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Wind Loads on Components of Multi-Layer Wall Systems with Air-Permeable Exterior Cladding

Results Obtained from Full-Scale Wind Tunnel Tests

Comparing the Wind Loads Experienced by Porous Exterior Siding, Wall Sheathing, and Interior Gypsum Wall Board during Full-Scale Wind Tunnel Tests with Dynamic Pressure Chamber Tests

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ABSTRACT

Post-hurricane damage assessments have documented the failure of wall components and connections including the loss of various types of siding materials. In addition, recent U.S. model building/energy code changes are expected to lead to increased use of continuous insulation, particularly foam sheathing attached to the exterior surface of light-frame wall framing, to achieve advanced energy code compliance. A particular need for multi-layer wall systems is the understanding of wind loads on the various layers so that designers and product manufacturers can ensure acceptable building envelope performance of energy efficient wall systems in high-wind events, such as hurricanes.

To address the knowledge gaps and practical concerns related to multi-layer wall systems with air-permeable exterior cladding, the Foam Sheathing Committee (FSC) of the American Chemistry Council (ACC), the Vinyl Siding Institute (VSI), the National Association Home Builders Research Center (NAHB RC), State Farm Mutual Automobile Insurance Company, Insurance Institute for Business & Home Safety (IBHS), and others have initiated research into wind loads on layers of multi-layer wall systems. Results presented in this paper include determination of wind

pressure loading on layers of exterior wall assemblies that include vinyl siding, continuous insulation (rigid foam sheathing) on the exterior side of the wall assembly or Oriented Strand Board (OSB) exterior sheathing, insulation in the wall cavity and gypsum board interior sheathing.

This paper presents results obtained from full-scale wind tunnel tests and compares them with results obtained using dynamic pressure chamber tests. The full-scale wind tunnel tests indicate that porous exterior siding experiences higher wind loads and that the interior gypsum wall board experiences lower loads than previously measured in dynamic pressure chamber tests. Results of the different test methods are compared and implications are discussed.

INTRODUCTION

Wind action on exterior walls of buildings can produce complex loading patterns. When the wall is composed of multiple layers, as is typical for cavity wall construction, there is an opportunity for load sharing between the various layers as the wall reacts to the applied wind loads. When there are leakage paths across the layers or one or more layers are porous, it becomes a challenge to apportion the appropriate loads to the various layers. The commentary to Chapter 30 of ASCE 7-10 provides some guidance related to determining loading on individual layers of multi-layer wall systems due to pressure equalization. Pressure equalization can reduce design loads because as the pressure equalizes on opposite sides of a layer, the net loads developed by the pressure difference across the layer are reduced. At any point in time, the sum of the pressures across all of the layers has to add up to the net load (pressure difference) across the entire wall. However, due to the complexities of the pressure fluctuations between layers, the maximum loads on a particular layer will vary considerably and the design of that layer will need to reflect the expected loads across that layer. The commentary cautions that the sum of the peak design pressures across individual layers will often exceed the peak net pressure across the system, and conservatively suggests that each load carrying layer be designed for the full pressure differential across the building envelope. Standards that provide for the application of pressure equalization include ASTM D3679 - 11 Standard Specification for Rigid Poly (Vinyl Chloride) (PVC) Siding and ASTM E1300 - 09a Standard Practice for Determining Load Resistance of Glass in Buildings.

Prior to the construction of the IBHS Research Center, which has the capability to test full-scale structures in its large wind tunnel, the evaluation of wind loads on wall systems was conducted using pressure chambers, where the same pressure is applied over the entire surface of the test specimen. The most common tests have involved quasi-static loading of the wall assembly. More recently, pressure chamber testing has involved the application of dynamic loads where the pressure in the chamber is varied with time so that it reproduces the time history of wall pressure fluctuations measured using wind tunnel models. The model pressures are scaled in magnitude and time so that appropriate full-scale pressures corresponding to some target windstorm are reproduced. Nevertheless, the pressures at any point in time are still basically uniform across the entire surface of the test wall. The studies conducted at the IBHS Research Center and reported in this paper are the first where wall pressures between various layers are measured in a realistic wind environment that reproduces the temporal and spatial variations of wind pressures on the wall surface and simultaneously applies the wind flow around the building.

Pressure Chamber Tests

An NAHBRC white paper summarizes issues and research related to wind pressure resistance of exterior walls in residential construction (NAHBRC, 2010). Among other things, this white paper references the treatment of pressure equalization considerations for vinyl siding in Annex A1 of ASTM D 3679-09. This annex applies a 0.36 pressure equalization factor (PEF) to determine design pressures for vinyl siding. In this case the PEF is applied as a factor to increase rated resistance in lieu of reducing the wind load. This means that the rated capacity of the siding is obtained using code specified design pressures as well as a load resistance factor of 1/0.36. The PEF factor of 0.36 is based on a 2002 study by Architectural Testing, Inc. (ATI) for the VSI.

The ATI 2002 study evaluated PEFs for six representative types of vinyl siding. Wall assemblies were subjected to a series of sudden, uniform negative pressure “gusts” at a low, medium or high pressure levels. A series of three separate “gusts” were applied to a given wall at each pressure level, for a total of nine loadings per specimen. Results of the ATI study produced PEFs for the vinyl siding that ranged from 0.03 to 0.18. The highest value was doubled to establish a design basis PEF of 0.36 in the ASTM D3679 standard.

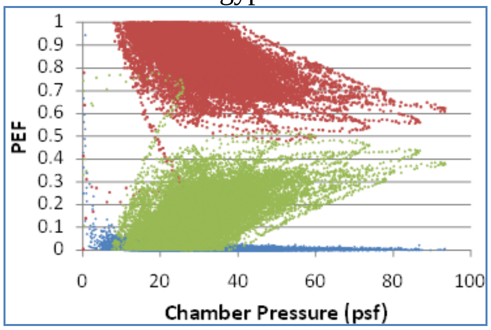
Recent studies conducted at the University of Western Ontario (UWO) and the NAHBRC have used dynamic pressure chambers equipped with a computer controlled system, which can replicate the time histories of wind pressures on walls, to study the pressure distribution through multi-layer walls (Kopp and Gavanski, 2012; NAHBRC, 2012). Both studies showed that the PEFs tended to vary with the magnitude of the applied negative load. In general, the higher the magnitude of the applied load, the lower the PEF could be for the exterior sheathing layer.

Results of the Kopp and Gavanski study showed wall assemblies that included interior sheathings and air sealing details exhibited between two and five times greater ultimate capacities, as compared to the ultimate capacity of the exterior sheathing alone. PEFs for the OSB sheathing ranged from between 0 and 0.3 with minimum air sealing to between 0.4 and 0.6 with house wrap applied. PEFs for foam sheathing ranged from 0 to 0.4, with wall assemblies having greater air sealing (i.e., joints and perimeter of panels taped) also having the correspondingly greater PEF. Interestingly, PEFs for the vinyl siding (when present) were almost consistently near 0, or in other words the vinyl siding was experiencing essentially no load during the testing (e.g., near perfect pressure equalization). The study notes, however, that the loading methodology did not allow for spatial variations in pressure across the surface of the wall, which is believed to be a significant factor in the pressure equalization performance of vinyl siding.

The NAHBRC 2012 study evaluated the performance and capacities of residential exterior wall configurations using rigid foam sheathing as the primary exterior sheathing material. Each assembly was subjected to a series of dynamically applied uniform pressure traces that replicated the exterior wall, negative pressure fluctuations observed during scale-model wind tunnel testing conducted by UWO. The wind tunnel pressure traces were scaled in both magnitude and time to produce full-scale equivalent loading traces of 15 minutes in length. Each assembly was subjected to three pressure traces of incrementally increased mean wind speeds.

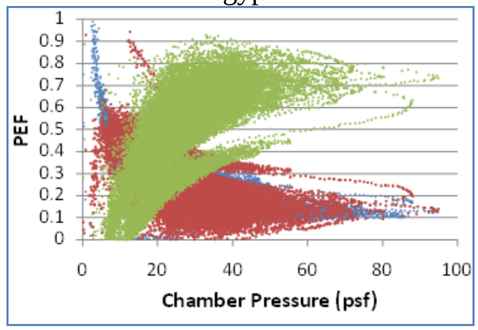
Results indicate a marked increase in the ultimate capacity of the wall assemblies with multiple sheathing layers over the assembly with the isolated foam sheathing; up to five times. Results also confirm pressure equalization through the assembly layers and show that the magnitudes of the PEFs vary with the dynamically applied uniform negative chamber pressure, which is in line with results obtained by Kopp and Gavanski. Figure 1 illustrates the effect that the air-sealing details have on the PEF. Measured PEFs for the vinyl siding layer were generally negligible; particularly when no house wrap was installed. Consequently, the PEFs for the exterior foam layer and the gypsum layer tended to mirror each other, as seen in Figure 1a. When house wrap was installed, the behavior of the system changed; the vinyl siding PEFs increased while the foam sheathing PEFs decreased. At maximum pressures applied, the PEFs for both the vinyl siding and the exterior foam sheathing were generally between 0.1 and 0.2 while the gypsum sheathing PEFs with the house wrap installed were between 0.6 and 0.8.

Blue • – vinyl siding
Red • – taped rigid foam sheathing
Green • – interior gypsum



(a) Sheathing joints taped, (Group 3C)

Blue • – vinyl siding and housewrap
Red • – un-taped rigid foam sheathing
Green • – interior gypsum



(b) Sheathing joints not taped, house wrap installed (Group 3B)

Figure 1: Sample PEFs by Individual Layer from NAHBRC 2012 Testing.

Objective

The primary objective of this research was to investigate the wind performance and pressure equalization characteristics of typical multi-layer wall systems that include vinyl siding and continuous insulation (rigid foam sheathing) on the exterior side of the wall assembly in the IBHS RC full-scale wind tunnel and compare results with previous tests conducted in dynamic pressure chambers.

METHODS AND MATERIALS

The core facility at the IBHS Research Center (IBHS RC) is a specially-designed open-jet wind tunnel with an exceptionally large test chamber: 145 ft. wide by 145 ft. long with a clear interior height of 60 ft. The test chamber is large enough to subject full-scale, one- or two-story residential structures and commercial buildings to a variety of wind-related or wind-influenced natural perils. The IBHS RC is shown in Figure 2. Details of the facility and results of validation testing are presented in a companion paper by Morrison et al 2012. An illustration of a typical one-story structure in the test chamber identifying the location of the reference anemometer in relation to the fans, test structure on the turntable, and the direction of wind flow in the chamber is provided in Figure 3.

Simulated Wind Characteristics

Wind conditions for the testing conducted in this study consisted of a wind profile and turbulence characteristics typical of open country terrain as defined by ASCE 7-10. The achieved wind profile of typical open country in the full-scale wind tunnel facility at the IBHS RC is shown in Figure 4. Target values for the longitudinal and lateral turbulence intensities, as well as the mean wind speed for typical open country winds, are indicated by the ESDU curves in Figure 4. Measured values at the relevant curves.

Figure 2: Aerial Photograph of the IBHS Research Center.

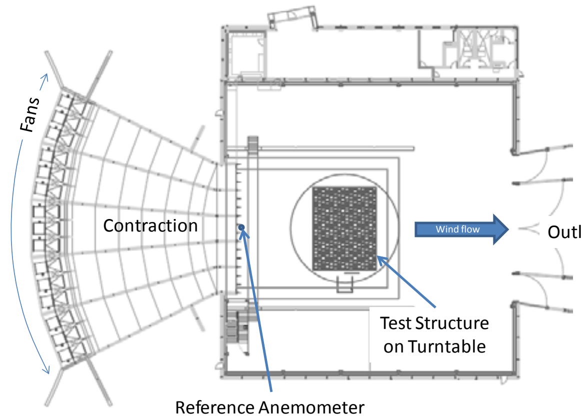


Figure 3: Plan View of Typical Structure in Test Chamber.

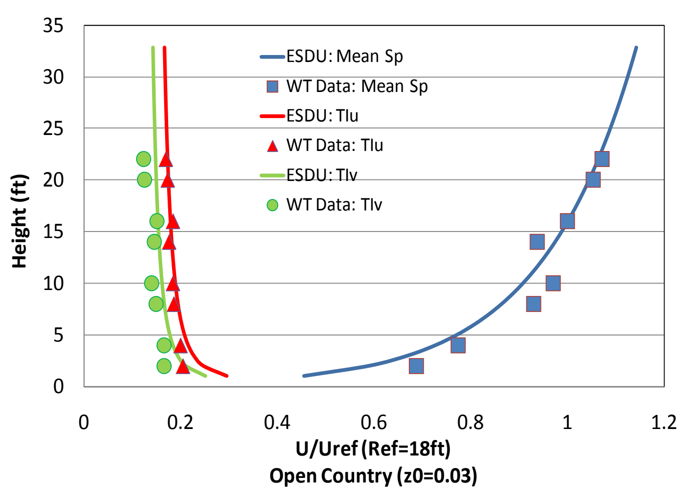


Figure 4: Open Country Mean Wind Speed Profile and Turbulence Intensities

Test Structure and Instrumentation

The test building consists of a single story steel frame to which wall sections and a roof are attached. When fully outfitted for testing the structure is enclosed, yet the use of the steel frame allows for interchangeability of wall systems without changing the roof structure. The roof has a 6 on 12 pitch with one gable end and one hip end. The structure is 30 ft wide by 40 ft long, with an additional 1 ft overhang on the roof and a mean roof height is 17 ft.

The test wall assemblies were constructed in place along the 40 ft. long sides of the test frame shown in Figure 5. The shorter 30 ft sides of the structure were enclosed with wall sections consisting of typical 2x4 wood frame construction (SPF wood species) with studs spaced at 16”oc and OSB or plywood sheathing. To maintain proper corner detailing for the vinyl siding, a 4 ft wrap-around of the vinyl siding was installed at the corners as shown in Figure 6.

Figure 5: Construction of Gable/Hip Test Building with 6-on-12 Pitch Roof

Figure 6: Cornering Detail on Vinyl Siding

Pressure taps were installed during wall assembly construction at 32 locations on each 40 ft. side. A total of three pressure taps were installed at each location to allow determination of pressures on the outside surface and between each of the wall layers as shown in Figure 7. P_1 is mounted with its opening flush with the outside surface of the vinyl. P_2 is mounted to the inside surface of the vinyl siding such that it measured the pressure in the cavity between the vinyl siding and either the 1-inch foam sheathing or the house-wrap/OSB wood structural panel combination. P_3 is mounted such that it measured the pressure in the fiberglass batt filled cavity between the foam or OSB sheathing and the interior gypsum wallboard. In addition, eight pressure sensors were installed inside the building and connected so that they monitored the internal pressure in the building near locations where wall pressure taps were installed. All wall pressure taps as well as seven of the eight internal pressure measurements were referenced to the static pressure inside the test chamber. The eighth internal pressure measurement inside the test specimen was referenced to the atmospheric static pressure outside the test facility.

Pressure tap locations are shown in Figure 8. Labels for the wall locations include a combination of letters F, O, G, and H for the foam assembly wall, the OSB assembly wall, the gable end, and the hip end respectively. The dark vertical lines on the side walls identify wall studs. The lighter colored horizontal lines on the wall sketched illustrate the horizontal runs of the vinyl siding and the lighter colored short vertical lines that cross two lines of the siding indicate where the siding laps were located. Following VSI installation guidance, the laps were located at the mid-point between adjacent studs. The vinyl siding was fastened to each wall stud using nails installed through the middle of the slotted openings provided in the nailing hem on the vinyl siding.

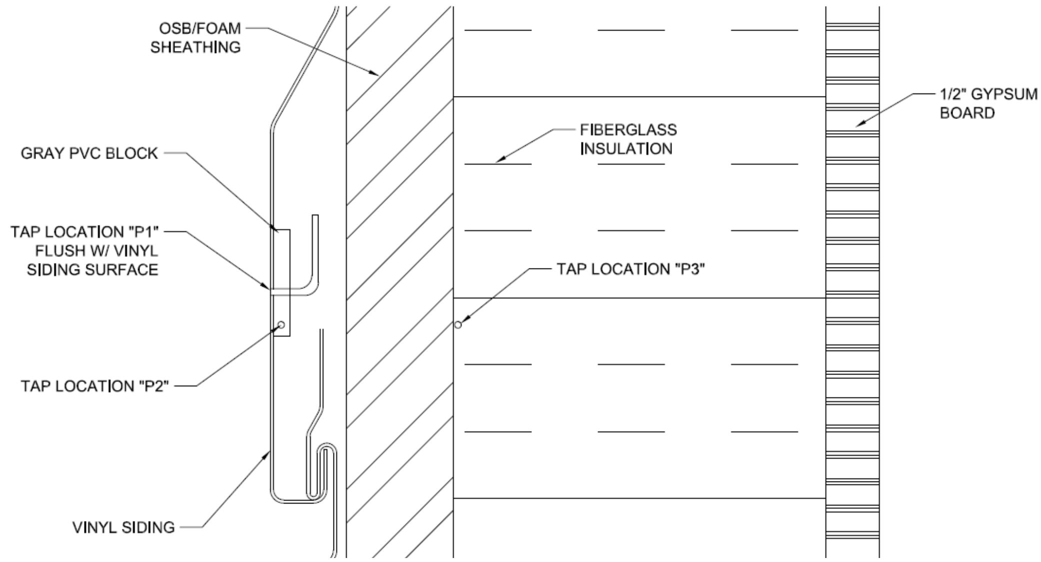


Figure 7: Configuration of Pressure Measurements in Exterior Wall System.

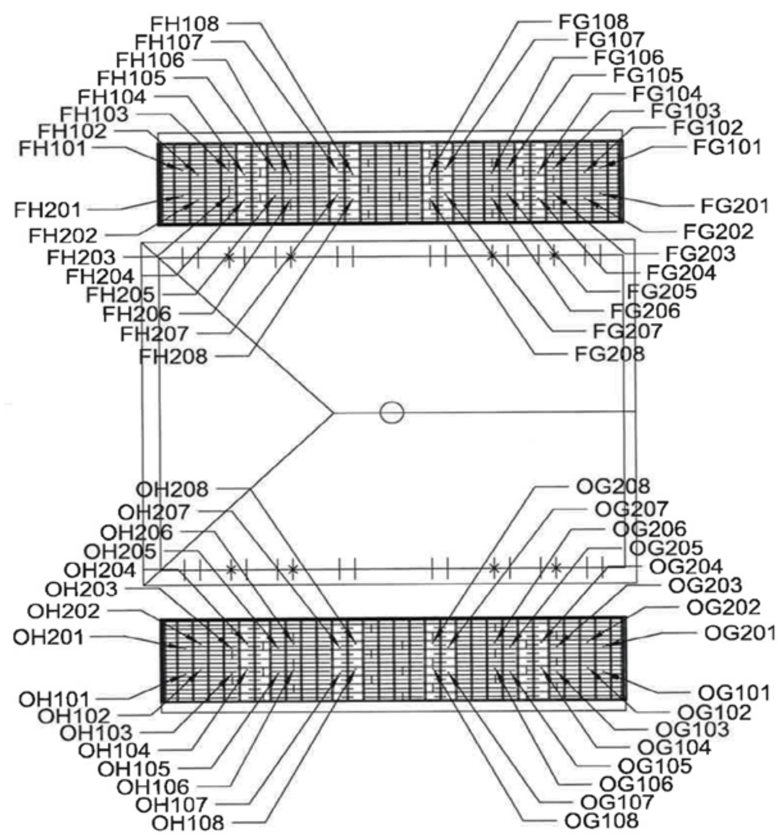


Figure 8: Pressure Tap Locations for Phase 1 Testing.

Wall Assemblies

The two wall assemblies tested include one foam-sheathed wall assembly and one wood-sheathed wall assembly. Materials and construction details are consistent with prior testing of wall assemblies by NAHBRC 2012. Descriptions of the materials and fastening schedules are provided in Table 1 and Table 2. Details of the wall construction, including roof to wall and wall to floor connections are provided in Figures 9 and 10. The XPS version of the wall assembly occurs along the entire length of one of the 40 ft sides and the OSB wall detail occurs along the entire length of the opposite 40 ft side. Gypsum wallboard seams were taped and mudded on both wall assemblies.

Table 1: Materials for Wall Assemblies

Material	**Description**
Wood Framing	2x4 (SPF) at 16”oc
Foam Sheathing	1” XPS (Type X, ASTM C578)
Wood Sheathing	7/16” OSB (DOC/PS 2, wall sheathing)
Vinyl Siding	5” Dutchlap; max test pressure of 28.3 psf
Building Wrap	Typical housewrap
Joint Tape	Typical joint (flashing) tape
Cavity Insulation	Fiberglass batt
Interior Finish	½” gypsum wallboard

Table 2: Fastener Schedule for Wall Assemblies

<table>
<tr><th>Description</th><th>Fastener type and dimensions</th><th>Fastener spacing</th></tr>
<tr><td>1” XPS Foam Sheathing</td><td>2”x0.105” (12ga.wire) Ring Shank Button Cap</td><td>12” O.C. Edges / 12” O.C. Field</td></tr>
<tr><td>7/16” OSB Sheathing</td><td>2-1/2” x0.120” Full Head Pneumatic Gun Nail</td><td>6” O.C. Edges / 6” O.C. Field</td></tr>
<tr><td rowspan="2">Vinyl Siding & Accessories</td><td>Foam wall assembly: 2-1/2”x 0.120 dia. Roofing Nail</td><td rowspan="2">1 nail at every stud through nailing hem at top of every panel (10” O.C. for accessories)</td></tr>
<tr><td>OSB wall assembly: 1-1/2”x 0.120 dia. Roofing Nail</td></tr>
<tr><td>Gypsum Wallboard</td><td>1-1/4” drywall screws</td><td>16” O.C</td></tr>
</table>

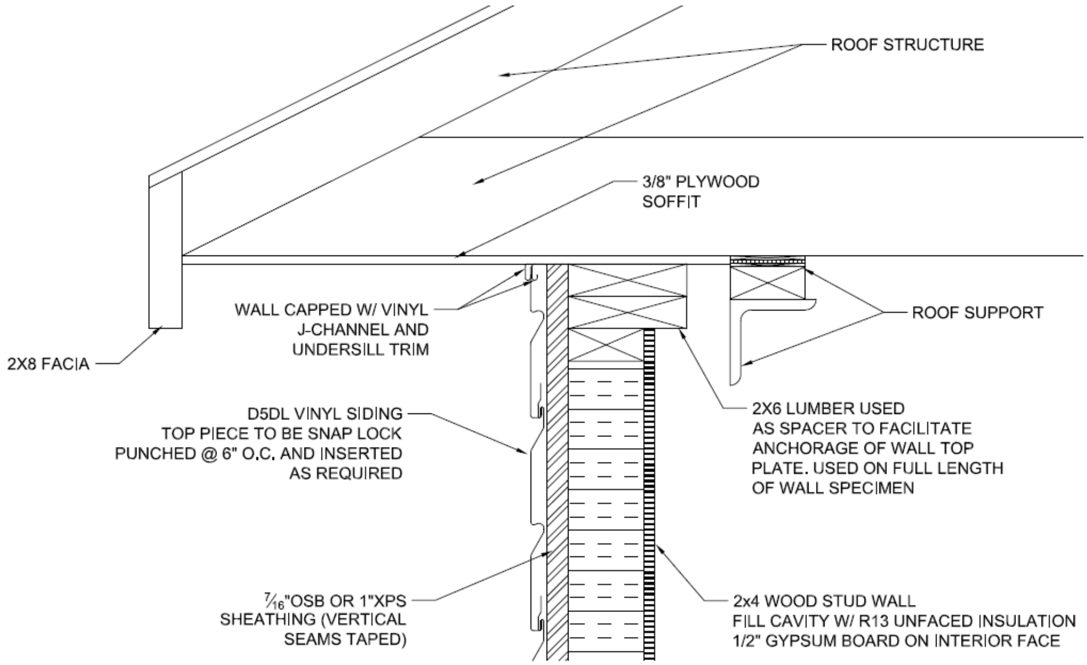


Figure 9: Wall to Roof Construction Detail.

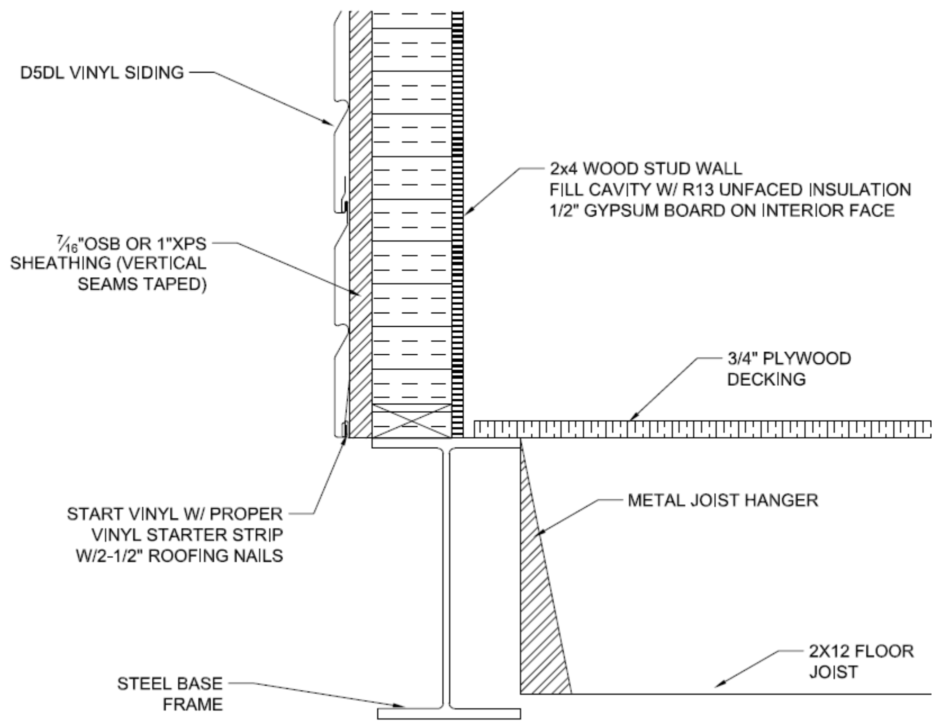


Figure 10: Wall to Floor Construction Detail for Phase 1 Testing.

Tests

The building was rotated and tested at 10 degree increments for a full 360 degrees to ensure that enough data was collected to allow checking of results for different corners and conditions. Consequently, the wall assemblies were subjected to directionally-dependent wind flow characteristics, including positive and negative wind pressure conditions. Wind pressure data were collected using an automated data acquisition system reading the output from the pressure sensors attached to each of the pressure taps. The test plan matrix consisted of three separate sequences described in Table 3. The wind conditions for all three sequences are generic open country wind profile and turbulence characteristics with a 15 minute wind record for each building rotation listed. For a given desired wind speed level, the same input record was used at each building rotation.

Table 3: Test Plan Matrix for Phase 1 Wall Pressure Testing

Sequence	Pressure taps[1]	Building rotation[2]	Gust wind speeds[3] (16 ft above floor)	Description
1	All	360° rotation with tests at every 10° (36 angles)	43-46 mph (wall pressures < 10psf)	15 min time history each wind angle
2	All	0°, 10°, 20°, 160°, 170°, 180°, 190°, 200°, 340°, 350°	58-63 mph (wall pressures < 15psf)	15 min time history each wind angle
			75-79 mph (wall pressures < 25psf)	15 min time history each wind angle
3a	All;	0° and 180°	87-103 mph (wall pressures < 30psf)	Tests that caused some damage to vinyl siding.
3b	FH101, FH102, FH201, FH202	0°	105-107 mph (wall pressures < 35psf)	15 min time history repeated three times. Vinyl siding removed for these tests.

1. Data for the testing performed in this study was sampled at 100 Hz, with the exception of the four taps during test sequence 3b, which were sampled at 1000 Hz. All data was filtered to 10 Hz with a low-pass Chebyshev filter to remove noise.
2. Zero degrees is defined as the hip roof side of the building facing the fan inlet, and 180 degrees is defined at the gable end side of the building facing the fan inlet.
3. The same 15 minute wind record results in slightly different achieved maximum gust wind speeds in the test facility as a result of atmospheric conditions and variable frequency drive performance characteristics, hence a range of values are reported.

The first two sequences include testing of the entire group of pressure tap locations in both of the wall assemblies. Data obtained from the first test sequence lead to the refinement of the angle selection in the second test sequence. The third sequence involved testing at higher wind speeds to investigate the performance of the wall assembly during and after possible damage to the vinyl siding.

Method of Deriving Pressure Equalization Factors

The pressure loadings on each layer of the wall assembly and across the entire wall assembly were computed for each test and pressure measurement location by creating new time histories of the instantaneous values of the pressure differences across each layer. These time histories were computed from the pressure records for the individual taps shown in Figure 7 at each location on the test walls and for each individual test as described below.

The pressure differential across the vinyl siding, Δ_4, is the difference between pressures P_1 and P_2, as shown in Equation 1.

$$\Delta_4(t) = P_1(t) - P_2(t) \quad (1)$$

The pressure difference across the foam sheathing or the house-wrap/OSB depending on the wall configuration, Δ_5, is the difference between pressures P_2 and P_3 as shown in Equation 2.

$$\Delta_5(t) = P_2(t) - P_3(t) \quad (2)$$

The pressure differential on drywall, Δ_6, is the difference between pressures P_3 and the internal pressure within the test building, P_I, as shown in Equation 3.

$$\Delta_6(t) = P_3(t) - P_I(t) \quad (3)$$

The total pressure on wall assembly at the particular tap location in question, Δ_T, is the difference between pressures P_1 and P_I as shown in Equation 4.

$$\Delta_T(t) = P_1(t) - P_I(t) \quad (4)$$

The PEFs for the various wall layers were calculated following Equation 5.

$$PEF_i(t) = \frac{\text{pressure gradient across layer}}{\text{total pressure gradient across wall}} = \frac{\Delta_i(t)}{\Delta_T(t)} \quad (5)$$

where $PEF_i(t)$ is the time varying fraction of the total pressure across the wall assembly applied to an individual wall layer and i = 4, 5, and 6.

RESULTS

There are two ways to assess the wind loads and pressure equalization factors that are applied to the various elements of a multi-layer wall system. One is to calculate instantaneous PEFs for each point in time by creating time histories of the pressures being applied to each layer and then dividing each value in the time history by the corresponding value of the load being applied across the entire wall system. This is the approach used in the NAHBRC 2012 study discussed in the introduction. Plotting the instantaneous PEF values against the magnitude of pressures applied across the wall system results in a scatter plot of the ratios with a very large dispersion at lower pressure levels. Results obtained using this approach to analyze pressure chamber data are shown in Figure 1. As the pressure magnitude increases, the scatter is reduced. A second approach is to use the time histories of the wind pressure loads to determine the maximum load applied to a particular layer regardless of wind direction or time and then divide that load by the maximum wind load regardless of wind direction or time across the entire wall at the same tap location. This approach provides an estimate of the maximum load on a particular layer as a fraction of the maximum load on the wall system and is similar to the envelope approach used in ASCE 7 to specify design loads for components and cladding. Both methods are illustrated in the sections that follow.

Instantaneous Pressure Equalization Factors

A sample of the PEF values observed at a single wall measurement location using the first method described above is provided in Figure 11. PEFs were also obtained for larger tributary areas by averaging the pressure values from groups of two and four taps at each time step, as demonstrated by the samples provided in Figures 12 and 13. A review of the data indicates that the PEF values obtained by full-scale wind flow tests exhibit similar trends of wide dispersion at lower magnitudes of pressures and decreasing PEF with increasing pressure magnitude as seen in prior testing using pressure chambers. However, the values of PEFs for the full-scale wind flow tests cases are different from those obtained in the dynamic uniform pressure chambers.

The data provided in Figures 11 through 13 illustrates that both negative PEF values and PEF values greater than 1.0 can occur when a layer within the wall experiences a pressure loading of opposite sign from the pressure across the entire wall assembly. Note that the sum of the pressures across all of the layers must add up to the net load across the entire wall assembly. For example, if an instantaneous negative pressure occurs in the cavity between the gypsum drywall and the exterior wall sheathing, while the exterior pressure on the vinyl siding is positive, the gypsum dry wall will have a negative PEF. Similar values below zero and greater than 1.0

appear to have occurred in the earlier UWO and NAHBRC studies, though the graphs have been truncated at zero and 1.0 (see Figure 1).

Figures 11 to 13 include data from all wind angles and velocities in sequences 1 and 2, but only at one location on the test structure with a tributary area varying between 1 ft^2 (Figure 11) and 7.1 ft^2 (Figure 13). A comprehensive illustration of the instantaneous PEF values for vinyl siding during the wind testing for all test sequences except 3b at all angles and at all individual tap locations on the structure is presented in Figure 14 for negative external pressures. A similar graph is presented for foam sheathing PEF values for negative external pressures in Figure 15. These two figures include dashed-line curves representing the upper bound of the observed instantaneous PEF values for individual locations on the wall assemblies. The results indicate that vinyl siding will experience up to 80 percent of the negative pressure load on the wall assembly and that foam sheathing will experience up to 60 percent of the negative pressure on the wall assembly.

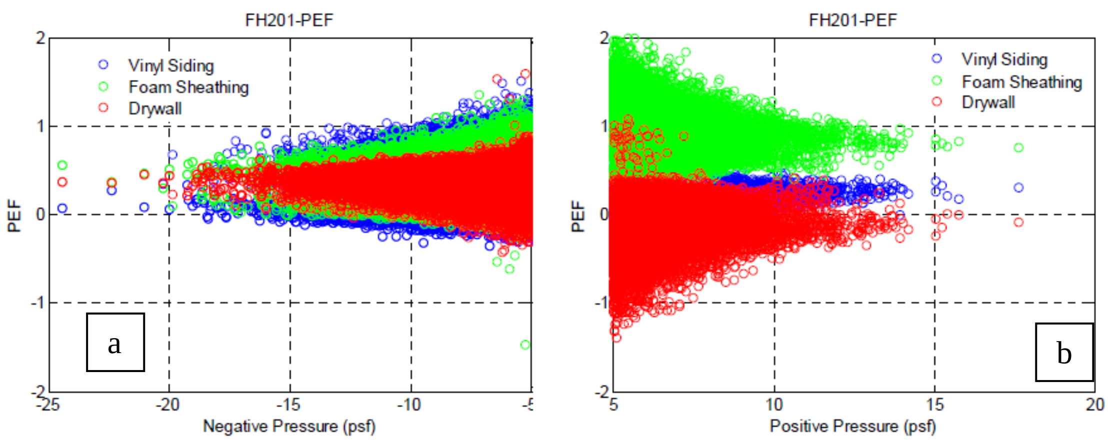


Figure 11: PEF Results for Location FH201 for (a) Negative and (b) Positive Pressures.

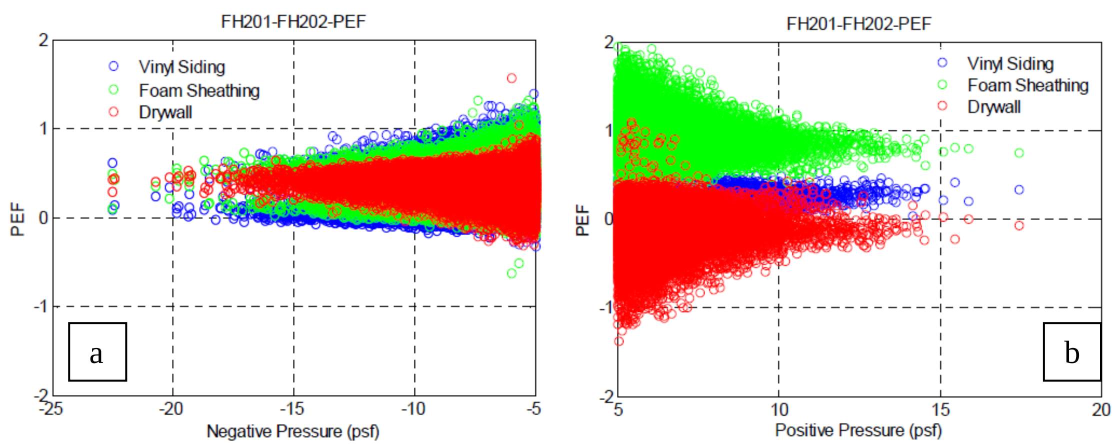


Figure 12: PEF Results for Two Adjacent Taps FH201 and FH202 (16-inch Horizontal Separation Between taps) for (a) Negative Pressures and (b) Positive Pressures.

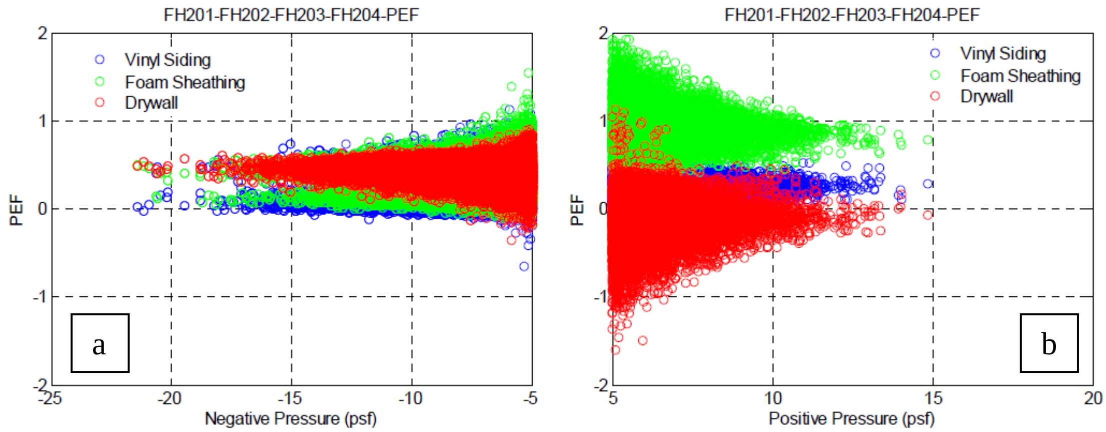


Figure 13: PEF Results for Four Adjacent Taps in a Horizontal Line FH201 - FH204 (64-inch Separation) for (a) Negative and (b) Positive Pressures.

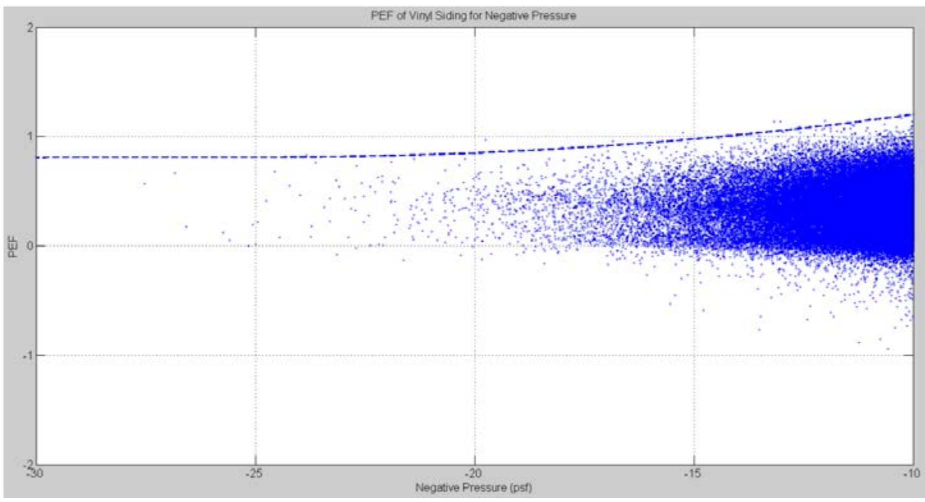


Figure 14: Vinyl Siding PEF Results for All Taps and Wind Directions during Negative External Pressures from Test Sequences 1, 2, and 3a.

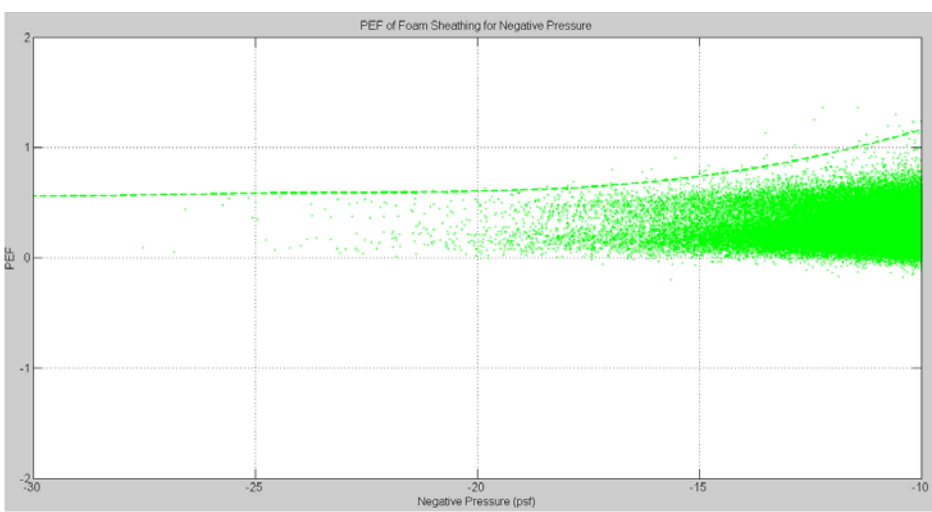


Figure 15: Foam Sheathing PEF Results for All Taps and Wind Directions during Negative External Pressures from Test Sequences 1, 2, and 3a.

Envelope Approach to Analysis of Wind Effects on Wall layers

The second analysis approach, referred to here as the envelope approach, includes using the time histories of the wind pressure loads to determine the maximum load applied to a particular layer regardless of wind direction or time and then dividing that load by the maximum wind pressure load regardless of wind direction or time across the entire wall at the same tap location. Using this method to develop an understanding of the relative magnitudes of the dynamic pressures across the vinyl and sheathing layers, the minimum (largest magnitude negative) and maximum pressure (largest magnitude positive) pressure across the vinyl siding (Δ_4) and the foam sheathing or house wrap/OSB sheathing (Δ_5) are divided by the minimum or maximum pressure across the entire wall (Δ_T) at the same tap location. These minimum and maximum values of Δ_4, Δ_5 and Δ_T are the largest magnitude values obtained from any of the records regardless of wind direction or wind speed used in the testing. Consequently, the largest values may or may not occur at the same wind direction or even the same record at the same wind direction. This approach is similar to the envelope approach used to establishing pressure coefficients for components and cladding loads in ASCE 7.

Pressure measurement locations 101, 102, 201 and 202 roughly fall within ASCE 7 wall zone 5 and the remainder fall within wall zone 4. The ratios between the enveloped maximum and minimum values of Δ_4 to Δ_T, Δ_5 to Δ_T, and Δ_6 to Δ_T for individual tap locations are summarized in Table 4. Similar ratios for the averaged pressures from two adjacent horizontal locations (16-inch horizontal separation) are summarized in Table 5. Ratios for the averaged pressures for larger areas: 1) four adjacent wall pressure tap locations – 64-inch total horizontal separation; and, 2) four wall pressure tap locations consisting of two adjacent in the horizontal direction from the upper row of wall pressure locations combined with the two directly below in the lower row; are shown in Tables 6 and 7, respectively. The ratios presented in Tables 4 through 7 represent data from test sequences 1 and 2 as shown in Table 3.

A comparison of the upper bound of the instantaneous PEF values for vinyl siding and foam sheathing presented in Figures 14 and 15 and the percentages shown in Tables 4 through 7 indicates that the two methods achieve similar end results for determining the maximum loading effects on each layer of the wall assembly. Given the trend of decreasing PEF with increasing pressure, it is possible that the percentages provided in Tables 4 through 7 could decrease further with higher wind pressures, though the shape of the curve fit for the upper bound of the instantaneous PEF values shown in Figures 14 and 15 indicates that the change is likely to be small.

Table 4: Peak Pressures Across Wall Layers as a Percentage of Peak Pressure Across the Entire Wall (Tributary Area = 1 ft^2, Maximum Δ_T Pressures < 30 psf)

	ASCE 7 Wall Zone	Wall Type	Negative – Outward Acting Pressure Ratios			Positive – Inward Acting Pressure Ratios		
			Smallest	Average	Largest	Smallest	Average	Largest
Vinyl Siding Δ_4/Δ_T	5	Foam	72%	88%	91%	41%	51%	74%
		OSB	68%	74%	81%	35%	45%	53%
	4	Foam	52%	72%	87%	45%	59%	80%
		OSB	51%	70%	82%	49%	63%	79%
Sheathing Δ_5/Δ_T	5	Foam	43%	50%	61%	55%	67%	86%
		OSB	38%	51%	61%	41%	61%	81%
	4	Foam	36%	56%	81%	18%	49%	78%
		OSB	44%	65%	94%	40%	59%	75%
Drywall Δ_6/Δ_T	5	Foam	40%	47%	61%	35%	41%	50%
		OSB	43%	54%	68%	36%	52%	65%
	4	Foam	34%	53%	69%	36%	53%	78%
		OSB	43%	55%	68%	36%	59%	88%

Table 5: Peak Pressures Across Wall Layers as a Percentage of Peak Pressure Across Entire Wall for Two Adjacent Locations (16-inch Horizontal Separation, Tributary Area = 1.3 ft^2, Maximum Δ_T Pressures < 30 psf)

	ASCE 7 Wall Zone	Wall Type	Negative – Outward Acting Pressure Ratios			Positive – Inward Acting Pressure Ratios		
			Smallest	Average	Largest	Smallest	Average	Largest
Vinyl Siding Δ_4/Δ_T	5	Foam	75%	78%	82%	47%	53%	60%
		OSB	65%	67%	68%	38%	39%	41%
	4	Foam	56%	71%	84%	37%	54%	68%
		OSB	56%	66%	79%	37%	56%	73%
Sheathing Δ_5/Δ_T	5	Foam	55%	56%	56%	57%	65%	74%
		OSB	45%	50%	54%	44%	58%	73%
	4	Foam	42%	57%	78%	19%	52%	81%
		OSB	51%	62%	82%	43%	60%	74%
Drywall Δ_6/Δ_T	5	Foam	46%	51%	57%	44%	48%	51%
		OSB	52%	54%	56%	63%	76%	89%
	4	Foam	41%	54%	65%	19%	56%	85%
		OSB	49%	57%	68%	52%	69%	89%

Table 6: Peak Pressures Across Wall Layers as a Percentage of Peak Pressure Across Entire Wall for Four Adjacent Locations (64-inch Total Horizontal Separation, Tributary Area = 7.1 ft^2, Maximum Δ_T Pressures < 30 psf)

	ASCE 7 Wall Zone	Wall Type	Negative – Outward Acting Pressure Ratios			Positive – Inward Acting Pressure Ratios		
			Smallest	Average	Largest	Smallest	Average	Largest
Vinyl Siding Δ_4/Δ_T	4	Foam	50%	63%	73%	40%	47%	59%
		OSB	41%	54%	67%	37%	47%	55%
Sheathing Δ_5/Δ_T	4	Foam	47%	62%	75%	29%	56%	73%
		OSB	50%	61%	71%	46%	62%	75%
Drywall Δ_6/Δ_T	4	Foam	53%	57%	64%	43%	51%	68%
		OSB	54%	63%	71%	45%	56%	61%

Table 7: Peak Pressures Across Wall Layers as a Percentage of Peak Pressure Across Entire Wall for Four Adjacent Locations (16-inch Horizontal x 36-inch Vertical, Tributary Area = 4 ft^2, Maximum Δ_T Pressures < 30 psf)

	ASCE 7 Wall Zone	Wall Type	Negative – Outward Acting Pressure Ratios			Positive – Inward Acting Pressure Ratios		
			Smallest	Average	Largest	Smallest	Average	Largest
Vinyl Siding Δ_4/Δ_T	5	Foam	NA*	79%	NA*	NA*	37%	NA*
		OSB	NA*	67%	NA*	NA*	36%	NA*
	4	Foam	55%	69%	78%	40%	50%	60%
		OSB	53%	62%	70%	41%	53%	63%
Sheathing Δ_5/Δ_T	5	Foam	NA*	48%	NA*	NA	55%	NA*
		OSB	NA*	45%	NA*	NA	49%	NA*
	4	Foam	45%	55%	69%	18%	53%	78%
		OSB	43%	58%	74%	44%	61%	71%
Drywall Δ_6/Δ_T	5	Foam	NA*	50%	NA*	NA*	40%	NA*
		OSB	NA*	58%	NA*	NA*	60%	NA*
	4	Foam	51%	59%	67%	44%	52%	73%
		OSB	50%	59%	68%	44%	65%	92%

**There is only one group of four adjacent taps in the area of the wall in ASCE 7 wall zone 5, so there is no range of PEF values for multiple groupings of pressure taps as in ASCE 7 wall zone 4*

A detailed review of the data shows that the peak negative loads across the vinyl siding did tend to occur at the same wind directions where the largest values of Δ_T occur. However, the peak positive pressures across the vinyl siding may not occur for directions with the largest positive values of Δ_T. There is also a small range of wind directions where the pressure across the vinyl exhibits relatively large positive and negative pressure coefficients. For these wind directions, the vinyl siding will be buffeted by these positive and negative pressure fluctuations. The impact of this buffeting action is not well understood and could be investigated further.

Data from Tables 4 - 7 for vinyl siding and sheathing is presented in Figure 16 to compare the percentage of peak pressure for the wall layers over varying tributary areas. This figure illustrates that the percentage of the peak pressures exerted on these wall layers remains consistently high over a large area of the wall relative to the expected tributary area of an individual fastener.

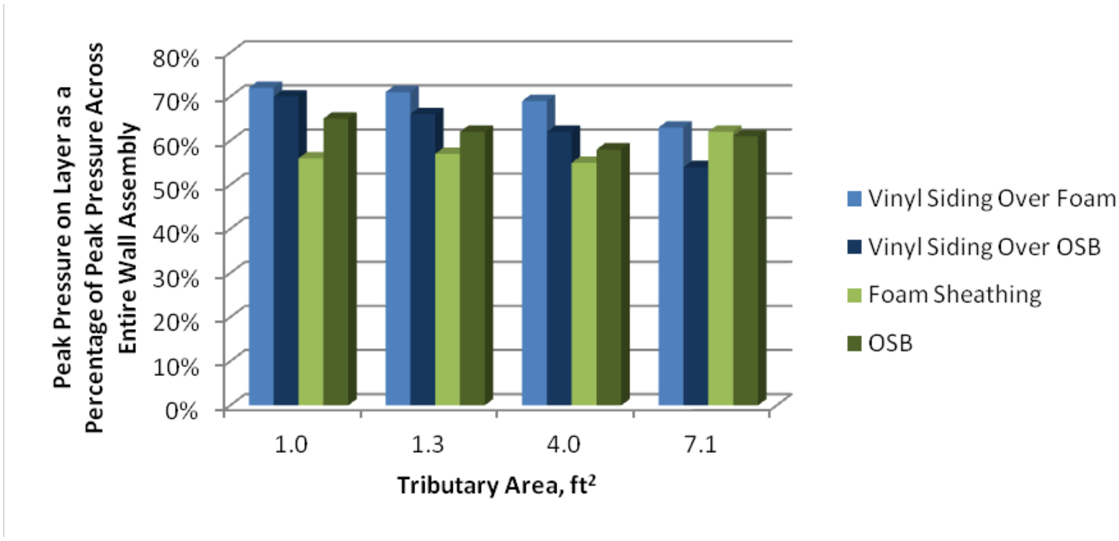


Figure 16: Comparison of Peak Pressures Across Wall Layers as a Percentage of Peak Pressure Across Entire Wall for Varying Tributary Area in ASCE 7 Wall Zone 4, Average Results from Negative Pressure Conditions in Previous Tables.

Comparison of Instantaneous PEFs to Envelope Approach

Regardless of which method (instantaneous PEF or envelope procedure) is used to estimate the portion of the net loads experienced by the various wall layers, the ratios of the loads on a particular layer as a fraction of the net load across the wall are similar. Both methods of analyzing the data indicate that the vinyl siding is resisting as much as 75 to 80 percent of the exterior negative design pressures. As long as the siding remains in place, the sheathing experiences on the order of 55 to 60 percent of the peak negative and positive pressure acting on the wall system. The peak pressures across the gypsum wall board were generally on the order of 50 to 60 percent of the pressure across the wall system.

SUMMARY AND CONCLUSIONS

The full-scale wind flow tests did produce results that are significantly different from those obtained using dynamic wind loads applied using pressure chambers where the wind pressures act uniformly across the entire specimen. The dynamic pressure chamber systems apply larger loads to the interior wall sheathing and little or no loading to the porous siding unless a house wrap is used. With some modifications, however, it may be possible to appropriately calibrate and use the much less expensive dynamic pressure chamber tests to evaluate the capacities and performance of the various wall layers.

The results from the full-scale wind flow tests indicate that the vinyl siding experiences on the order of 75 percent to 80 percent of the negative wind pressures acting on the wall. The peak negative and positive loads on the exterior wall sheathing, as long as the siding remains in place, can be as much as 60 percent of the negative and positive wind pressures acting on the wall. Further research is planned to evaluate the relationship between the measured loads and failure scenarios, and to develop practical design criteria codes and standards modifications.

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