Final Report:

Improving the Wind Uplift Capacity of Wood Roof Panels Retrofitted with ccSPF Adhesives

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FOREWORD

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SUMMARY
This report documents an experimental investigation sponsored by NCFI Polyurethanes (NCFI) to determine the wind uplift capacity of roof sheathing panels retrofitted with closed-cell spray-applied polyurethane foam (ccSPF) adhesive product. The work was conducted at the University of Florida (UF) under the direction of Principal Investigator, Dr. David O. Prevatt, assisted by civil engineering graduate and undergraduate students and technicians. The main project goal was to evaluate the improvement in wind uplift resistance (if any) provided by SPF adhesive foam sprayed to the underside of wood roof panels.

Post-hurricane field investigations continue to show that building components and cladding elements in residential construction and the roofing systems in particular, suffer disproportionately large amount of wind damage as compared with other types of construction. The roof sheathing to rafter connection appears to be particularly vulnerable to damage.

UF conducted static wind uplift tests on thirty (30) wood roof panels that consisted of ½ in. thick by 4 ft by 8 ft oriented strand board (OSB) sheathing screwed to 2 in. by 4 in. southern yellow pine (SYP) wood members spaced 2 ft apart. The screws were used during fabrication of the panels to hold the sheathing to the wood but they were removed just before testing. The focus of this experiment was the determination of the additional structural resistance of the ccSPF alone. We tested roof panels having three configurations of ccSPF retrofits applied as follows:

1. Configuration A: ccSPF Fillet along sheathing to wood joints in panel
2. Configuration B: ccSPF Fillet plus ½ in. thick foam layer, and,
3. Configuration C: ccSPF 3 in. foam layer.

The ccSPF retrofits were installed to the roof panels by NCFI technicians in mid-August 2007 and the retrofitted panels were tested approximately 2 weeks later to allow the ccSPF time to cure. All fabrication, retrofit and testing activities were conducted at UF's East Campus laboratory using a steel pressure chamber and vacuum pump following a modified ASTM E330 test procedure. The suction (negative pressure) on the exterior surface of the OSB sheathing was increased in stages until failure occurred.

The ultimate failure capacities of the retrofitted panels were recorded and are presented in this report. The mean failure pressures of the three ccSPF retrofit configurations were 209 psf, 178 psf and 199 psf, respectively for Configurations A, B and C. These results confirm that the ccSPF retrofit configurations tested provided significant structural improvement in wind uplift capacity of roof panels as compared with non-retrofitted panels (1/2 in. OSB fastened to 2 in. by 4 in. SYP members using 8d common and ring shank nails installed using a conventional 6 in./12 in. fastening schedule).

KEYWORDS: Closed-cell Foam; Polyurethane; Wind uplift; Sheathing; Roof; Retrofit; ASTM; Structural Adhesive.

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1. INTRODUCTION

This report details the methods, results, and conclusions of a test sequence investigating the potential structural retrofit benefits of closed-cell Spray-applied Polyurethane Foam (ccSPF) used as a structural adhesive in the residential roof construction. Tests were conducted on wood roof panels and three configurations of ccSPF retrofits applied as follows:

(1) Configuration A: ccSPF Fillet along sheathing to wood joints in panel;
(2) Configuration B: ccSPF Fillet plus ½ in. thick foam layer, and,;
(3) Configuration C: ccSPF 3 in. foam layer.

The panels were fabricated by UF graduate and undergraduate students and the ccSPF retrofits were installed by NCFI technicians. The main deliverable from this research is this report documenting the test methods, results and findings.

1.1 Background

Spray-applied Polyurethane Foam (SPF) is a foam product originally developed for use as an insulating material in building (exterior wall and roof) construction. SPF can be spray-applied to the undersides of roof decks and to wall cavities to act as a thermal break between the exterior environment and the temperature controlled interior spaces. SPF forms a tenacious bond to many construction materials when sprayed in a controlled fashion. A recent experimental study at UF using closed-cell spray-applied polyurethane foam (ccSPF) found that this bond results in significant improvements in wind uplift capacity of roof panels (Prevatt 2007). This study was one of the first to scientifically determine the structural benefits of using ccSPF.

In traditional (stick-built) construction of wood residential structures, the structural frame of the building's exterior walls and roof are erected, and then structural sheathing is fastened to the frame using nails. For residential roof construction, typical framing materials are pre-fabricated wood trusses of 2 in. by 4 in. wood members. Roof trusses are installed at 2 ft. o.c. spacings. Roof sheathing materials, (i.e. oriented strand-board (OSB) or plywood sheet) are fastened through the narrow edge of the truss top chord members using nails. The nail dimensions can vary depending on the building location and minimum code requirements, but 6d and 8d common or 8d ring shank nails have been used.

Building codes include minimum requirements for fastener dimensions and fastener spacing. Roof sheathing is installed using nails set at specified "fastening schedules" or spacing between nails. Fastening schedules vary with location and building code requirements. For example, for roof sheathing installed in the designated high wind zones established by the Florida Building Code (ICC 2004) the fastening schedule is 6 in./6 in. (i.e. 6 in. on center spacing along the sheathing edges and 6 in. o.c. at interior locations) except at gable ends where the required spacing is reduced to 4 in. In other less severe wind exposure zones, the fastening schedules can be 6 in./6 in. except at the roof corners where the required spacing is reduced to 4 in. Prior to the 2000 building code changes, the FBC specified a 6 in./12 in. fastening schedule for all residential construction. When properly installed the nail shanks will not be visible, and so it is nearly impossible to determine the withdrawal capacity of fasteners to estimate the wind uplift capacity of installed roof sheathing.

1.2 Focus of Research

Due to the large potential variability of nails and fastening schedules in installed roof sheathing, it is difficult to estimate the wind uplift capacity of existing roof construction by non-destructive inspection. The focus of this research therefore, is to determine the additional wind uplift capacity that is attributable to ccSPF adhesive applied to roof panels in which mechanical fastenings have been removed.

2. LITERATURE REVIEW

2.1 Fastening Schedules for Roof Sheathing

The Florida Building Code (ICC 2004) was first published in 2001 as a revision of the South Florida Building Code (Dade County 1994). The nailing requirements for roof sheathing have changed several times over the years. Table 2.1 compares the progressive changes of minimum nail dimensions and fastener schedules of several commonly used building codes. In the 2004 Florida Building Code (with the 2007 supplement), a 6 in./6 in. fastening schedule using 8d common nails is required except at the roof corners where a 4 in. nail spacing is required. A minimum roof sheathing thickness of 5/8 in. is also required. In the High-Velocity Hurricane Zones (HVHZ) (Section 2322) of the Florida Building Code, (defined as Broward and Dade Counties), the required fastening schedule is 6 in./6 in. using 8d ring shank nails except at the gable end where a 4 in. nail spacing is required. From our interpretation of Clause *2322.2.5.3* of the HVHZ, it appears that oriented strand board is not permitted as a roof sheathing material. Also, Clause *2322.2.5.3* states that "Other products with unique fastening methods may be substituted for these nailing requirements as approved by the building official and verified by testing." Another nailing schedule is provided in the 2006 International Building Code (IBC) (ICC 2006) where a 4 in./8 in. fastening schedule is prescribed using 8d common nails.

Table 2.1 – Sheathing Fastening Schedules

Building Code	Nail	Sheathing	Fastening Schedule (edges/intermediate)
1988 South Florida Building Code (Dade County 1988)	6d common 8d common	½ in. or less greater than ½ in.	6"/12" on center
1994 South Florida Building Code(Dade County 1994)	8d common	up to 19/32 in.	6"/12" on center except at gable ends 4" on center
1997 Standard Building Code (SBCCI 1997)	6d common 8d common	½ in. or less 19/32 in. or greater	6"/12" on center
2000 International Building Code (ICC 2000)	8d common	¾ in. or less	6"/12" on center
2004 Florida Building Code (ICC 2004)	8d common	¾ in. or less	6"/6" on center except 4" on center at roof corners
2004 Florida Building Code High-Velocity Hurricane Zone (ICC 2004)	8d ring shank	Minimum 19/32 in.	6"/6" on center except 4" on center at gable ends
2006 International Building Code (ICC 2006)	8d common	¾ in. or less	4"/8" on center

2.2 University of Florida Wind Uplift Tests on Roof Sheathing

In July 2007, University of Florida (UF) conducted wind uplift tests (Prevatt 2007) on wood panel specimens fabricated with 6d common and 8d ring shank nails. In that study, a control sample of 10 panels using 8d ring shank nails placed at 6 in./12 in. fastening schedule were tested without ccSPF adhesives, resulting in a mean failure pressure of 78 psf. A further control set of five panels fastened with 6d common nails at 6 in./12 in. fastening schedule and no ccSPF adhesives were tested, resulting in a mean panel failure pressure of 75 psf.

2.3 Retrofit Structural Adhesive of Sheathing-to-Wood Member Connection

Jones (1998) conducted suction tests on 4 ft by 8 ft roof sheathing panels in a pressure chamber loading the panels monotonically until failure. Roof specimens were constructed using two sheathing materials, a) 19/32 in. OSB and b) 15/32 in. 3-ply CDX plywood, fastened using power-driven 8d common nails to wood members placed 2 ft apart. Jones' test used a 6 in./12 in. fastening schedule.

In all, this study tested 97 roof specimen panels, including 11 combinations of nails, sheathing type and adhesive arrangements. A control set of 19 panels was also tested. The retrofitted panels had among other configurations, the two-part foaming adhesive sprayed continuously along the sheathing-to-wood member joints.

Table 2.2 shows the basic statistics of Jones' results.

Table 2.2 – Failure Pressures Using Structural Adhesives (Jones 1998)

Description of Test	Sample Size	Mean Failure Pressure (psf)	COV (%)
19/32 in. OSB control panels	10	87	28
15/32 in. CDX plywood control panels	9	72	19
19/32 in. OSB with single pass of adhesive on both sides of wood members	4	185	16
19/32 in. OSB with double pass of adhesive on both sides of wood members	5	314	9
15/32 in. CDX plywood with single pass of adhesive on both sides of wood members	10	213	14

Jones found that the sheathing type affects the wind uplift capacity of roof specimens. For the 15/32 in. CDX plywood, the continuous adhesive application plus nails provided approximately 200% increase in the uplift capacity of the sheathing over the control specimens. Whereas, for the 19/32 in. OSB sheathing, the increase in wind uplift capacity for the adhesive retrofitted specimens ranged from 100% to 300%, depending on the amount of adhesive used.

2.4 Florida International University Wind Uplift Tests on Roof Sheathing

In 2004/2005 researchers at Florida International University (FIU) conducted wind uplift tests on 4 ft by 8 ft roof panels using a pressure chamber and vacuum pump to determine the uplift resistance of various mechanical fasteners (i.e. nails and staples) (FIU 2004; FIU 2005). The roof panels consisted of ½ in. and 5/8 in. thick CDX plywood fastened to 2 in. x 4 in. wood members (Southern Yellow Pine), at 2 ft o.c. spacings. The panels were connected using a 6/12 fastening schedule in all cases.

Unfortunately, several errors and omissions in this diminishes its usefulness, (e.g. the units of pressure are incorrectly identified as "psi" - we believe the units of pressure should be "psf", and limited information is provided regarding the materials used, the test protocols and load sequences and source(s) of previous test results). However, in Table 2.3 we present results for mean uplift capacity of the roof panels tested by FIU.

Table 2.3 – FIU Test Results

Fastener	Sheathing	Sample Size	Mean Uplift Capacity (psf)
1.5 in. Staple[1]	⅝ in. CDX plywood	15	67
2 in. Staple[1]	⅝ in. CDX plywood	15	79
8d Common nail[2]	½ in. CDX plywood	50	108
8d Ring Shank (Sheather Plus)[1,2]	½ in. CDX plywood	50	140

[1] Source: FIU (2005)
[2] Source: FIU (2004)

3. INVESTIGATION OF CLOSED-CELL SPF RETROFITTED PANELS

On 17 August 2007, University of Florida civil engineering students fabricated 30 wood specimen roof panels at UF's East Campus laboratory. On 30 August 2007, an NCFI technician visited the laboratory to install the ccSPF adhesive, under the direction of Mr.

Jason Hoerter, NCFI Product Manager. The ccSPF-retrofitted panels were tested on 11 to 14 September 2007, following a modified ASTM E330-02 procedure (ASTM 2004).

3.1 Test Materials

A test materials list is provided in Table 3.1.

Table 3.1 – Materials Used for Specimen Fabrication and Tests

Test material	Description	Manufacturer
Roof Sheathing	½ in. x 48 in. x 96 in. oriented strand board (OSB), Exposure 1, 32/16 span rating	Norbord, Toronto, Ontario, Canada
Wood Member	2 in. x 4 in. southern yellow pine (SYP), untreated, No. 2 Grade	K-D Wood Products Inc., Bingham, ME
Structural Adhesive	InsulStar®, 2 pcf closed-cell sprayed polyurethane foam (ccSPF)	NCFI Polyurethanes, Mount Airy, NC
Drywall screws (temporary attachment)	2” long, coarse thread	
Plastic Sheet	2 mil (0.002 in.) thick clear polyethylene sheet	Contractor’s Choice
Duct tape	L155-XW	3M

The specimen roof panels were fabricated using the roof sheathing fastened to five equally spaced wood members, 2 ft o.c. The end wood members of each panel were placed with their outboard face flush with the edge of the sheathing rather than centered over on the edge, as is the case in actual roof construction (Figure 3.1).

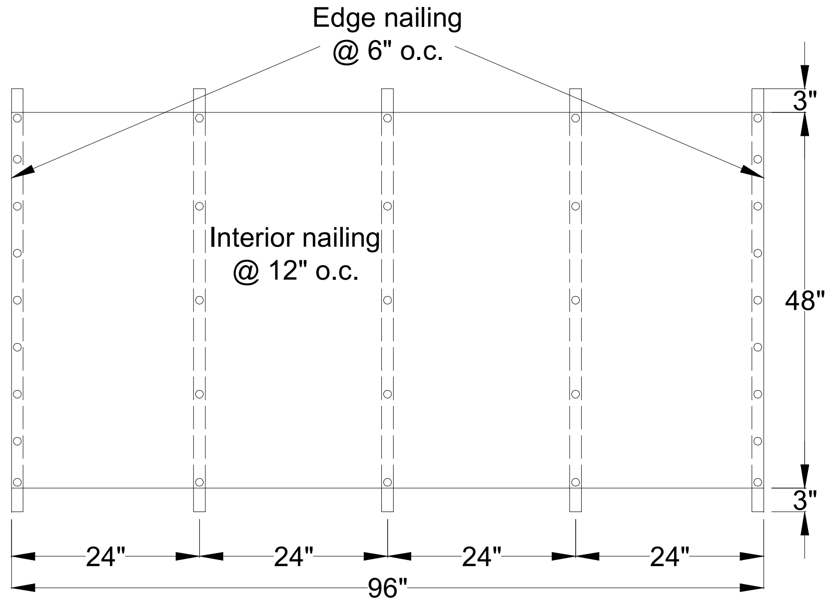

Figure 3.1 – Test Specimen Layout and Fastening Schedule

The wood members were cut to 4 ft-6 in. and centered on the sheathing so that their ends extended 3 in. beyond the sheathing (Photo 1). We used drywall screws installed at 6/12 fastening schedule to temporarily fasten the sheathing to the wood members. The completed specimens were inspected to identify defects and numbered prior to applying the ccSPF adhesive.

In order to determine the strength of the ccSPF adhesives, the dry wall screws had to be removed prior to testing the roof panels. For tests on the first three panels (Specimens Nos. 2, 20 and 30), we removed all drywall screws from all wood members. However, these panels failed at the exterior wood member, which appeared due to excessive rotation caused by unbalanced load on wood members. In all subsequent tests, only the screws installed into the interior wood members were removed.

3.2 Spray Foam Application

NCFI supplied a high-pressure spray apparatus that was used to apply the ccSPF adhesive. ccSPF is made by mixing two chemicals, Part A and Part B together under high temperature and pressure. The Part A component, or “A-side” is an isocyanate liquid (di-phenyl methane di-isocynate or MDI) manufactured by Huntsman, and Part B or the “B-side” is a proprietary liquid resin blend manufactured by NCFI Polyurethanes under the InsulStar® brand. When these chemicals are mixed, they react to form the ccSPF liquid which turns to foam, increasing the liquid volume by 20 to 30 times (Photo 2). As the foam cools, it solidifies to a seamless, closed-cell material bonded to the substrate upon which it was sprayed. The test panels were propped up almost vertically to be sprayed (Photo 2). We divided the 30 test specimens into three treatment groups of ten specimens each, with foam retrofits installed as follows:

- **Configuration A: Foam fillet along sheathing to wood member joints.** The technician held the spray nozzle approximately 18 in. to 24 in. away from the sheathing to apply several passes of foam along the sheathing to wood member joints. In this way, a triangular foam fillet approximately 3 in. tall by 3 in. wide was built up in layers. The technician allowed a few (3 to 5) seconds between each pass to allow the foam to cool. Foam fillets were installed along the inboard joints of the exterior wood members and along both joints of the interior wood members (Photo 3).

- **Configuration B: Foam fillet plus ½ in. thick foam layer on sheathing.** The technician fabricated foam fillets as described for Configuration A specimens above and then a ½ in. deep foam layer, approximately 4 in. wide was applied along the sheathing edges between the wood members. Finally, the interior sheathing area was coated with ccSPF layer using several passes in 4 in. to 5 in. wide overlapping rows. Jason Hoerter of NCFI used a depth gauge to spot-check the thickness of foam and the ccSPF was applied until the desired thickness was achieved (Photo 4).

- **Configuration C: Full 3 in. thick foam layer on sheathing.** Before installing the Configuration C foam, the applicator changed the nozzle on the spray gun to a larger one allowing more foam to be applied in a given pass requiring fewer passes with the spray gun to build up to the 3 in. thickness. For this thickness, the technician allowed a longer cool-down period between passes (30 sec. to 1 minute) to avoid trapping heat within the foam that could result in damage to the finished product (Photo 5).

During the initial foam application of the 3 in. SPF layer (Configuration C) panels to two panels, large air bubbles formed between the foam and the sheathing. The bubbling, some as large as 12 in. by 30 in. long, occurred within seconds of the first foam layer application. The spray technician discovered that the bubbling was caused by excessive moisture output from the compressor. After checking the equipment, the technician discovered the cause was excessive moisture collecting within the spray apparatus. The technician emptied the water reserve chamber of the built-in dehumidifier, and spray application proceeded without further problems. The liquid resin in the ccSPF is highly reactive to water, forming large quantities of carbon dioxide. Consequently, one of the panels sprayed (#22) was unsalvageable and had to be discarded. The loose foam on the other panel (#21) was removed and the ccSPF was reapplied.

After spraying, the specimen panels were moved into a dry storage facility and covered with a tarpaulin to allow the ccSPF to cure. A 7-day minimum cure period was established in previous tests.

3.3 Test Chamber

A list of test equipment is provided in Table 3.2 below. All pressure tests were carried out using a 6 in. deep steel pressure chamber, with hot-rolled channel sections welded to a sheet steel base. The chamber is connected by PVC pipe to two vacuum pumps through a 2 in. hole in the chamber wall. The pressure gauge is installed through a ½ in. threaded hole in the chamber wall. The test setup is shown in Figure 3.2 below.

Table 3.2 – Test Equipment Used in this Test

Equipment	Description	Capacity/Range
Pressure gauge	DPG 8000-VAC gauge by Omega, Serial #1015044, purchased Sept 2007, most recent calibration date: 07/06/2006	30.0 in Hg
Pump 1	CP15, rotary vane single stage vacuum pump, by US Vacuum, Serial # 8817	Flowrate: 15 CFM Max vacuum: 2100 psf
Pump 2	CP15, rotary vane single stage vacuum pump, by US Vacuum, Serial #9053A	Flowrate: 15 CFM Max vacuum: 2100 psf

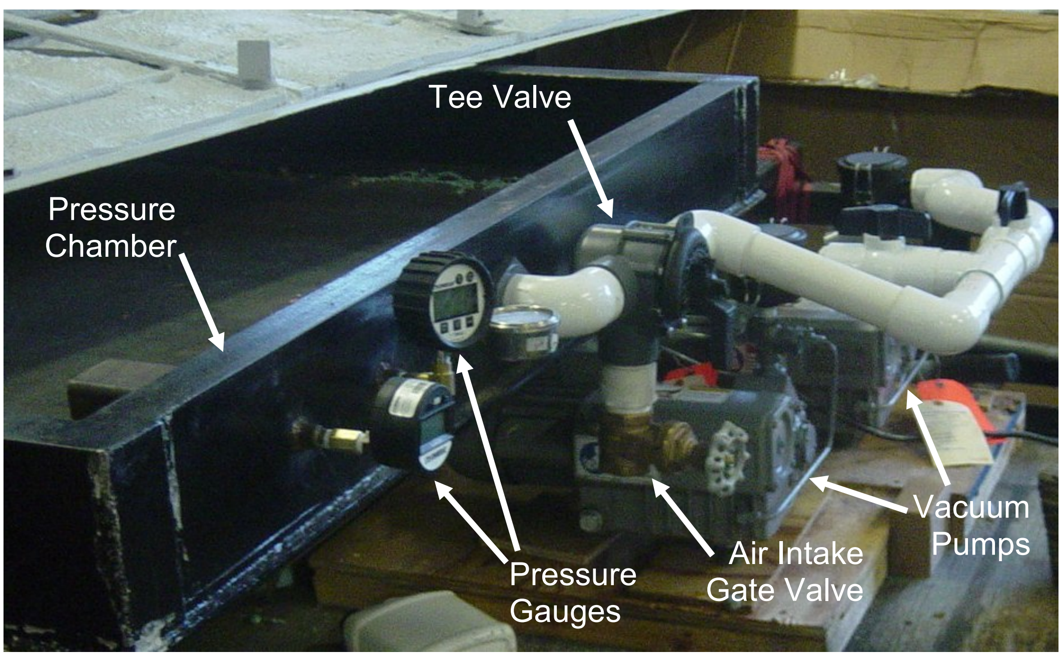

Figure 3.2 – Pressure Chamber, Vacuum Pumps and Controls

3.4 Test Procedure

The testing method used is modified from ASTM E330-02 (Standard Test Method for Structural Performance of Exterior Windows, Doors, Skylights and Curtain Walls by Uniform Static Air Pressure Difference) (ASTM 2004). Currently no standard test procedures exist for the determination of wind uplift performance of wood roof structures. The main modifications to ASTM E330 test procedure were as follows:

- pressure is applied in one direction only, i.e. suction or reduced pressure within the test chamber,
- no deflection readings are taken to record permanent deformation of the panels,
- the chamber pressure is reduced in 15 psf increments, applied and maintained for approximately 10 seconds, and
- the recovery period for stabilization specified in ASTM E330 is not used.

Each test specimen was placed on the pressure chamber, sheathing side down, with wood members spanning the short dimension of the chamber. The test specimen was covered loosely with a single thickness the plastic sheet. Care was taken to ensure the membrane did not restrict specimen movement or prevent failure. Extra folds of the plastic were used at corners and around the wood members to minimize “tenting” of the sheet. The plastic taped to the test chamber using duct tape to create an airtight seal (Photo 6).

We reduced the pressure in the chamber by 15 psf by slowly adjusting the inlet gate valve. We held this pressure for 10 seconds and then reduced the chamber pressure by a further 15 psf, also held constant for 10 seconds. The test proceeded in this manner until panel failure occurred at which time we recorded the peak reduction in pressure achieved.

Specimen failure was defined as the load at which hairline cracks appeared in the foam, or when structural failure of one or more wood members occurred (audible fracture). We closely observed each specimen during the progress of the tests to detect the first signs of failure. After failure had occurred, we removed the plastic sheet to carefully examine the specimen, noting the failure modes and locations of failure.

4. RESULTS AND OBSERVATIONS

4.1 Failure Modes for ccSPF Retrofitted Roof Panels

We observed five distinct failure modes in the roof panel specimens. This section briefly describes these failure modes. Failure can occur in the wood member (fracture) or in the ccSPF itself. For this discussion, the wood member and sheathing are called the adherents and the ccSPF, the adhesive (Figure 4.1).

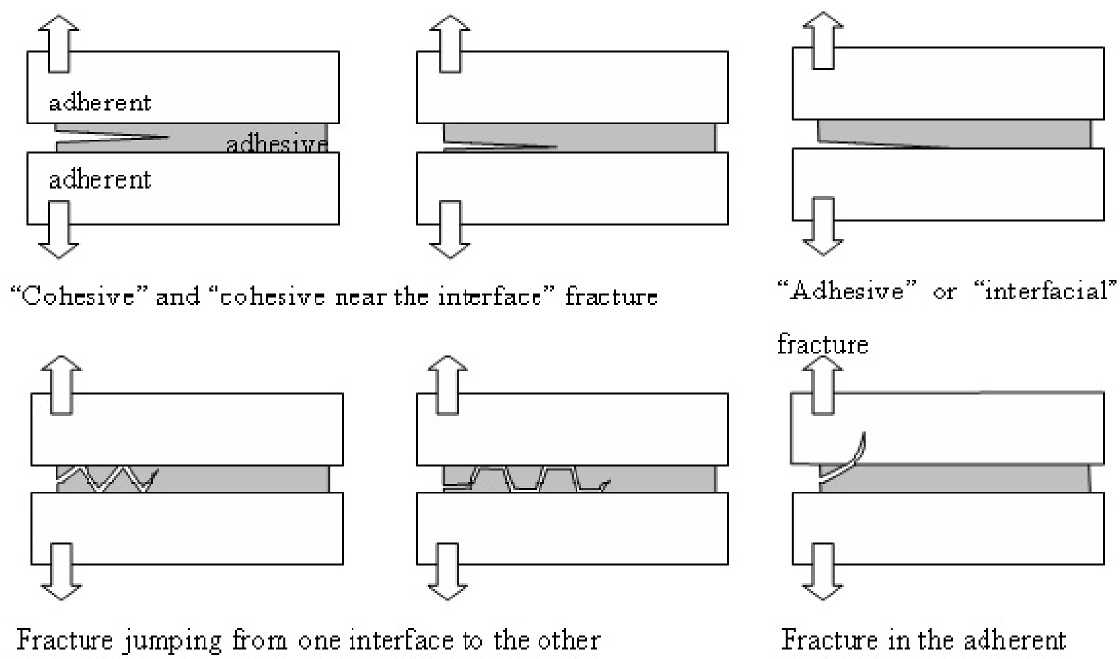

Figure 4.1 – Adhesive Failure Modes (from http://wikipedia.org)

The failure modes are described as follows:

- ***"Cohesive" Fracture*** – A crack propagates through the adhesive and portions of the fractured adhesive remain on the adherent material (wood members and sheathing).
- ***"Adhesive" Fracture*** – Debonding occurs between the adhesive and the adherent. For ccSPF application to wood, adhesion is achieved in two possible methods. The first is by a chemical bond between the wood and the adhesive. The second is by mechanical interlocking with the adhesive working its way into small pores in the wood. The *Wood Handbook* (Forest Products Laboratory 1999) and Cognard (2006) discuss these phenomena in more detail.
- ***Mixed Fracture*** – Failure occurs if the crack propagates as a cohesive fracture in some places and as an adhesive fracture in other places.
- ***Alternating Crack Path*** – The crack jumps from one interface to the other due to tensile pre-stresses in the adhesive.
- ***Fracture in the Adherent*** – The adhesive remains intact but the adherent fractures due to a tougher adhesive than adherent.

4.2 Results

Table 4.1 summarizes the wind uplift capacities of the tested roof panels.

Table 4.1 – Ultimate Failure Pressures of Test Specimens

Test Dates	Configuration A		Configuration B		Configuration C	
	ID #	Failure (psf)	ID #	Failure (psf)	ID #	Failure (psf)
9/11/2007	*2*[1]	*250*	*20*[1]	*149*	*30*[1]	*215*
9/12/2007	1	184	19	193	29	214
	3	186	18	246	28	178
	4	185	17	151	27	197
	5	223	16	127	26	165
9/14/2007	6	193	15	136	25	195
	7	184	14	180	23	169
	8	224	13	196	24	257
	9	257	12	197	21	203
	10	209	11	209	*31*[2]	*192*
Mean (psf)	209.3		178.4		199.0	
Std. Dev (psf)	27.8		37.3		28.2	
COV (%)	13.3%		20.9%		14.2%	

[1] Note: These panels had the screws removed from all of the wood members. In the remaining specimens, the nails were only removed from the three interior wood members.
[2] Roof panel fabricated in June 2007 with 15/32 in. OSB on SYP fastened with 8d common nails at 6/12 fastening schedule. This data point *is not* included in the calculation of the mean and standard deviation for this configuration

Three different types of failure modes were observed for Configuration A (Photos 7 and 8), described below.

1. *Separation of the wood member from the foam*. This foam separation from the wood member was sometimes an adhesive fracture evidenced by little or no foam residue remaining on the wood member. Sometimes we observed a cohesive failure evidenced by significant foam residue remaining on the wood member.

2. *Separation of the foam from the sheathing, remaining intact with wood member.* This failure mode was always a cohesive failure since there was always significant foam residue remaining on the sheathing.
3. *Combination of Failure Modes 1 and 2 above*.

For Configuration B, the typical failure modes (Photos 9 and 10) were nearly identical to that of Configuration A. The ½" foam infill did not separate from the OSB sheathing during the testing. When the ½ in. foam layer fractured, the width of the fractured foam strip was approximately equivalent to the fillet width (~3 in.) Therefore, the failures were the same as for Configuration A.

There were four different types of failure modes for the Configuration C specimens (Photos 11 and 12).

1. *Wood member separates completely from foam and foam remains intact on the sheathing*. The separation from the wood member was sometimes an adhesive fracture evidenced by no foam residue on the wood member and sometimes a cohesive failure evidenced by significant foam residue remaining on the wood member. Sometimes when separation occurred from the wood member, approximately half of the wood member (in the 3.5 in. dimension) would have significant foam residue remaining and the other half would not (mixed failure). This is most likely due to one of the lifts of foam achieving a stronger bond with the wood than the other lift.

2. *Foam separates from the sheathing but remains intact on the wood member*. In this failure mode, the failure was always a cohesive failure since there was

always significant foam residue remaining on the sheathing. When the foam remained on the wood member and separated from the sheathing, the amount of foam that broke from the sheathing varied. Any where from approximately a 3-10 in. width of foam would remain attached to the wood member.

3. A combination of failure modes 1 and 2 above.
4. *Wood member failed by splitting (adherent failure).* This failure mode occurred in 1 of 9 specimens tested. The wood member failed at a knot in the wood.

5. DATA ANALYSIS

Figure 5.1 shows a comparative boxplot of the results for the three tested configurations. The top and bottom of the vertical lines in the boxplot represent the spread of the data (maxima and minima). The lowest and highest horizontal lines represent the first and third quartiles of each data set, and the middle horizontal line represents the median.

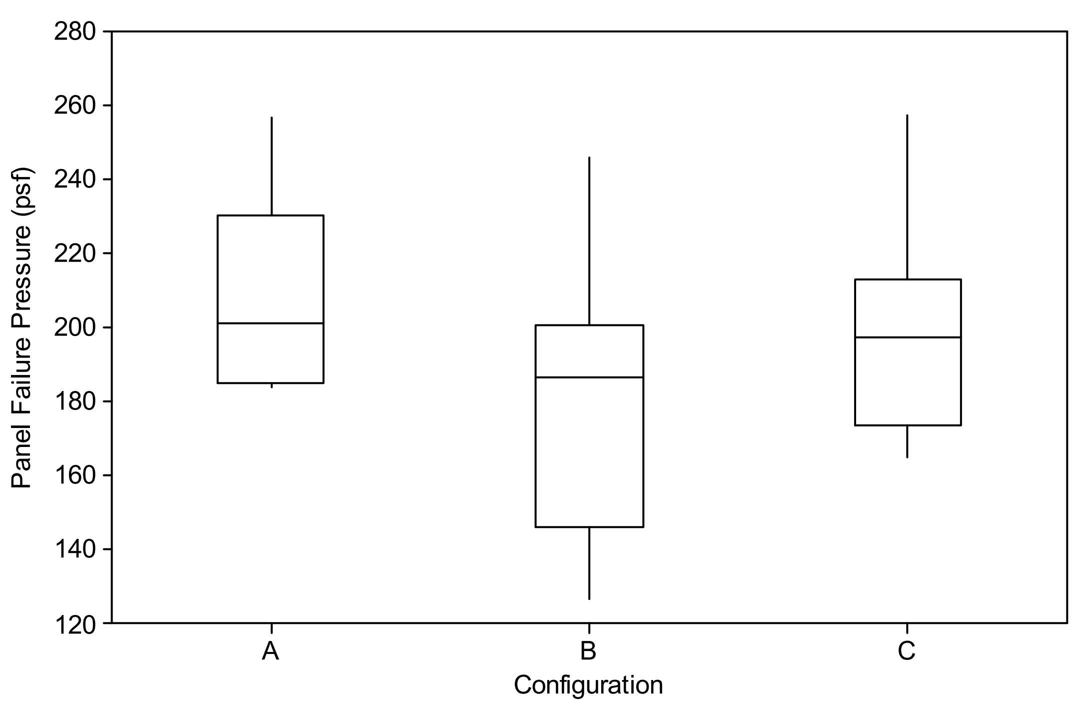

Figure 5.1 – Comparative Boxplot of Results for the 3 NCFI Configurations

A statistical analysis of the data from the 29 ccSPF specimens was performed, assuming a 0.05 (α = 0.05) significance level for all tests. Student's *t*-tests were conducted assuming unequal variances between the different configurations. The P-value, or observed significance level, is defined as the probability that the *t*-statistic, which quantifies the difference in two sample population means, is equal to zero. It thus provides a measure of the likelihood that the two samples are drawn from the same population.

If the P-value is large, this implies that the difference in the sample means is likely to be small. On the other hand, a small P-value indicates that the difference in the sample means is likely to be large, providing plausible evidence that the two samples were not drawn from the same population. When the P-value matches or is smaller than our predefined significance level of α = 0.05, there is a 1 in 20 or smaller possibility that the difference in two sample means is zero. Therefore, we can conclude there is sufficient statistical evidence supporting the likelihood that the sample means are not the same.

The P-value results of the Student's *t*-test on the difference in sample means of each treatment are 0.051, 0.431, and 0.191 respectively for the A to B, A to C, and B to C comparisons.

6. DISCUSSION OF RESULTS

Results are presented above for the wind uplift pressure tests on 29 wood roof panel specimens retrofitted with ccSPF adhesives in three configurations, tested without mechanical fasteners. It was found that mean wind uplift capacity for the 10 Configuration A specimens (ccSPF fillet) was 209 psf, or about 2.75 times greater than previous University of Florida control specimen failure capacities (Prevatt 2007). The observed ultimate failure capacity also exceeds the failure capacities of mechanically fastened panels tested by others in previous studies, although a direct comparison of results cannot be made because different materials were used and the details of the test method was not provided.

The mean wind uplift failure capacities of the nine Configuration C specimens (3 in. foam layer) was 199 psf and for the 10 Configuration B specimens (ccSPF fillet and ½ in. foam layer), 178 psf. However, there is no statistical difference in failure pressures among the three configurations tested, at the α = 0.05 significance level. Therefore, assuming that the three sample sets are drawn from the same population, the overall mean wind uplift failure capacity and coefficient of variation (COV) are 196 psf and 17.0%, respectively.

Figure 6.1 shows the 95% confidence intervals for the mean failure load of the three configurations tested and a comparison with the failure load for a control group (unretrofitted) roof panels tested in previous studies (FIU 2004; FIU 2005; Jones 1998; Prevatt 2007). The two control values shown from the previous UF tests (Prevatt 2007) are for two different nail “failures modes”, namely (a) the 8d ring shank nails pulled through the sheathing and remained attached to the wood members and (b) the 6d common nails withdrew from the wood members and did not damage the sheathing.

Comparing our results with the results obtained by others (FIU 2004; FIU 2005) it is noted that the ccSPF retrofit with no mechanical fasteners resulted in 81% increase in wind uplift capacity over panels fastened using 8d common nails alone and approximately 40% increase over panels fastened using 8d ring shank (Sheather Plus) nails only. However, as previously stated, the FIU results cannot be directly compared because: a) FIU reports limited information on their test procedures and load sequence and b) FIU tests used a different roof sheathing material (½ in. CDX plywood), as opposed to the ½ in. OSB sheathing used in these tests.

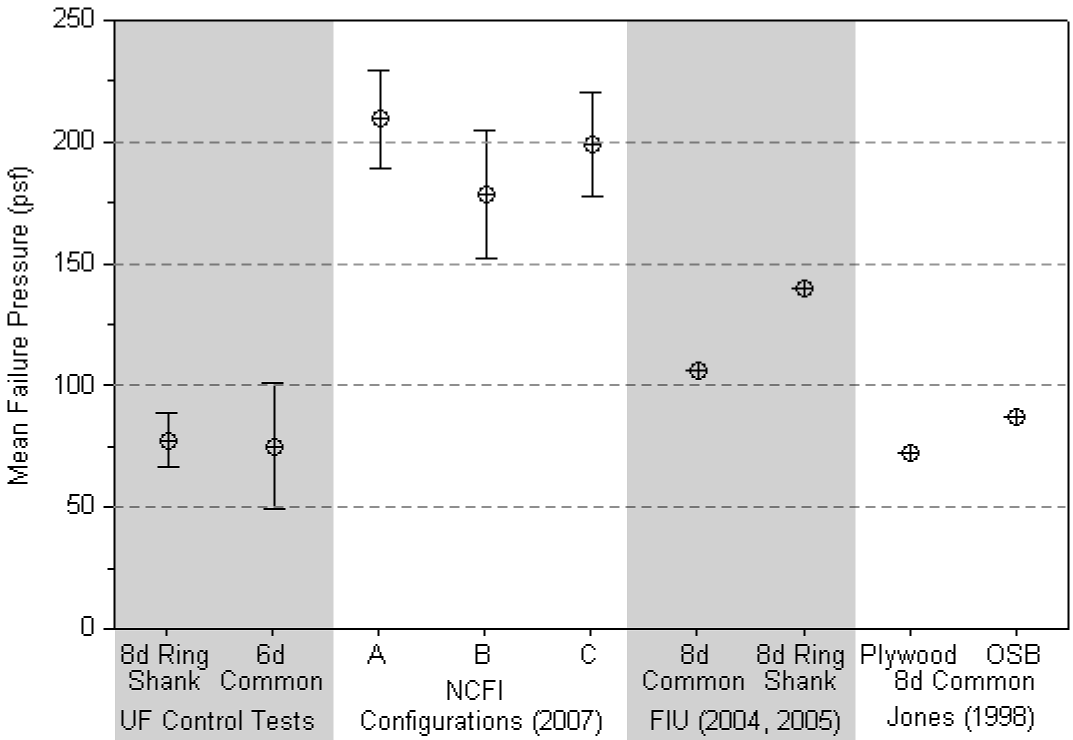

Figure 6.1 – Mean Uplift Capacities of Roof Panel Specimens from NCFI Tests Compared with Previous Results (Horizontal ticks indicate the 95% confidence interval of mean failure load)

It can be concluded that ccSPF retrofits to wood roof panels tested in accordance with methods outlined in this study will increase the roof panel wind uplift capacity approximately 2.6 times the uplift capacity of similarly constructed roof panels fastened using nails at a 6 in./12 in. schedule. This suggests that ccSPF can provide significant hurricane resistance to existing residential construction that was constructed before recent building code changes that modified fastening schedules to 6 in./8 in. or 4 in./6 in. as is the case today.

However, the reader is cautioned that these results are based on relatively small sample sizes (about 10 samples per configuration), that were fabricated under controlled laboratory conditions. It appears that the effective bond strength of ccSPF is sharply reduced by the presence of moisture in the spray application equipment and probably by moisture on the substrates. Dynamic (fluctuating) wind loads are likely to produce different results for all roof panels, including panels that have ccSPF retrofits and those that are conventionally fastened. Additional testing of field-installed ccSPF retrofits is required in order to verify the wind uplift capacity of ccSPF retrofitted roof panels installed in new and existing wood construction.

It appears that wood members with foam applied on one side only (i.e. at exposed gable ends) may have different a (lower) failure capacity due to unbalanced stress distribution.

6.1 Comparison between NCFI Configurations

Based on previous testing (Prevatt 2007), it was expected that the Configuration C panels (3 in. foam coverage) would produce the highest wind uplift capacity. However, Configuration A panels (fillet only) achieved the highest mean failure pressures, although statistically there is little difference among the three configurations tested. There was greater consistency in results (i.e. lower coefficient of variation) for the fillet only (Configuration A) specimens and the 3 in. foam layers (Configuration C) roof panels. The ccSPF retrofit with foam fillet and ½ in. foam layer (Configuration B), had the lowest mean failure capacity and largest COV in our tests.

6.2 Sources of Error

At failure, Configuration A and Configuration B roof panels sheathing visibly distorted accompanied by a loud sound. This made it easy to pinpoint the failure. However, for some Configuration C panels, the failure point was not quite so obvious. Some Configuration C (3 in. foam layer) panels failed more slowly, as the thick foam layer camouflaged the displacement of the sheathing. Prior to some failures, we observed the propagation of hairline cracks in the foam near to and parallel to the wood members. At such occurrences, we maintained the pressure in the chamber and inspected the crack. If the crack was small (barely visible), we would then continue to increase the pressure until more noticeable separation occurred.

7. CONCLUSIONS

- The wind uplift capacity of conventionally installed roof sheathing is significantly improved by the application of ccSPF as a retrofit structural adhesive. Tests show that roof panel wind uplift capacity can be increased by 2.6 times the uplift capacity of control roof panels fastened with nails only (8d common and 8d ring shank) at conventional nailing 6 in./12 in.
- There is no statistical difference between the ultimate failure capacities observed among the three ccSPF retrofit configurations (fillet only, fillet plus ½ in. foam layer, 3 in. foam layer) tested in this research.
- The average ultimate wind uplift capacity of roof sheathing panels retrofitted with ccSPF consisting of ½ in. OSB on 2 in. x 4 in. SYP wood members is 196 psf.

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Photo 1

Completed panel before foam is applied.

Photo 2

Application of ccSPF by NCFI technician. (Configuration B)

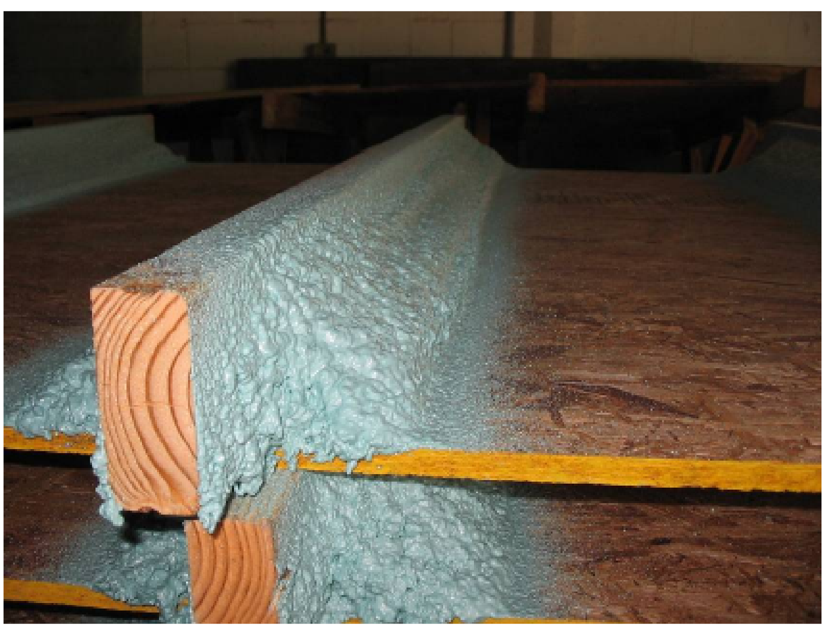

Photo 3

Close-up view of ccSPF foam fillet for Configuration A

Photo 4

Completed Configuration B panels (foam fillet plus ½ in. foam layer)

Photo 5

Completed Configuration C panels (3 in. foam layer).

Photo 6

Configuration A panel mounted on pressure chamber and sealed with polyethylene sheet.

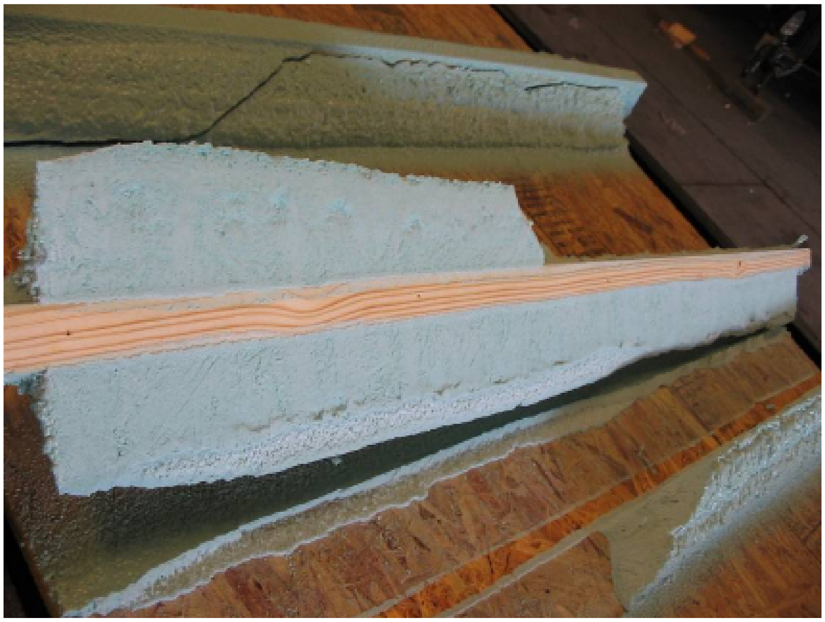

Photo 7

Failure of Configuration A panel showing underside of wood member and crack patterns in foam.

Photo 8

Failure of configuration A.

Photo 9

Failure of configuration B where the ccSPF was detached from wood.

Photo 10

Failure of ½ in. foam layer showing ccSPF detached from wood on left side of member and ripped on right side of member.

Photo 11

Cracking of fillet in 3 in. foam layer at failure.

Photo 12

Failure of 3 in. foam layer where ccSPF was detached from the wood on the left side of the member and sheared on the right side.