What Do We Learn from Wind Uplift Tests of Roof Systems?

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ABSTRACT

There are several industry-accepted test protocols to evaluate the wind uplift resistance of commercial roofing systems (ASTM E1592, UL1897, UL580, FM 4470 etc.). These tests apply pneumatic pressure to full-scale roof specimens installed on a pressure chamber, and increasing the pressure until failure. The wind uplift design pressure is then determined by reducing the peak pressure by an accepted factor of safety (e.g. 1.5 or 2.0). A critical question to be asked on the results is the meaning or validity of these static test results when hurricane winds produce dynamic roof pressures that are constantly fluctuating in time and space? The presenter reviews similarities and limitations of common wind uplift test methods for standing seam metal panels, and mechanically attached single ply roofing systems that have been the industry-standard for many years and reports on research results for these systems. Most of the test protocols provide comparative results, absent any verifiable relationship to roof performance in actual wind storms.

Of particular interest now is the determination of the wind design pressure for light-framed wood roof systems, for which there exists no industry-accepted test protocol. The fastener schedules and minimum fasteners included in current ICC building code today appear to be based on research conducted immediately after Hurricane Andrew. Recent experimental studies at the University of Florida revisited those studies and developed a new dynamic test protocol for wind uplift testing of roof sheathing panels. The results have shown inconsistency in previous tests and that static pressure testing of wood roofs may over-estimate their failure capacity when compared with dynamic pressure test methods. The presentation concludes with a proposal for standardizing the wind uplift testing of wood roof systems based on dynamic pressure fluctuations. The conclusion has far-reaching implications as similar modifications may be required to calibrate current static pressure test methodologies for commercial roof systems so that they for hurricane-prone locations.

INTRODUCTION

Hurricane Katrina made landfall on August 29th, 2005 over southeast Louisiana, causing an estimated $81 billion dollars in damage. (NOAA, 2007) Reports of building envelope damage extended across a 14500 square kilometer (5600 square mile) area. (FEMA, 2006) Interior issues such as mold and ceiling collapse resulted from moisture intrusion through the failed envelopes. (FEMA, 2006) (Figure 1). Damage to roof structures contributes by far the majority of economic losses to residential damage due to extreme winds.

Figure 1. Ceiling collapse due to moisture intrusion after roof membrane failure. [FEMA News Photo/ FEMA 549, 2006]

As ground level wind flow encounters a building's face, it is forced to go up and over the structure. Negative (uplift) pressures result from the separation of flow from the roof. (Figure 2) To further complicate the issue, wind directions are not always normal to the building and, most importantly, wind flow is dynamic. (Figure 3) Upwind surface roughness (trees, buildings, etc.) disrupt the wind flow creating turbulence. Wind tunnel studies have confirmed this phenomenon, showing that that these pressures vary both temporarily and spatially with the highest pressures near corners and edges of the roof. (A. a. S. Baskaran, T.L., 2005) A roof system (i.e. membrane, insulation, fasteners, decking, etc.) must resist these dynamic loads while maintaining weathertightness.

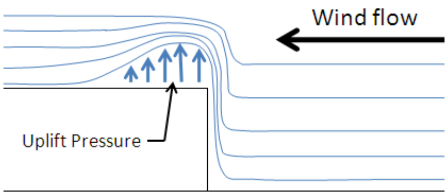


Figure 2. – Wind flow over building

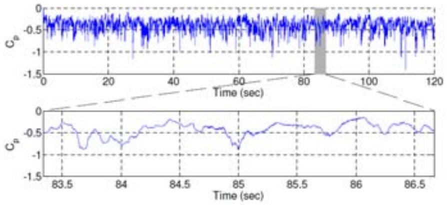


Figure 3. Time-history of wind pressure fluctuations in wind tunnel showing highly dynamic behavior.

To determine uplift capacities of roof assemblies, standardized test protocols have been establish (i.e. ASTM E1592, UL 1897, etc.). These tests typically apply uniform quasi-static uplift pressure on full scale roof specimens until failure. (RICOWI, 2007) However, results of these static approximation tests have come into question by the Federal Emergency Management Agency (FEMA) and the Roofing Industry Committee on Weather Issues (RICOWI). (2007) (2005b) Their issues are twofold:

1) Static tests do not account for dynamic effects, which may have a significant impact on a systems performance.
2) Failure modes observed by these organizations after hurricanes do not match failures generated by standardized tests.

The purpose of this paper is to make a case for the need of improved standardized roof uplift tests. To accomplish this, attention must be given to how the dynamic component of wind may affect systems. This can be categorized into three groups:

1) Systems that utilize materials with low plastic deformation resistance (structural standing steam metal roofing)
2) Lightweight or flexible coverings (mechanically attached single-ply membranes)
3) Systems who's connections are heavily reliant on frictional force (nailed connections such as wood roof sheathing over wood truss members)

The systems mentioned above are in wide-spread use throughout hurricane prone southeast and their performance during hurricanes is well documented. Their failures during storms provide a useful comparison to failure generated by current standardized tests, possibly showing where the tests may not be appropriate. Finally, a look into research devoted towards improved testing methods is presented to give a glimpse to where testing may go into the future.

STRUCTURAL STANDING SEAM METAL ROOFING (SSMR)

A SSMR is a system of 30.5 to 61 cm. (12 to 24 in.) wide metal panels laid side by side and mechanically seamed to adjacent panels to form watertight joints. Concealed within these seams are steel clips which attach the panel to roof purlins below, thus allowing the system to "float" over the structural framing and accommodate thermal cycling. This single layer system serves as a roof covering and structural framing. Non-structural standing seam systems commonly found on residential structures require a structural decking for support, such as wood sheathing.

Post-hurricane damage assessments noted that SSMR systems installed after 1999 performed better than older installations, and investigators suggested this to be the result building code changes that increased roof uplift load requirements. (RICOWI, 2006, 2007) However, SSMR systems continue to fail more frequently than non-structural metal installations (FEMA, 2005b). The performance of SSMR systems relies on the integrity of the seamed joints. The dominant failure mechanism is clip separation from the seam. Once compromised, unzipping of the seam occurs, resulting in blow-off of complete panel sections. (RICOWI, 2007) Seam failure can be attributed to several factors:

1) Poor detailing of the eave edge condition where uplift pressures are highest. This occurs when clips are spaced too far from the roof edge. (RICOWI, 2006) (Figure 4)
2) Weakening of seam due to pressure variation. Under wind load, the panels deflect upwards, rotating about their fixed edges. The low plasticity limit of the thin metal panels allows permanent deformations to take place at the seamed joints. As shown in Figure 5, this has a prying effect on the seam, working it loose from the clip by either opening or horizontally translating the

seam. Upward deflection of the panels causes rotation along their fixed edges. Blow-off occurs when the panel disengages from the seam.

3) Internal pressurization of the building due to failures of windows, doors, garages, etc. Application of this positive force on the underside of the roof has an additive uplift effect on the roof. The single-layer construction of SSSMR makes it vulnerable to pressurization.

Figure 4. Improperly detailed eave caused failure of SSMR roof – note clips remained fastened to structural framing. (RICOWI, 2007)

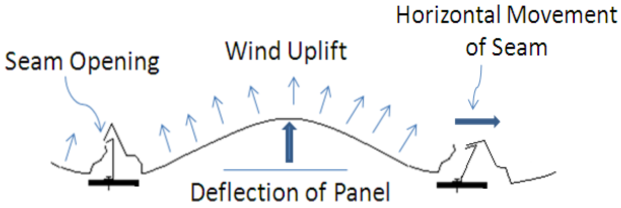


Figure 5. Typical seam failures due to panel deflection.

Other failures observed include flashing failure at the ridge and rake edges due to poor detailing. (RICOWI, 2006, 2007).

The ASTM E1592 was developed in 1988 to establish the wind uplift resistance of SSMR systems. (Shoemaker, 2009) Each test specimen contains a minimum of three fully seamed panels and integrated clips fastened to roof purlins installed in a 3.65 m by 7.32 m (12 ft by 24 ft) pressure chamber. To maintain pressure in the chamber, the test allows the use of plastic sheeting under the roof panels. Pressure is applied using a blower (i.e. regenerative fan) connected to the chamber, through a manual-controlled valve, and the chamber pressure monitored using a pressure transducer. The static test protocol begins by applying a reference pressure of 0.24 kPa (5 psf) for one minute to the specimen. Pressure is then increased to one-third the anticipated failure pressure, held constant for a minute before decreasing pressure to the reference level. For each subsequent pressure step above the reference pressure, the pressure is increased by one-sixth the failure pressure, held for 1 minute and returned to reference pressure. The vertical deflections of the panels along the seam and at center of the panel are recorded at each step and again when panel is under reference pressure. (ASTM, 2005) Deflection measurements provide insight on the panel's behavior throughout the load cycle. Clip separation from the panel seam is the predominant failure mode generated by this test.

Uniform air pressure tests do not account for the spatial variation of pressures that roofs undergo during wind loading. Surry et al. (2007) studied this effect using 34 electromagnets suspended over an E1592 approved setup. That study only examined the cornering wind load condition that produces the highest wind pressure on a roof. ASTM E1592 tests conducted in parallel to this experiment provided a comparison between the static and dynamic test results. After subjecting the specimen to dynamic wind load equivalent of Hurricane Andrew, the results showed that the E1592 method had a conservatism of 50% for the corner condition (Surry, et al., 2007). Still, it is not accepted that the electromagnetic effects produces complete realistic wind loads on the roof, for all possible failure modes observed after hurricane events. However, this conservatism is not completely supported by roof failure observations in less than design-level wind events.

Prevatt et al. (1995) compared the E1592 protocol with a dynamic pressure trace in an effort to improve the standard uplift pressure test. They established how loads transfer to the metal clip through use of influence surface experiments and correlated the data to the static and dynamic tests. They concluded that uniform pressure tests are valid if the distribution of load is also determined. Additionally, specimens tested with end restrains cause permanent deformations at the seams at lower pressures than specimens tested with no end restraints. This may have an effect on ultimate failure pressures.

MECHANICALLY-ATTACHED SINGLE-PLY MEMBRANES

Single-ply membranes consist of thin (.1143-.1778 cm.) reinforced sheet made from one of three materials; thermoplastic olefin (TPO), polyvinyl chloride (PVC), or ethylene propylene diene monomer (EPDM). The membrane is typically installed over rigid insulation supported by structural decking (concrete or steel deck). Mechanically attached screws with barbed plates (or continuous battens) fasten the bottom membrane along each overlap (Figure 6). For TPO and PVC systems, a hot-air welding process physically bonds the top sheet to the bottom creating a monolithic roof surface. EPDM membranes cannot be welded together; rather liquid adhesive and bar-over attachments secure the overlapping membranes.

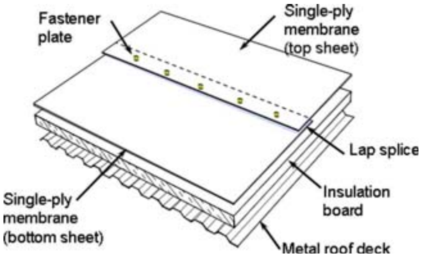


Figure 6. Mechanically attached single-ply roofing membrane system.

Conceptually, the single-ply membrane system is relatively simple but complicated problems exist literally under the surface. Cook (1992) demonstrated that the frequency of pressure fluctuations determines which system component will encounter the load. In static uplift, the flexible membrane rises off of the roof, creating tension along the membranes surface. This tension travels along the membrane into the fasteners that transfer the load into the deck (Figure 7). Since the membrane is more flexible than the structural decking this may produce different load transfer depending on frequency of incident wind fluctuations. Frequency response time represents the length of time a material takes to respond to a dynamic load input. For systems having several components with different stiffnesses, they will see dynamic loads at differing rates. For example, if the wind pressure fluctuation is faster than the membrane's response time, the membrane never experiences the high-frequency load which is not transferred through the structural load path. The load does not simply disappear; rather it is transmitted directly to the stiffer structural deck components. Meaning, the rate of loads transmitted to the deck through the fasteners may differ from the rate of loads transferred directly to the deck. (Cook, 1992) Additional shear stress to the connection membrane interface results from this non-linear behavior. The impact of non-linear behavior will be discussed later.

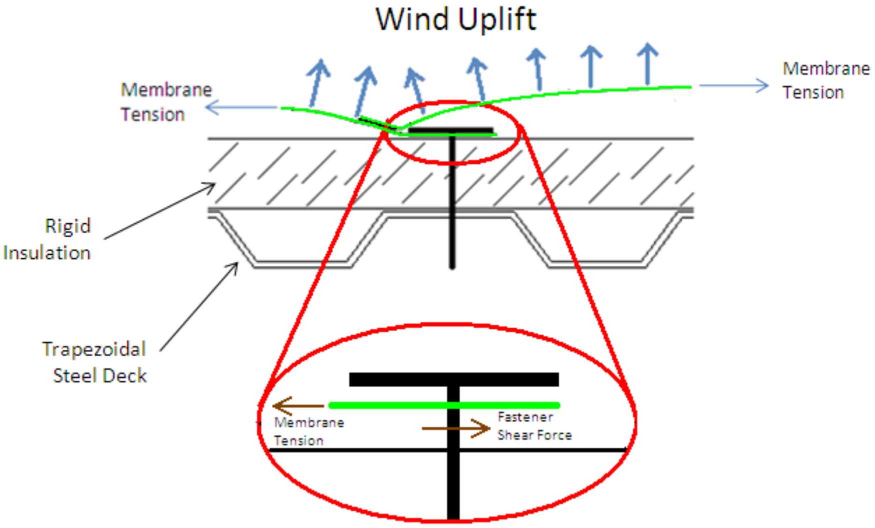


Figure 7. Membrane in-plane tension from uplift. (Note: vapor barrier and fastener plate not shown for clarity).

Like standing seam metal roofs, the United States' consensus single-ply uplift tests approximate dynamic wind pressure through quasi-static methods. The FM 4470 and Underwriters Laboratory 1897 both use similar standard test procedures, described briefly as follows:

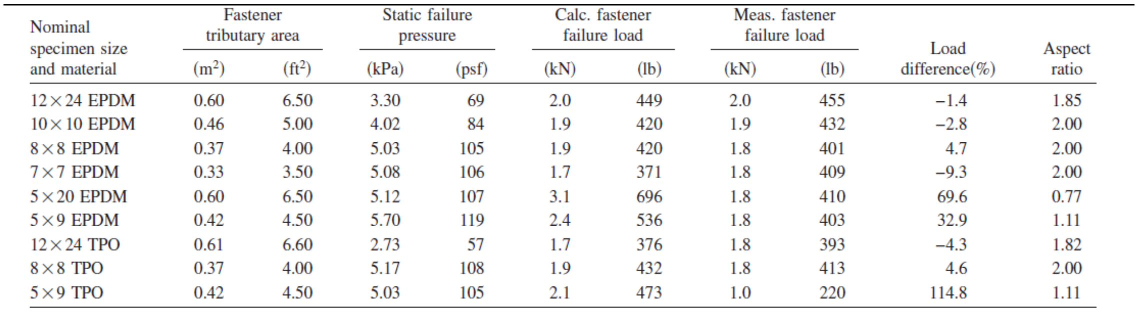
1) Pressurize underside of roofing membrane to 1.45 kPa (30 psf), hold for one minute, monitor roof.

2) Increase pressure by 0.72 kPa (15 psf) and hold for one minute.

3) Continue increasing pressure in 0.72 kPa (15 psf) increments, hold 1 minute until failure occurs.

The important difference between the two protocols is the size of specimen. While the FM 4470 requires a 3.7 m by 7.3 m (12 ft by 24 ft), the UL 1897 only requires a 3.0 m by 3.0 (10 ft by 10 ft) specimen. Originally, the FM 4470 protocol was developed for a 1.5 m by 2.74 m (5 ft by 9 ft) specimen. However, Smith (1989) compared results from that standard size with a larger, 3.7 m by 7.3 m (12 ft by 24 ft) specimen, observing the failure pressure for the larger specimen was 2.16 kPa (45 psf) lower than that of the small specimen. Malpezzi and Gillenwater (1993) confirmed Smith's findings, and shortly thereafter, FM changed their standard specimen size to 3.7 m by 7.3 m (12 ft by 24 ft). Finally, Prevatt et al. (2008) corroborated those findings with a study of seven chamber sizes and two single ply materials, EPDM and PVC, the results are presented below in Table 1.

Table 1. Calculated versus Measured Fastener Loads and Aspect Ratios



Nominal specimen size and material	Fastener tributary area		Static failure pressure		Calc. fastener failure load		Meas. fastener failure load		Load difference(%)	Aspect ratio
	(m^2)	(ft^2)	(kPa)	(psf)	(kN)	(lb)	(kN)	(lb)		
12×24 EPDM	0.60	6.50	3.30	69	2.0	449	2.0	455	−1.4	1.85
10×10 EPDM	0.46	5.00	4.02	84	1.9	420	1.9	432	−2.8	2.00
8×8 EPDM	0.37	4.00	5.03	105	1.9	420	1.8	401	4.7	2.00
7×7 EPDM	0.33	3.50	5.08	106	1.7	371	1.8	409	−9.3	2.00
5×20 EPDM	0.60	6.50	5.12	107	3.1	696	1.8	410	69.6	0.77
5×9 EPDM	0.42	4.50	5.70	119	2.4	536	1.8	403	32.9	1.11
12×24 TPO	0.61	6.60	2.73	57	1.7	376	1.8	393	−4.3	1.82
8×8 TPO	0.37	4.00	5.17	108	1.9	432	1.8	413	4.6	2.00
5×9 TPO	0.42	4.50	5.03	105	2.1	473	1.0	220	114.8	1.11

It was found that a 60% difference in failure pressure from the smallest chamber to largest chamber size and that another important factor is to maintain the aspect ratio of the chamber equal or near to 1.0

Effect of Dynamic Fluctuations on Failure Pressure

If specimen size, fastening schedule, and membrane width makes an appreciable difference on failure pressure, what about dynamic effects? The approach in the European roofing industry has been to simulate dynamic wind for flexible membrane system testing, per the UEAtc-551 standard. This test protocol attempts to simulate the expected numbers and amplitude of wind pressures produced that can occur on a roof during a severe extra-tropical storm event. In one tests using UEAtc protocol, Baskaran et al. (1999) showed after a 55 hour test simulating thousands of wind "gusts", fatigue-like failure occurred in the single-ply membrane. The UEAtc test approach acknowledges the dynamic wind effects but the length of time of each test was considered a drawback. Baskaran's (1999) Special Interest Group for Dynamic Evaluation of Roofing Systems (SIGDERS) research program developed a test methodology based on the UEAtc approach but with reduced testing time.

A rain-flow algorithm was used to count load cycles during a wind tunnel simulation of pressures on a low-sloped building, and this was to develop "gust" frequencies. Testing begins by first approximating dynamic wind pressure by cycling between zero load and a defined percentage of failure, stepping up in pressure until anticipated failure pressure is achieved. If the specimen passes, it is considered to be appropriate for field conditions. The next step, moves into testing the non-linear behavior described above. This is achieved by applying a static suction load while cycling between the static load and a defined percentage of load until the anticipated failure load is achieved. If a specimen passes this section as well, it is defined as appropriate for field and perimeter/corner conditions.

To compare the validity of this approach, Baskaran et al. (1999) conducted comparative testing of mechanically-attached single-ply membranes per the SIGDERS, UEAtc, and FM 4470 protocols. He found that the predominant failure mechanism in the FM static test protocol was fastener pullout from the structural decking, whereas the failures mechanisms in the dynamic SIGDERS and UEAtc test protocols were by shear failure of the membrane at the fastener shaft. Similar membrane shear failures were observed during a post-storm damage assessment survey of a single-ply membrane roof by Kramer (1994). While this may appear to be a minor difference, whichever component fails first determines the ultimate strength of the system. If non-realistic quasi-static testing produces different failure modes from those observed in field and dynamic testing, stress is not being applied correctly in the quasi-static case.

WOOD ROOF SHEATHING ON RESIDENTIAL CONSTRUCTION

Damage to wood sheathing caused by hurricane Andrew prompted investigation of the systems uplift capacity by Cunningham(1993), Mizzell (1994) and others. More recent studies have been done by IHRC (2004) and Prevatt et al. (2009). Uplift tests are performed on roof panels consisting of a single 1.22 m by 2.44 m (4 ft by 8 ft) sheathing fastened to wood framing members. This panel is installed on an open faced rigid pressure chamber and air pressure is supplied to the chamber until failure occurs. Unlike the commercial roofing systems described earlier in this paper, there exist no standard test protocols for wood roof panel systems. In fact, it appears very limited commercial testing has been performed on these systems. However, prescriptive guidelines in the building code for installing residential roofing have been developed from the work of early researchers.

Figure 8. Panel blow-off due to uplift related failures. [FEMA News Photo/ FEMA 549, 2006]

There are some issues to consider with this approach; a) the researchers used different (non-standard) pressure traces, ranging from monotonic increasing of rates from 1.44 kPa (30 psf) per minute (Cunningham, 1993) to more rapid 5.75 kPa (120 psf) per minute (Kallem, 1997) to near instantaneous (i.e. 0 to 3.83 kPa (80 psf) in less than 10 seconds) (Sutt, Reinhold, & Rosowsky, 2000). b) number and sample size not established: Cunningham tested only a single sample for each configuration tested, and other researchers had 5 to 10 samples. Most tests do not provide statistical significance of their results. A further consideration with current prescriptive design guides is few reports carefully specify the nail types, wood species and specific density that certainly will affect the withdrawal strengths. Further, any changes or improvements to manufacturing of wood sheathing will not be reflected in 15 year-old experimental test results.

Nails, staples, or screws are typically used to fasten wood sheathing to wood truss or joist members in light wood-framed residential structures. The sheathing can be plywood or oriented strand board (OSB) in 1.22 m by 2.44 m (4 ft by 8 ft) sheets. Building codes specify the minimum fastener schedule as 15.2 cm./30.5 cm. (6 in./12 in.) or nails fastened at 15.2 cm. (6 in.) o.c. along edge of sheathing and at 30.5 cm. (12 in.) o.c. for interior regions of a panel. Sheathing loads are transmitted to the connection in two ways: 1) vertically, caused by loads normal to the sheathing surface (i.e. wind uplift) and 2) in-plane shear loads, caused by lateral movement.

In uplift, the sheathing pulls vertically on the nail with the outer face of the sheathing bearing on the nail head. The nail resists from pulling out of the framing member by its frictional and mechanical interlock with the wood framing member. The resistance provided by each nail is a function of the nail's shank profile (smooth or deformed), shank diameter, nail head diameter, and embedment length. Furthermore, the force that a nail can transmit to the sheathing is limited by the pull through resistance of the sheathing. Connection failure occurs if either the nail embedment or sheathing bearing fails, which are the dominant failure modes observed in wood roof panels, i.e. nail pull through or nail withdrawal failure (FEMA, 2005a).

(a) (b)

Figure 7. (a) Pull-Through and (b) Withdrawal Failure of Sheathing Panels.

Proposed Static/Dynamic Wind Uplift Protocols for Wood Roofs

Prevatt et al. (2009) revisited the previous tests to attempt to quantify effect of moisture content, and specific gravity on uplift performance. They found large scatter in the results, perhaps due to differing loading sequences and materials used. In research at the University of Florida Hill (2009) conducted tests to develop standardized test procedures for evaluating the wind uplift capacity of wood roof sheathing systems. To accomplish this, Hill adapted the ASTM E330, Method B standard test protocol (2009), and called the University of Florida Wind Roof Sheathing Uplift Test (UF-WRSUT) Method. Hill proposed a static test procedure (Method 1) and a dynamic test procedure (Method 2) which is still under development.

The static procedure, Method 1, consisted of a 10-second long pressure step starting at 0.72 kPa (15 psf) and increasing in 0.72 kPa (15 psf) increments until failure occurs. The dynamic pressure trace for Method 2 was developed using wind tunnel test data for an individual roof pressure tap (full-scale tributary area of .186 m^2 (2 ft^2)). (Datin & Prevatt, 2009) A 10-second equivalent full-scale pressure trace was used to match peak pressure to the static pressure at each step. Figure 9 shows the wood panel installed on the pressure chamber during a test A computer controlled Pressure Loading Actuator (PLA) capable of accurately following a dynamic input pressure trace was used to supply air pressure The wood panel failure pressures for two nailing schedules, is shown in Table 2.

Figure 9. Complete Pressure Test Setup

The dynamic failure pressures reported in Prevatt et al. (2009) were nearly 20% lower that static failure pressures, however only limited conclusions could be drawn due to small sample sizes used (5 tests per group).

Recently additional tests were performed using a new nail and fastener schedule to compare the performance of another set of nails. In this test the dynamic pressure trace was developed using 4 pressure taps, representing the averaged wind pressure on a full 1.21 m by 2.44 m (4 ft by 8 ft) sheet. Included in the test were 16 wood panels harvested from two Florida homes. Thirty laboratory built panels used 6 cm (2-3/8 in.) .287 cm. (0.113 in.) diameter smooth shank nails at a spacing of 15.2 cm. (6 in.) exterior/ 20.3 cm. (8 in.) interior. Results and comparisons between this test and Hill (2009) are shown in Figure 10.

Table 2. Summary Results for Laboratory – Built Panels: Hill 2009 and Current Study

Test	*Fastener Schedule*	*Static*		*Dynamic*		*Ratio of Dynamic to Static*	P-value (α = .95)
		# of Panels	*Mean Failure Pressure (psf)*	*# of Panels*	*Mean Failure Pressure (psf)*		
Hill (2009)	6 in./ 12 in.	5	62	5	52	.84	.199
	6 in./6 in.	5	108	5	90	.83	.425
Current Study	6 in. /8 in.	15	101	15	96.3	.953	.496

There was minimal observed difference (~5%) in failure pressures between the static and dynamic tests from the current study, as compared to almost a 20% decrease in Hill's study. The two data sets are not directly comparable because the different nails were used, and the modified dynamic pressure trace used in the current study had fewer oscillations than the original trace. Figure 10 compares the 10-second trace of dynamic pressures for the two traces. Despite differences in dynamic content, the two traces had nearly identical mean pressures. When these two traces were analyzed using the ASTM E1049-85 "Standard Practices for Cycle Counting in Fatigue Analysis - Peak Counting Method" (1985) over an 80 second period, Hill's dynamic trace contained 69 cycles, while the current study had only 41. Studies are continuing to determine whether this reduction in cycle number is a major determinant for failure pressures of wood sheathing systems.

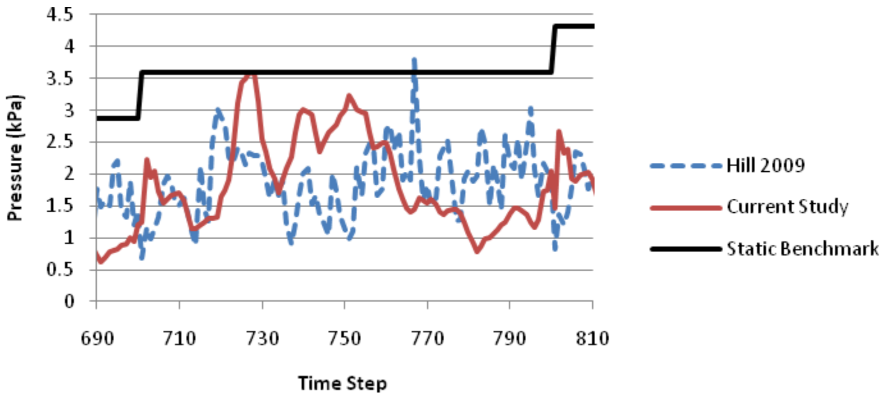


Figure 10. Comparison of Dynamic Traces with Static Step.

Conclusion

This paper presented an overview of testing methods available for two flexible commercial roofing systems, mechanically-attached single ply membranes and structural standing seam metal roof panels. The standard tests, both static uplift pressure methods provide reasonable comparative uplift failure capacities but the results are unrelated to behaviors under actual dynamic wind pressures generated in extreme wind events. Recent Canadian research developed dynamic test protocols for single-ply membranes and are pointing towards the direction for future development. The paper also highlighted the lack of an industry-standard wind uplift test method for wood residential roof structures, or indeed the appreciation that testing is necessary. The current building code prescriptive requirements for fastening of wood sheathing were developed after hurricane Andrew using small data sets of non-standard testing conducted by academic and industry researchers. The paper proposes two test methods, (the UF-WRSUT Methods), one static (Method 1) and one dynamic (Method 2, still under development), that can be used to evaluate the performance of wood roof structures. Ongoing studies at the University of Florida will continue to evaluate the effect of dynamic fluctuations on residential roofs and to improve the prediction of wind uplift performance of aged roof systems subjected to long-term environmental loads and exposure.

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