and S. Lee, eds., Huntsman International LLC, Everberg, Belgium.

Dinwoodie, J. M. (1983). "Properties and Performance of Wood Adhesives." Wood Adhesives: Chemistry and Technology, A. Pizzi, ed., Marcel Dekker, Inc., New York, New York.

FBC. (2001). "Florida Building Code 2001." S. o. Florida, ed., Tallahassee, FL.

FEMA. (2005). "Mitigation Assessment Team Report: Hurricane Ivan in Alabama and Florida - Observations, Recommendations, and Technical Guidance." FEMA 489, Federal Emergency Management Agency.

FEMA. (2010). "Wind Retrofit Guide for Residential Buildings." *P-804*, U.S. Department of Homeland Security.

FL DCA. (2007a). "FL9975-R1." Florida Department of Community Affairs, Tallahassee, FL.

FL DCA. (2007b). "FL13001." Florida Department of Community Affairs, Tallahassee, FL.

Forest Products Laboratory. (2010). "Wood Handbook: Wood as an Engineering Material." United States Dept. of Agriculture Forest Service, Madison, WI.

Hendron, R., Anderson, R., Reeves, P., and Hancock, E. (2002). "Thermal Performance of Unvented Attics in Hot-Dry Climates." National Renewable Energy Laboratory, Golden, CO.

Hill, K. (2009). "Development of Time-Varying Wind Uplift Test Protocols for Residential Wood Roof Sheathing," University of Florida, Gainesville.

Hill, K., Datin, P., Prevatt, D., Gurley, K., and Kopp, G. (2009). "A Case for Standardized Dynamic Wind Uplift Pressure Test for Wood Roof Structural Systems." 11th ACWE, Puerto Rico.

HUD. (1993). "Assessment of Damage to Single-family Homes Caused by Hurricanes Andrew and Iniki." U.S. Department of Housing and Urban Development, Washington, DC.

Hudson, E. (2010). "Personal Communication about 2009 U.S. Housing Characteristics between K. McBride and E. Hudson." K. McBride, ed., Upper Marlboro, MD.

IBHS. (2011). "Strengthening an Existing Roof - Options Other than Re-roofing." Institute for Business & Home Safety, Tampa, FL.

ICC. (2009). *2009 International Residential Code for One- and Two-family Dwellings*.

IHRC. (2004). "Hurricane Loss Reduction for Housing in Florida: Final Report." International Hurricane Research Center, Florida International University, Miami, FL.

Jones, D. T. (1998). "Retrofit Techniques Using Adhesives to Resist Wind Uplift in Wood Roof Systems," MS Thesis, Clemson University, Clemson, SC.

Kallem, M. R. (1997). "Roof Sheathing Attachment for High Wind Regions: Comparison of Screws and Nails," Clemson University, Clemson, S.C.

Kemp, G. (2008). "New hurricane test facility allows repeatable full-scale building testing." *Test Engineering and Management*, 70(4), 10-13.

Kumaran, M. K., Lackey, J. C., Tariku, F., and van Reenen, D. (2002). "A Thermal and Moisture Transport Property Database for Common Building and Insulating Materials." ASHRAE.

Lee, K. H., and Rosowsky, D. V. (2005). "Fragility Assessment for Roof Sheathing Failure in High Wind Regions." *Engineering Structures*, 27(2005), 857-868.

Mantell, S. C., Davidson, J. H., Mittelman, G., DiMuoio, G. I., Mosiman, G. E., Carmondy, J. C., Okazaki, T., Shield, C. K., Siljenberg, B. J., and MacDonald, D. H. (2008). "Manufactured Panelized Roof System for Residential Buildings." ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA.

MathWorks. (2009). "Matlab R2009b." The MathWorks Inc., Natick, MA.

Mizzell, D. P. (1994). "Wind Resistance of Sheathing for Residential Roofs," MS Thesis, Clemson University, Clemson.

Morley, M. (2000). *Structural Insulated Panels: Strength and Energy Through Structural Panel Construction*, Taunton Press Inc., Newton, CT.

Murphy, S., Schiff, S. D., Rosowsky, D., and Pye, S. (1996). "System Effects and Uplift Capacity of Roof Sheathing Fasteners." Structures Congress, ASCE, New York.

NAHB. (2003). "Roof Sheathing Connection Tolerances." NAHB Research Center, Upper Marlboro, MD.

NCDC. (2011). "Quality Controlled Local Climatological Data." NOAA National Climatic Data Center, Asheville, NC.

NRCA. (2011). "Asphalt Shingles." National Roofing Contractors Association, Rosemont, IL.

NSB. (2007). "Hurricane Warning: The Critical Need for a National Hurricane Research Initiative." National Science Foundation, Arlington, VA.

Parker, D. (2005). "Literature Review of the Impact and Need for Attic Ventilation in Florida Homes." Florida Department of Community Affairs.

Parker, D., and Sherwin, J. (1998). "Comparative Summer Attic Thermal Performance of Six Roof Constructions." Florida Solar Energy Center/University of Central Florida, Cocoa, FL.

Prevatt, D. O. (2007a). "Improving the Wind Uplift Capacity of Wood Roof Panels Retrofitted with ccSPF Adhesives." NCFI Polyurethanes, Mount Airy, NC.

Prevatt, D. O. (2007b). "Wind Uplift Behavior of Wood Roof Sheathing Panels Retrofitted with Spray-applied Polyurethane Foam." Report No. 03-07, University of Florida, Department of Civil & Coastal Engineering, Gainesville, FL.

Rose, W. "Measured Summer Values of Sheathing and Shingle Temperatures for Residential Attics and Cathedral Ceilings." *Performance of Exterior Envelopes of Whole Buildings VIII: Integration of Building Envelopes*, Clearwater Beach, FL.

Rudd, A., and Lstiburek, J. (1998). *Vented and Sealed Attics in Hot Climates*, ASHRAE Transactions.

Rudd, A., Lstiburek, J., and Ueno, K. (1999). "Unvented-cathedralized Attics: Where We've Been and Where We're Going." Building Science Press.

Sengoz, B., and Topal, A. (2005). "Use of asphalt roofing shingle waste in HMA." *Construction and Building Materials*, 19(5), 337-346.

SFBC. (1994). "South Florida Building Code 1994." Board of County Commissions, Dade County, FL.

Shanmugam, B., Nielson, B. G., and Prevatt, D. O. (2009). "Statistical and Analytical Models for Roof Components in Existing Light-framed Wood Structures." *Engineering Structures*, 31, 2607-2616.

Skaggs, T., and Readling, B. (2005). "Hurricane Katrina: Structural Performance of Wood-frame Buildings in the Aftermath." APA - The Engineered Wood Association, Tacoma, WA.

Smits, G. (1994). "Effect of Cellsize Reduction on Polyurethane Foam Physical Properties." *Journal of Building Physics*, 17(4).

Sparks, P. R., Schiff, S. D., and Reinhold, T. A. (1994). "Wind Damage to Envelopes of Houses and Consequent Insurance Losses." *Journal of Wind Engineering*, 53(1994), 145-155.

Spelter, H., McKeever, D., and Alderman, M. (2006). "Status and Trends: Profile of Structural Panels in the United States and Canada." U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI.

Straube, J., and Burnett, E. (2005). *Building science for building enclosures*, Building Science Press.

Sutt, E., Reinhold, T., and Rosowsky, D. (2000). "The Effect of in-situ Conditions on Nail Withdrawal Capacities." World Conference on Timber Engineering, Whistler, B.C.

TenWolde, A., and Rose, W. (1999). "Issues Related to Venting of Attics and Cathedral Ceilings." *ASHRAE Transactions*, 105(1), 851-857.

Terrenzio, L. A., Harrison, J. W., Nester, D. A., and Shiao, M. L. "Natural vs. Artificial Aging: Use of Diffusion Theory to Model Asphalt and Fiberglass-reinforced Shingle Performance." *Fourth International Symposium on Roofing Technology*, Gaithersburg, MD.

Thomas, D., Mantell, S. C., Davidson, J. H., Goldberg, L. F., and Carmody, J. (2006). "Analysis of Sandwich Panels for an Energy Efficient and Self-supporting Residential Roof." *Journal of Solar Energy Engineering*, 128(August 2006).

Timusk, P. C. (2008). "An Investigation of the Moisture Sorption and Permeability Properties of Mill-Fabricated Oriented Strandboard," PhD Dissertation, University of Toronto, Toronto, Ontario, CA.

Turner, M. A., Plaut, R. H., Dillard, D. A., Loferski, J. R., and Caudill, R. (2009). "Tests of adhesives to augment nails in wind uplift resistance of roofs." *Journal of Structural Engineering*, 135(1), 88-93.

U.S Department of Labor. (2011). "CPI Inflation Calculator." United States Bureau of Labor Statistics, NE Washington, DC.

US Census Bureau. (2003). "Census of population and housing (2000)." US Dept. of Commerce, Economics and Statistics Administration, Washington, D.C.

van de Lindt, J. W., and Dao, T. N. (2009). "Performance-based Wind Engineering for Wood-frame Buildings." *Journal of Structural Engineering*, 135(2), 169-177.

van de Lindt, J. W., Graettinger, A., Gupta, R., Skaggs, T., Pryor, S., and Fridley, K. J. (2007). "Performance of Wood-Frame Structures during Hurricane Katrina." *Journal of Performance of Constructed Facilities*, 21(2), 108-116.

Wang, J., Clark, J., Symons, P., and Morris, P. (2010). "Time to Initiation of Decay in Plywood, OSB and Solid Wood under Critical Moisture Conditions." International Conference on Building Envelope Systems and Technologies (ICBEST 2010), Vancouver, Canada.

Wheeler, A. J., and Ganji, A. R. (2004). "Statistical Analysis of Experimental Data." Introduction to Engineering Experimentation, Pearson Education, Inc., Upper Saddle River, NJ.

Wherry, G. D. (2009). "Trends and Diversification in the Factory-Built Home Industry," Virginia Polytechnic Institute, Blacksburg, VA.

Zabel, R. A., and Morrell, J. J. (1992). *Wood Microbiology: Decay and Its Prevention*, Academic Press, Inc., San Diego, CA.

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