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High-R Walls for New Construction Structural Performance: Wind Pressure Testing

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NAHB Research Center

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High-R Walls for New Construction Structural Performance: Wind Pressure Testing

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Definitions

2 × 4	Nominal 2-in.-wide by 4-in.-deep framing lumber dimension
2 × 6	Nominal 2-in.-wide by 6-in.-deep framing lumber dimension
Advanced framing	An optimized framing system to reduce extraneous framing members while maintaining structural integrity with the goals of increased thermal performance and lower cost
Btu	British thermal unit
FSC	Foam Sheathing Coalition
High-R wall	Reference to wall systems generally having an R-value of 1.5 to 2.5 times that of current energy code requirements for a given climate zone
hp	Horsepower
Hz	Hertz
ICC	International Code Council
in.	Inch
IRC	*International Residential Code*
IBS	*International Building Code*
LVDT	Linear variable differential transducer
NAHB	National Association of Home Builders
PEF	Pressure equalization factor
PER	Pressure equalization rain screen
PLA	Pressure loading actuator
psf	Pounds per square foot
psi	Pounds per square inch
UWO	University of Western Ontario
XPS	Extruded polystyrene (foam insulation board)
WUFI	A menu-driven software program that allows realistic calculation of the transient coupled one-dimensional head and moisture transport in multilayer building components exposed to natural weather.
WRB	Water-resistive barrier

Executive Summary

Within the U.S. Department of Energy Building America Program, a prominent approach to constructing higher R-value walls includes the use of exterior rigid-foam insulation. Although this approach has met some success, recent building code changes have raised some performance issues for exterior rigid-foam sheathing (e.g., its ability to resist wind pressures) that indicate a need for continued wall system performance testing. To optimize performance and lower costs when employing exterior rigid sheathing, builders and researchers have investigated alternative bracing techniques to eliminate the use of wood structural sheathing. Structural characteristics, especially in the direction perpendicular to the sheathing, have been reevaluated for the building codes including pressure equalization issues across multiple layers of the wall system. As a result, exterior sheathings may now need to undergo more extensive design analysis to substantiate the capability to adequately resist wind pressures.

These issues, combined with the importance of limiting cost increases when switching to higher R-value wall systems, have prompted the need for structural testing and optimized wall framing designs. This technical report describes laboratory testing conducted at the NAHB Research Center. The testing evaluated wind pressure performance characteristics for wall systems constructed with exterior insulating sheathing. These test results will help to facilitate the ongoing use of nonstructural sheathing options and lead to a more in-depth understanding of wall system layer performance in response to high wind perturbations normal to the surface.

Out-of-plane wind pressure testing of various wall configurations with insulating sheathing showed that the interactive response of material layers in a whole-wall performance analysis, including wall board interior finishes, nonstructural insulating sheathings, and vinyl siding, exceeds the wall performance with insulating sheathing alone in resisting wind pressures. The research team found that wall material configurations such as the degree and location of air sealing play a significant role in equalizing wind pressure.

Tests of full-wall assemblies with the foam sheathing fully taped along all vertical and horizontal joints indicated that the failure of the foam fasteners may become the controlling failure mode. Note that this configuration also reached the highest overall capacity. In full-wall assemblies with untaped foam sheathing or foam sheathing taped at vertical joints only, the load on the foam does not reach levels sufficient to fail at the foam fasteners. Instead, the failure is controlled by the wood framing and its connections.

These test results serve as a baseline of data for further material tests of other high-R wall systems and for comparison to whole-house wind pressure testing. This research also lays the groundwork for further testing of exterior finish connections to optimized framing systems.

1 Introduction

The NAHB Research Center Building America Industry Team's research on high-R wall systems focuses primarily on increasing the thermal performance of the wall while maintaining current constructability and affordability features. Designs of high-R wall systems for residential construction have centered on reducing the framing factor of the wall system to allow more area for insulation materials. The ultimate goal of this research is to promote options that will substantially increase wall insulation by cost effectively upgrading from 2 × 4 to 2 × 6 advanced framing and by addressing structural performance and wind loading on high performance walls constructed with insulating nonstructural sheathing.

One method of increasing the insulative value of the wall system is to add exterior rigid-foam sheathing to the wall design. This design, currently used in many new high performing homes, is emerging as one of the preferred ways to increase the R-value of walls. The use of exterior foam is expected to grow substantially and even become standard practice in parts of the country because of above code energy and green programs as well as more stringent energy codes. Increased use of exterior rigid-foam sheathing, especially with nonstructural sheathings on the exterior of framing members, has raised a number of design and performance questions, particularly in terms of structural performance and attachment.

This technical report outlines the research and testing of high-R wall systems for out-of-plane wind loading to address the questions of structural performance and attachment issues. It includes the results of the research outlined in the NAHB Research Center's Test Plan (NAHB Research Center 2011) for this project.

1.1 Background

A trend toward high performing homes, along with increasingly stringent energy codes, has led to opportunities for research into increasing wall insulation. Specifically for those approaches that include exterior, nonstructural insulating sheathing, a 2009 NAHB Research Center white paper reviewed the state-of-the-art performance information about wind pressure resistance of rigid foam and cladding systems (NAHB Research Center 2009a). In that paper, the authors identified a major code barrier to the use of exterior rigid foam in high-R wall assemblies. The study found that research was needed on the wind pressure performance of wall systems with rigid-foam sheathing. In particular, the authors identified the need for research on the pressure equalization between the layers of the wall systems. The research applies to new construction in which foam sheathing is attached directly to studs. It also applies to retrofits where foam sheathing is attached either directly to studs or over an existing sheathing material with limited out-of-plane capacity.

Most available test information about rigid-foam sheathed wall systems is limited to a single, ½-in. foam product. Test programs have focused on capturing the response of the vinyl siding instead of the foam sheathing. These limited test results do not provide sufficient information to adequately understand the observed response of walls with rigid-foam sheathing.

Furthermore, no standardized consensus-based test methods or engineering design procedures exist for determining the capacity of this type of wall system to resist out-of-plane wind pressure loads.[1] As an example of the significance of the identified information gaps, the FSC submitted a proposal to the 2012 International Code Council (ICC) code development process with provisions expanding the use of walls with exterior foam under the *International Residential Code* (IRC) and *International Building Code* (IBC). The proposal was disapproved, in part, because of objections that the out-of-plane structural behavior during wind events is unknown.

1.2 Relevance to Building America's Goals

Conducting testing and research to develop test methodologies for ensuring adequate performance of insulating products exterior to structural framing will make these products a viable option for builders in many climate zones. This research will also yield better empirical and design data on which to base methodologies for attaching exterior finishes over nonstructural sheathing. In addition, the research will allow prescriptive approaches, which currently have limited availability in the building codes, to be formalized. Developing new products and establishing test protocols for these products will broaden options for increasing wall system efficiencies while limiting cost increases that result from extensive engineering requirements.

1.3 Cost Effectiveness

Using exterior nonstructural insulating sheathing presents an opportunity to significantly increase the R-value of wall systems. Toward this end, this testing will help solidify the use of these products with design data that support alternative approaches to the use of additional structural members. The out-of-plane testing described in this report provides the fundamental data set with which wall designs incorporating exterior nonstructural insulating sheathing can be compared to ensure that they meet minimum wind pressure resistance requirements.

1.4 Tradeoffs and Other Benefits

The study team expects that the results of this research will be used in the design of high-R wall systems, especially those incorporating exterior nonstructural sheathings. Additional benefits emerge as the testing is evaluated for the performance and failure modes of various wall system layers. In particular, the performance of exterior finishes attached through the nonstructural sheathing to the framing members can be evaluated.

1.5 High-R Walls

Current Building America Program efforts have resulted in heating and cooling savings in new homes of 50% and higher. These saving accrue from incorporating advanced high-efficiency equipment and incrementally improving building envelopes by raising insulation levels and using air sealing. Higher heating and cooling reductions, however, are substantially more challenging because of cost and technological constraints. Building envelope improvements that a production builder can implement, such as high-R wall systems, are necessary steps toward further reductions in home energy use. This comprehensive effort will develop construction methodology and design details for the next level of highly insulated wall systems that address the following in a systems manner:

- Wall structural issues including wall bracing, structural framing design and optimization, wind pressure resistance of walls with exterior insulation, attachment methods for

[1] Since this research program started, the Foam Sheathing Coalition (FSC) has initiated an ongoing American National Standards Institute process to develop a consensus-based standard for designing walls with exterior sheathing materials.

exterior insulation and claddings, drainage plane location and installation, and cladding installation

- Performance issues such as moisture and bulk water handling and climate-specific optimum thermal characteristics
- Cost factors associated with material and labor.

The primary focus will be on developing integrated solutions for light-frame walls to achieve R-values ranging from 20 to 40 $h \cdot ft^2 \cdot °F/Btu$. Initially, individual measures will be evaluated. As systems or component details meet initial evaluation criteria, they will be applied to test homes.

2 Evaluating the Wind Pressure Performance of Walls with Exterior Rigid-Foam Sheathing

Attaching exterior rigid-foam insulation directly to wall studs has been a common residential construction practice in parts of the country for many years. Although this practice is permitted in Chapter 7 of IRC (2009) under a prescriptive set of conditions, there are currently no established consensus-based test methods or engineering design procedures for determining the capacity of this type of wall system to resist out-of-plane wind pressure loads (see footnote 1). Recent debates at the code and standard development forums have raised questions regarding the capacity of these systems to resist out-of-plane wind pressures, and the possible need for appropriate limitations on the use of this technology.

The objective of this research effort was to conduct exploratory laboratory testing to determine the out-of-plane performance of wall systems with exterior rigid-foam insulation. The testing focused on measuring the pressure equalization characteristics and the capacity of various wall systems with rigid-foam sheathing attached directly to the studs. The results will advance efforts to develop design procedures and prescriptive code provisions.

The specific objectives and scope of this study were to:

- Evaluate the capacity of wall systems with 1-in. extruded polystyrene (XPS) rigid-foam sheathing attached directly to studs.
- Assess the impact of individual wall layers on the performance of XPS rigid-foam sheathing.
- Evaluate the effects of typical exterior residential wall air sealing details on the pressure equalization of rigid-foam insulation.
- Measure the pressure equalization factors (PEFs) across each wall layer.

2.1 Background

The impetus for this testing program is presented in a white paper entitled "Summary of Code and Standard Barriers to the Implementation of High Performance Home Systems Designs." (NAHB Research Center 2009a). The white paper discusses the need to characterize the out-of-plane performance of walls with exterior rigid insulation. It also presents results of a literature review on the topic including design wind loads, existing test methods and test results, and existing design methods, among others. Salient points highlighted in the white paper include the following:

- Typical negative design wind pressures on claddings in exposure B range between –15.1 and –31.5 psf for 90- to 130-mph wind speeds.
- The results of limited testing of wall systems with rigid-foam insulation installed directly over wood studs demonstrate that the rigid-foam insulation does not experience 100% of the applied load at higher pressures.
- The pressure equalization mechanism observed for rigid-foam insulation is similar in principle to that used in design for pressure equalization rainscreen (PER) systems.

- Direction of the loading can influence pressure equalization across layers and needs to be evaluated; however, negative pressures are 25% higher on average and are expected to control the design.
- From single-pulse dynamic testing, the observed range for the PEF for ½-in. rigid-foam insulation installed directly over studs was between 0.15 to 0.35 for wall systems without a water-resistive barrier (WRB) and between 0.20 to 0.45 for wall systems with a WRB.
- A single PEF is expected to apply to a given wall assembly at all performance levels.

2.2 Methods and Materials

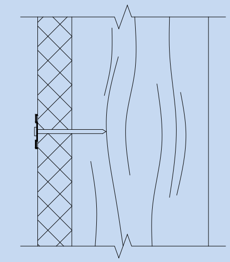
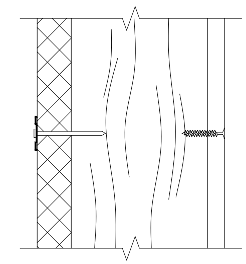
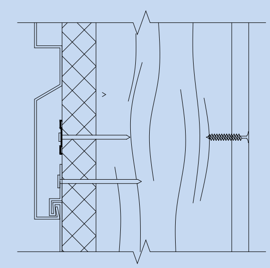
2.2.1 General

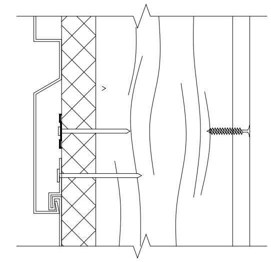
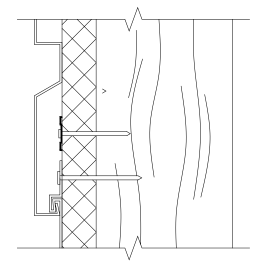
Testing was conducted at the NAHB Research Center Laboratory Facility in Upper Marlboro, Maryland, from November 2010 through February 2011. The researchers constructed wall specimens using materials purchased from local suppliers. Table 1 summarizes the test matrix for this program and includes a purpose statement for each tested configuration. Four primary wall groups were tested:

- XPS foam sheathing attached to 2 × 4 wood studs (no other wall components included)
- XPS foam sheathing (exterior face) and gypsum wallboard (interior face) attached to 2 × 4 wood studs. (Note that two configurations of Group 2 were tested—fully taped and untaped foam)
- Full-wall assembly including vinyl siding, foam insulation, 2 × 4 wood studs, batt insulation, and interior gypsum wallboard. (Note that several configurations of the full assembly were tested with a secondary set of variables including air sealing details at the exterior or interior layers or both, installation of a WRB, and installation of electrical outlets)
- Gable roof wall assembly with vinyl siding installed over sealed foam insulation attached to 2 × 4 studs without interior gypsum wall board.

Group 1 was used to establish a baseline of the capacity of the XPS foam insulation and its fasteners when tested in an isolated configuration without the contribution of any other wall layers. Group 2 was designed to determine a baseline for the pressure equalization across XPS foam insulation when a rigid, low-air-permeable layer (i.e., gypsum wallboard) is installed on the interior face of the wall. Wall specimens of Group 3 were used to benchmark the capacity of the entire wall system and to provide the pressure equalization across XPS foam sheathing in full-wall assemblies. Group 4, representing a gable roof wall assembly, provided the capacity of the foam sheathing attached to framing with the additional fasteners from the vinyl siding.

Table 1. Test Matrix of Wall Configurations

Group	Config-uration	Rigid Foam (Taped/ Untaped)	House Wrap	Vinyl Siding	Drywall (Standard/ Air Sealed at Plates)	Electrical Outlets	Purpose	Diagram
1	A	Untaped	None	None	None	None	Benchmark capacity of exterior rigid foam and its fasteners tested in an isolated configuration	
2	A	Untaped	None	None	Standard Drywall	None	Evaluate pressure equalization across exterior rigid foam when rigid, low-air- permeable layer (gypsum wallboard) is installed on the interior face of the wall	
	B	Taped	None					
3	A	Taped	None	5-in. Double Dutchlap	Standard Drywall	None	Evaluate pressure equalization effects in a full-wall assembly and to determine the full system's capacity	

3	B	Untaped	Yes	5-in. Double Dutchlap	Standard Drywall	None	Same as 3A for a system with a house wrap	
	C	Taped	None		Drywall air sealed at top and bottom plates		Same as 3A for a system with air sealed drywall	
	D	Taped	None	5-in. Double Dutchlap	Standard Drywall	Exterior and Interior	Same as 3A for a system with electrical outlets and wiring installed in predrilled studs	
	E	Only vertical joints taped	None	5-in. Double Dutchlap	Standard Drywall	None	Same as 3A for a system with foam not taped at top and bottom plates	
4	A	Taped	None	5-in. Double Dutchlap	Standard Drywall	None	Characterize capacity of a wall system without interior gypsum, typical of attic wall system at the gable end	

2.2.2 Specimen Construction

Table 2 summarizes the materials and details used in construction of the wall specimens. All wall specimens were 8 ft tall (nine 1½-in. studs and three 1½-in. plates, double top plate and single bottom plate) by 12 ft wide. Stud spacing in all wall specimens was 16 in. on center.

Table 2. Materials and Wall Construction

Material	Wall Construction
Exterior sheathing	1-in.-thick XPS 4 ft × 8 ft panels **Attachment:** 2-in.-long ring shank nails with nominal 1-in.-diameter plastic cap installed into studs at 12 in. on center spacing at sheathing panel edges and 16 in. on center in the panel field
Vinyl siding	Double 5 dutchlap (0.042-in.-thick) with single nailing flange **Attachment:** 2½-in.-long, 0.12-in.-diameter nail with ⅜-in.-diameter head at 16 in. on center. One nail located at each stud
WRB (where installed)	XPS foam sheathing with joints taped using 3-in.-wide construction tape (all joints were fully taped except Test 3E where only vertical joints were taped) OR Single continuous layer of house wrap over untaped foam sheathing (house wrap with 0.007 air penetration protection and moisture vapor permeance of 58) House wrap attachment: Two 2-in. ring shank nails with nominal 1-in. plastic cap for temporary purposes until vinyl siding is installed
Framing Lumber	2 × 4 Spruce-Pine-Fir studs (STUD Grade) 2 × 4 Spruce-Pine-Fir plates (#2) **Attachment** (plates to studs): (2) 16d nails (0.131-in.-diameter, 3¼-in.-long) at each stud end **Attachment** (double top plate): (2) 10d nails (0.148-in.-diameter, 3-in.-long) at 24 in. on center
Insulation	Unfaced R-13 batts **Attachment:** Friction fit between studs
Gypsum Wall Board	½-in.-thick panel installed horizontally, tape and mud at all joints and screw locations **Attachment:** 1¼-in. Type W screw at 16 in. on center **Standard drywall detail** (Table 1): no seal at top and bottom

Material	Wall Construction
	plates; a ¼- to ⅜-in. gap between the edge of the drywall, set up not to impede air flow; all vertical joints sealed **Air-sealed drywall detail** (Table 1): top and bottom plates air sealed with spray foam to minimize air flow
Outlets (Group 3D only)	 Exterior outlet: foam sheathing taped at the outlet location; outlet has standard rubber gasket Interior outlet: no special air sealing

2.2.3 Test Setup and Protocol

Figure 1, Figure 2, and Figure 3 show the test setup, which includes four primary elements: (1) specimen, (2) test frame, (3) pressure loading actuators (PLAs), and (4) controls.

Wall specimens were mounted onto the rigid test frame using a set of pull-action latch clamps and TimberStrand® composite lumber members. The interface connections were designed to limit air leakage through wall edges and attachment locations. Transparent plexiglass panels (¾-in.-thick) were used on the test frame face opposite of the specimen to allow observation of the response of the specimen's face inside the chamber during testing.

Through hoses and diffusers, the PLAs deliver suction to the test frame chamber, applying a negative pressure to the exterior surface of the specimen. Six PLAs were used to provide sufficient air flow to generate high-frequency, high-peak pressure pulses. The PLAs, with a peak capacity of ±400 psf, were designed and manufactured by the University of Western Ontario[2] (UWO) to generate high-frequency pressure traces that simulate realistic wind loading conditions on buildings.

A computer was used to control the PLAs and the data acquisition system (DAQ).

[2] Now Western University.

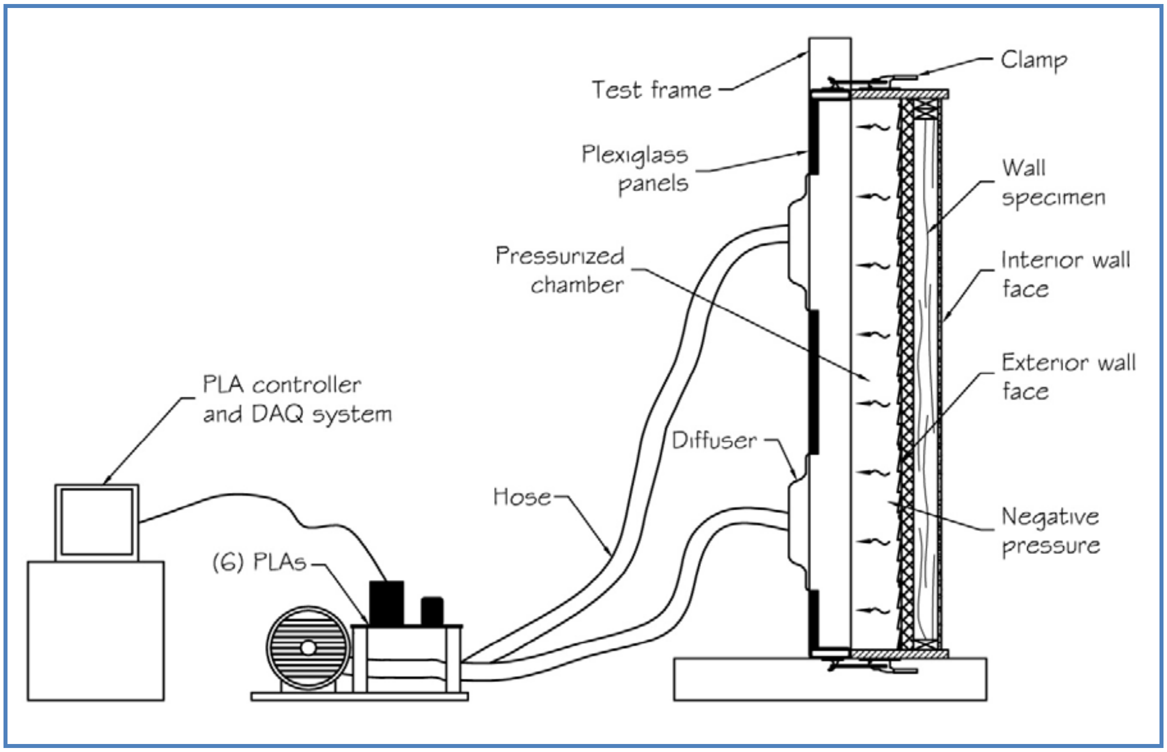


Figure 1. Labeled diagram of out-of-plane test apparatus

Figure 2. Testing frame with installed wall specimen

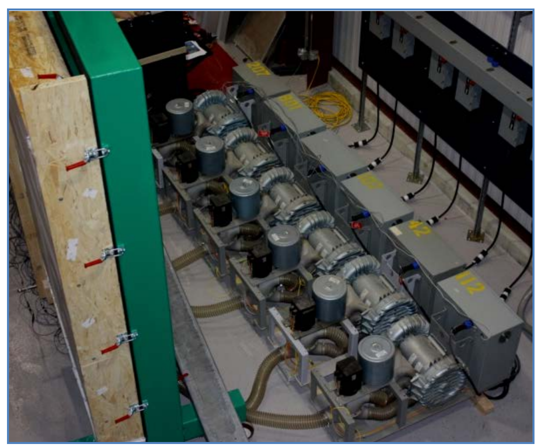


Figure 3. PLAs

Table 3 summarizes the pressure and deformation sensors that measured the response of the specimen. During construction of the wall specimens, up to 36 pressure transducers were mounted throughout the wall system at 12 different locations to measure the pressures at each wall layer (see Figure 4 and Figure 5). In addition, five string potentiometers were mounted inside two wall cavities to measure displacements of the wall sheathing material relative to the framing. Linear variable differential transducers (LVDTs) were used to measure global deflections on the interior face (i.e., gypsum side) of the wall at top and bottom supports and in the center of the wall relative to the test frame. Measurements were recorded at a frequency of 100 Hz per sensor.

Table 3. Measurement Sensors

Instrument (number)	Range
Pressure Transducers (39)	37 at ±5 psi 2 at ±1 psi
String Potentiometers (5)	0 to 2.8 in.
LVDTs (5)	4 at ±1 in. 1 at ±2 in.

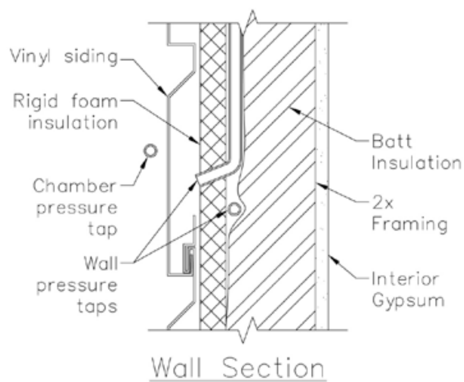


Figure 4. Location of pressure measurements in an exterior residential wall system

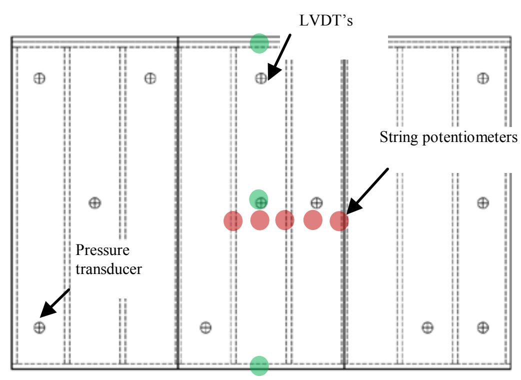


Figure 5. Pressure transducer locations in 12-ft-long by 8-ft-tall wall

The chamber pressure was measured by two pressure transducers: one with ±1 psi range and one with ±5 psi range.

The pressure inside the test chamber was controlled in accordance with dynamic high-wind pressure traces developed from scale-model wind tunnel tests conducted by the UWO. In this testing program, pressure traces replicating 60- to 145-mph wind tunnel conditions were used. The UWO developed and supplied all pressure traces. Kopp et al. (2010) and Murray and Kopp (2010) contain additional information on the pressure traces and their development. Figure 6 shows example pressure traces for four wind speeds. To provide pressure equalization results for a range of wind pressures, each specimen was tested using three pressure traces that represented incrementally increased wind speeds (exceptions are noted where walls failed before the third trace was applied). The wind speeds for the three incremental stages were selected with the intent to achieve performance levels ranging from serviceability limit states (i.e., no residual damage) at the lower wind speeds to a failure of the specimen at the highest wind speed. Each test pressure trace associated with a specific wind speed had a duration of 15 min (900 s).

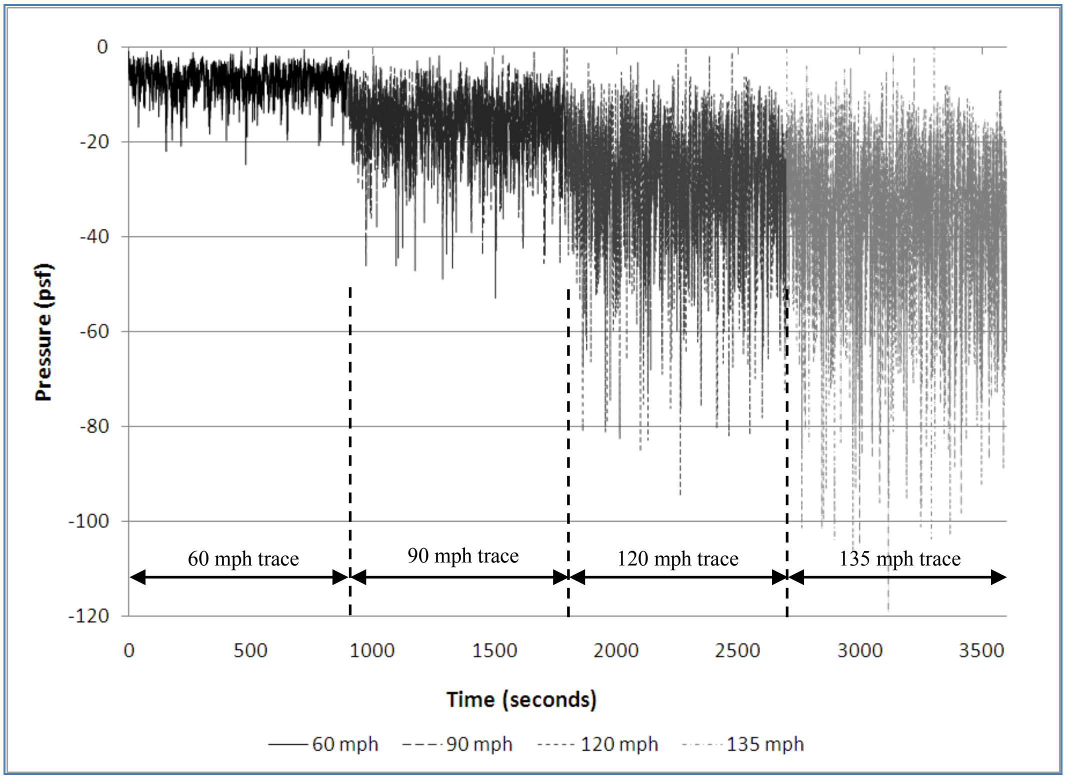


Figure 6. Example wind pressure traces for various wind speeds

To replicate the target wind pressures, the 11-hp PLA fans were operated at a fan speed of 30 to 60 Hz. The pressure was controlled through a proportional integral differential using a servomotor for adjusting the orifice controlling air flow in the system. The PLAs are capable of controlling pressure peaks changing at a frequency of up to 10 Hz. Figure 7 shows a 1-min snapshot comparison of the target and measured chamber pressures.

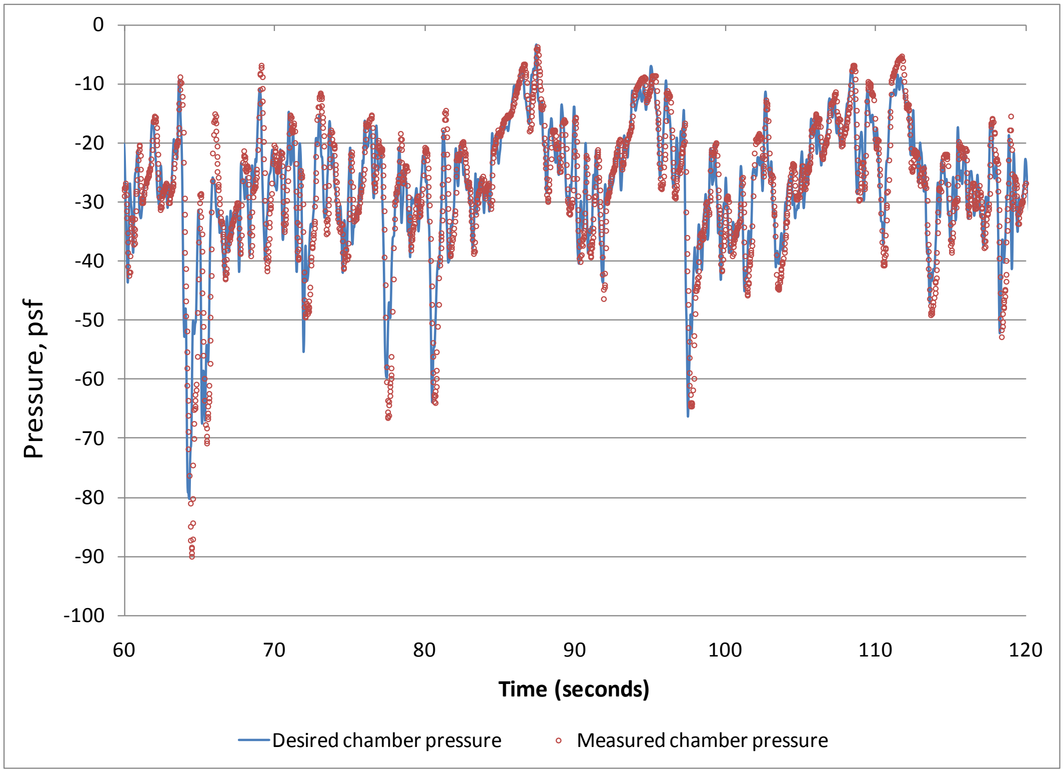


Figure 7. Comparison of desired and measured chamber pressures

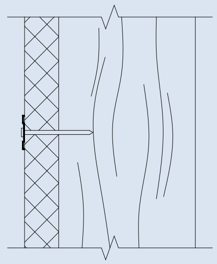
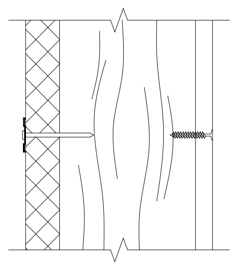
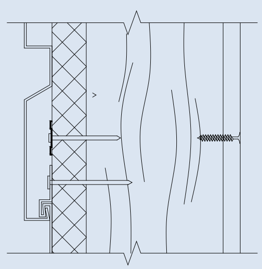
2.3 Results

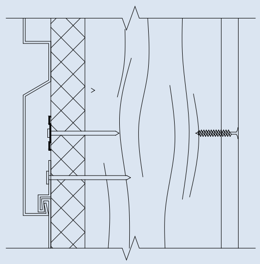
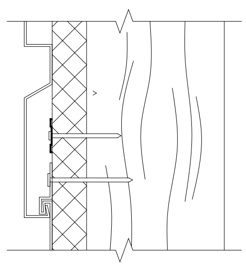
2.3.1 General

Table 4 summarizes the results organized by group and configuration, including test wind speeds, peak measured pressures, and descriptions of the observed failure modes. Figure 8 charts peak pressures by test group. The results indicate that the capacity of the wall system (Group 3) is as much as five times higher than the capacity of isolated foam (Group 1).

Comparison of the degree of improvement among groups 2, 3, and 4 indicates that both gypsum and vinyl siding fasteners contribute significantly to the system's capacity. The gypsum contributes through pressure equalization, whereas vinyl siding primarily contributes through the additional fasteners installed through the foam.

Table 4. Summary of Results

Group	Config-uration	Diagram	Description	Peak Pressure (psf)	Observed Damage/Failure
1	A	 Untaped foam only	Untaped foam only	–21	Complete failure of the nail plastic caps in the field of the foam sheathing panel
2	A	 Foam and gypsum	Foam untaped	–89	Complete shear failure of stud to top plate connections at two locations
	B		Foam taped	–51	Complete failure of the nail plastic caps in the field of the panel
3	A	 Full assembly	Foam taped	–134	Some damage around interior gypsum screws, slight failure at connections of vinyl siding and rigid-foam insulation

Group	Config-uration	Diagram	Description	Peak Pressure (psf)	Observed Damage/Failure
3	B	 Full assembly	Foam untaped, house wrap installed	–115	Complete shear failure in stud to top plate connections at one location and stud bending failure at one location
	C		Foam taped, air sealed drywall	–103	Slight shear failure in stud to top plate connections at two locations and complete bending failure of studs at four locations
	D		Foam taped, electrical outlets	–102	Complete bending failure of the studs at electrical wiring holes at two locations
	E		Foam taped at vertical joints only	–104	Bending failure of a stud
4	A		Gable end assembly, foam taped	–73	Failure at connections of vinyl siding and rigid-foam insulation

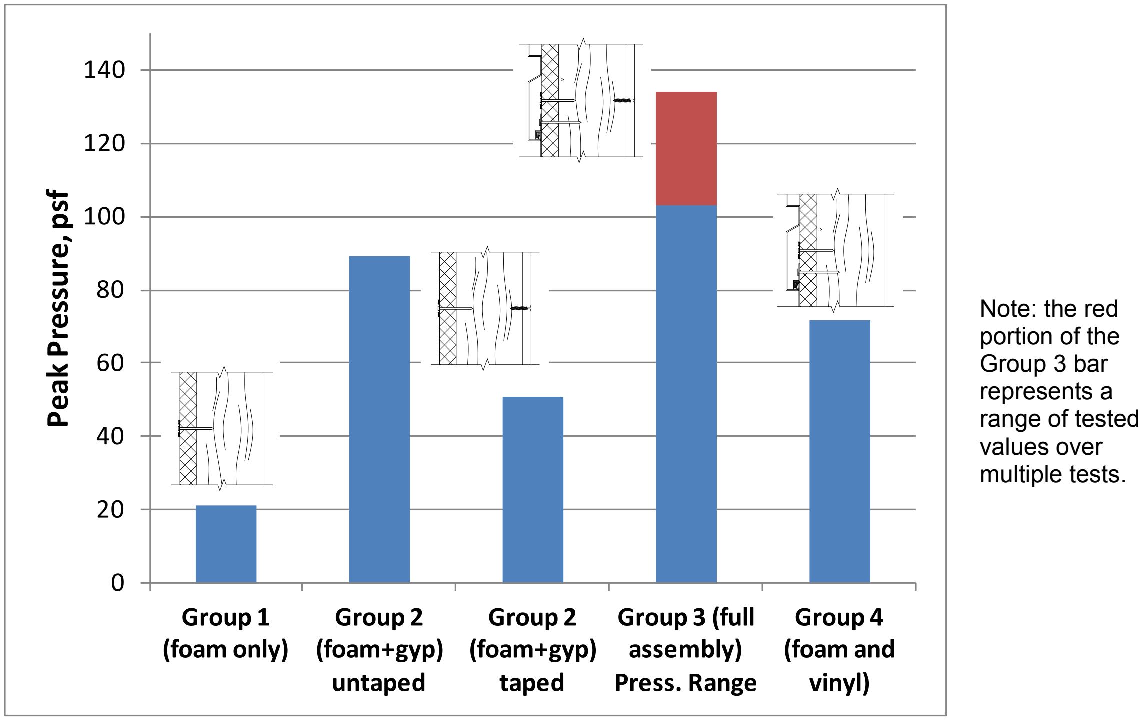


Figure 8. Wall capacities by test group

The peak capacity for the specimen with isolated foam sheathing measured at 21 psf and was limited by the failure of plastic cap nails in the field of the panel where the tributary area per fastener was the highest. The fasteners' primary failure mode was associated with the head of the nail pulling through the foam with some of the fasteners pulling the plastic cap through the foam as well (Figure 9).

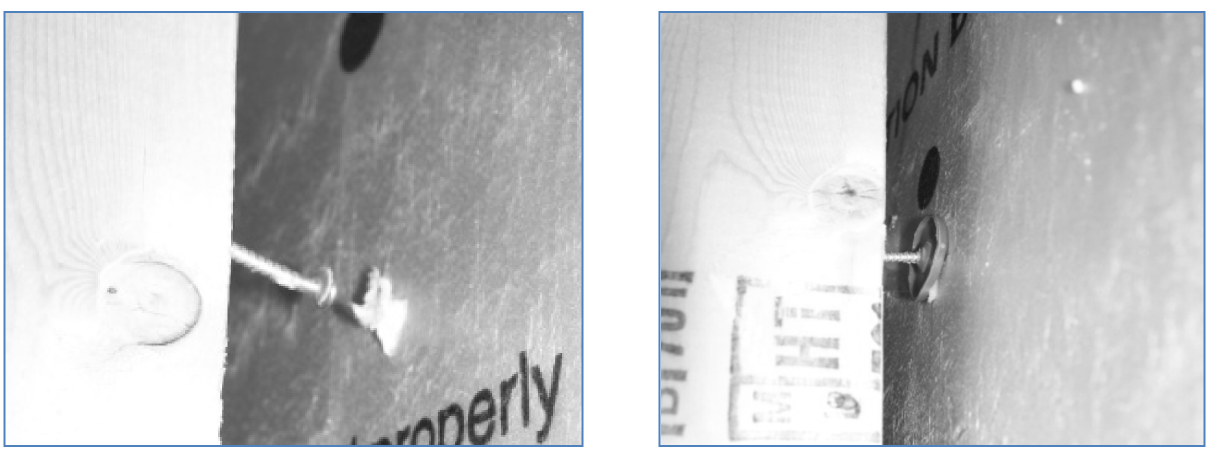


Figure 9. Group 1 failure mode

The addition of gypsum to the wall assembly (Group 2A) more than quadrupled the system capacity (89 psf) compared to the isolated foam (Group 1). The plate-to-stud connections of the wood frame failed and the gypsum broke (Figure 10), a response caused by the gypsum resisting the larger portion of the load. The distribution of the load between the layers occurred because air moved through the foam joints and the connections into the wall cavity, which led to load sharing between the foam and the gypsum.

Figure 10. Group 2A failure mode

Taping all horizontal and vertical foam sheathing joints (Group 2B) reduced the permeability of the exterior layer. This resulted in higher pressures applied on the foam and reduced the capacity of the overall wall system (51 psf). Figure 11 depicts the pressures on the foam layer for the Group B specimens plotted relative to the chamber pressure. Figure 11 also shows the upper boundary for the isolated foam test (Group 1) as a reference. The maximum pressure on the unsealed rigid-foam sheathing (Group 2A test) did not exceed 8 psf, whereas the pressures on the sealed foam sheathing (Group 2B test) peaked at about 21 psf—exactly the limit determined from the Group 1 test (foam sheathing only). Therefore, because less air moved through the joints of the foam sheathing, the foam sheathing layer experienced a higher portion of the total pressure. In fact, up to about 15 psf, the pressure on the foam followed the chamber pressure (linear portion of Group 2B line) before the onset of pressure equalization. Consistent with this observation, the failure mode was associated with the foam sheathing connections. The failure of the nail plastic caps in the field of the sheathing panel where the fastener tributary area was the highest was followed by the onset of failure of the perimeter nails (Figure 12). Because all foam joints (vertical and horizontal, including the specimen boundaries) were taped with a 3-in.-wide tape, Group 2B represents the most conservative loading case for the exterior foam. In a more typical construction configuration, the boundary joints at the top and/or bottom plates are not taped, allowing air to move in and out of the cavity. Results from Group 3 specimens (discussed next) indicated that taping only the vertical joints resulted in a range of PEFs for the foam more similar to those for the untaped foam configuration than the fully taped foam configuration.

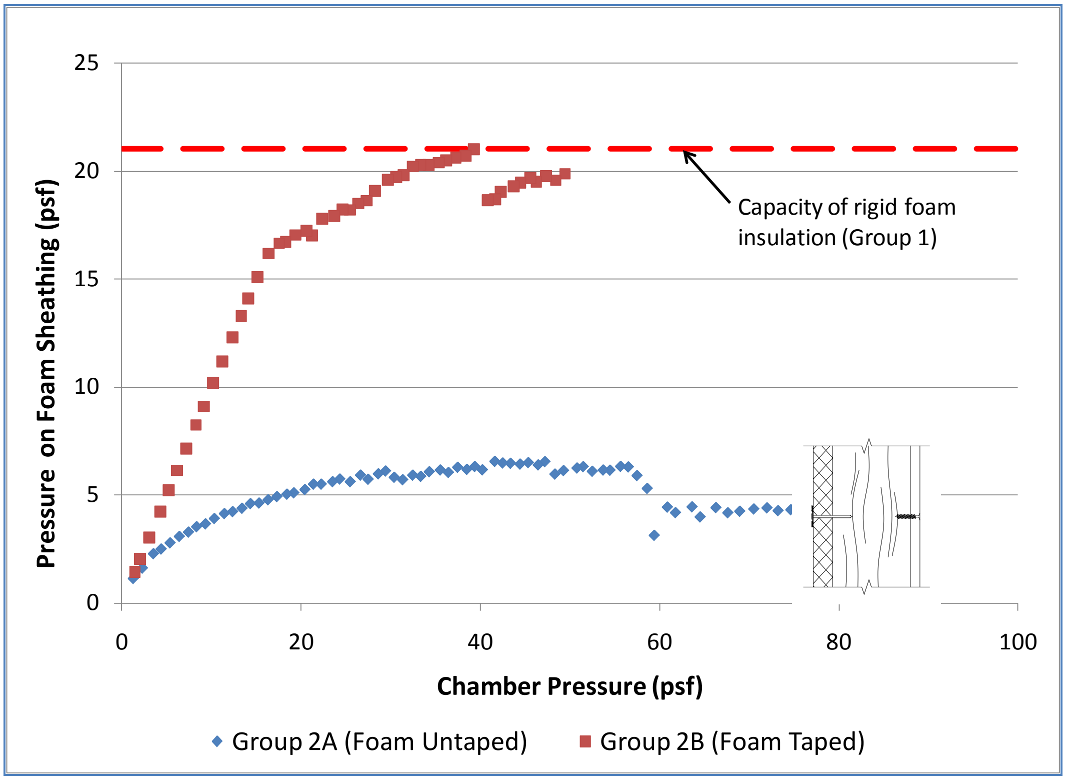
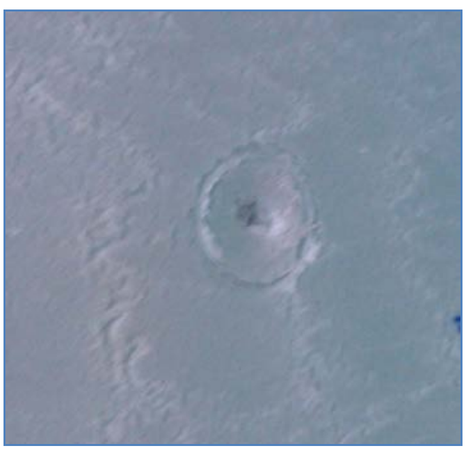


Figure 11. Pressures on rigid-foam insulation for Group 2 specimens



Washer imprint on sheathing

Washer after failure

Figure 12. Group 2B failure mode (sheathing nail pull-through)

Five Group 3 (full-wall assembly) configurations were tested (refer to Table 1 for a description of the configurations). Peak capacities ranged from 102 psf to 134 psf. The failure modes varied among the specimens, indicating that the system was close to balanced. The Group 3A specimen reached a pressure of 134 psf, which was limited by the capacity of the exterior sheathing/cladding system (Figure 13). The siding fasteners pulled from the framing and the foam sheathing fasteners either pulled out of the framing or pulled through the plastic cap. The damage exhibited as bulging of the vinyl siding.

Figure 13. Group 3A failure mode

The capacity of the rest of Group 3 specimens (B, C, D, and E) was limited by the capacity of the framing and/or framing connections (Figure 14, Figure 15, and Figure 16). This led to a collapse of the wall system and damage to interior drywall and the exterior layers. Where predrilled studs were used for the specimen with electrical outlets, the bending failure of the studs occurred at the predrilled holes. Note that a different batch of lumber was used starting on Specimen 3B. The observed change of failure mode from the wall's exterior sheathing fasteners to the framing members and connections again indicates that this system was close to a balanced design. Although Group 3 test variables had some small impact on the pressure equalization profile as discussed later in the report, the variance in capacity of system among the specimens appeared more affected by other factors such as the variance in framing lumber strength.

Figure 14. Group 3B failure mode

Figure 15. Group 3C failure mode

Figure 16. Group 3D failure mode

Although the capacity of the Group 4 specimen of 73 psf is a reduction of 30% or more compared to the full-wall assemblies (Group 3), it was a 3.5 times increase over the isolated foam sheathing test (Group 1). This comparison indicates that the vinyl siding fasteners contribute to the capacity of the foam sheathing. The failure mode of the Group 4 specimen was associated with pull-through of sheathing and siding fasteners in the field of the center panel (Figure 17) and showed on the exterior as bulging of the vinyl siding (Figure 18).

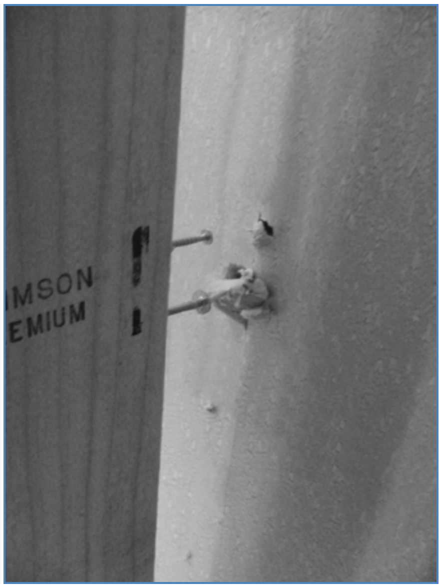


Figure 17. Group 4A failure mode, nail pull-through

Figure 18. Group 4A failure mode

2.3.2 Pressure Equalization Results

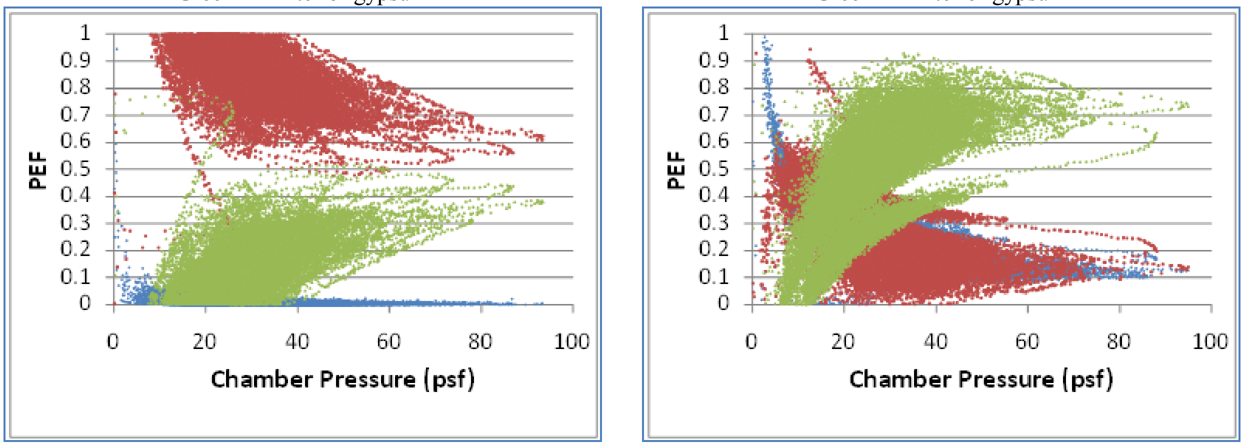
The pressures measured inside the wall assemblies were used to calculate a PEF for each layer of the wall system. The PEF is the percentage of the total applied pressure resisted by an individual wall layer according to Equation 1:

$$PEF = \frac{pressure\ gradient\ across\ layer}{total\ pressure\ gradient\ across\ wall}, \text{ where } 0 \leq PEF \leq 1.0 \qquad \textbf{(1)}$$

Figure 19 gives sample PEF graphs by layer for Specimen 3C (taped) and Specimen 3B (untaped) under a single wind pressure trace. These charts demonstrate that the PEFs are a function of the chamber pressure trace and the configuration of the wall system. For example, at pressures below 40 psf for the wall assembly with foam fully taped, the peak PEF across the foam sheathing layer was as high as 1.0 (Figure 19b). This means that the foam resisted as much as 100% of the total pressure at specific times along the pressure trace. As the pressure increased, the peak PEF for the rigid-foam insulation dropped below 0.7. For the wall assembly with untaped foam insulation and a house wrap (Figure 19a), the pressure gradient across foam was substantially reduced with the PEF trending below 0.40 at chamber pressures above 40 psf.

Blue • – Vinyl siding and house wrap
Red • – Untaped rigid-foam sheathing
Green • – Interior gypsum

Blue • – Vinyl siding
Red • – Taped rigid-foam sheathing
Green • – Interior gypsum



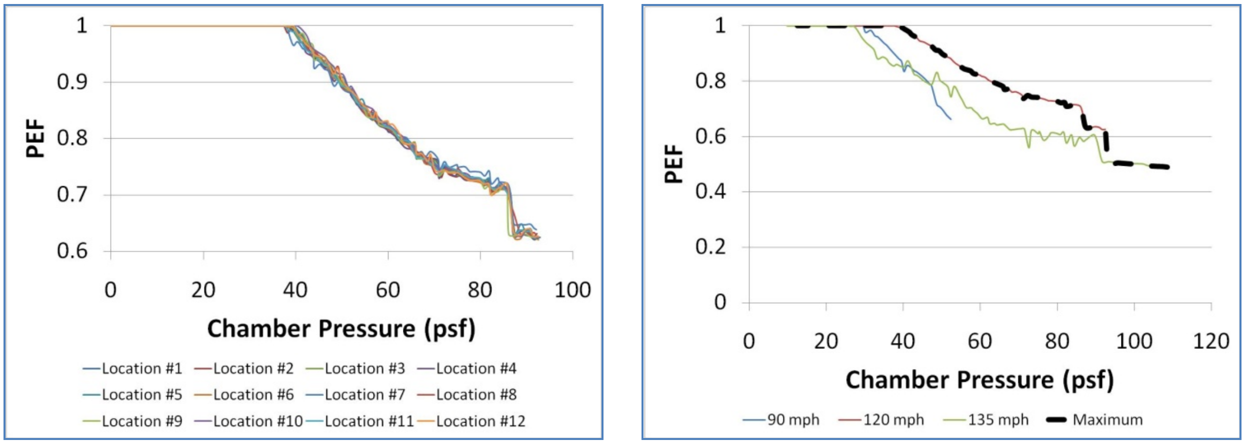
(a) Sheathing joints taped (Group 3C)

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

Figure 19. Sample PEFs by individual layers for Group 3 specimens

Figure 20a compares PEFs for 12 pressure sensor locations in the same wall for one of the specimens (refer to Figure 5 for locations of pressure sensors). The chart shows consistent results between various locations, indicating that there was little variability in response between different locations in the same wall. This conclusion holds true for all tested specimens.

To characterize the PEF of a wall layer over the range of test pressures and to enable consistent comparison of PEFs among different wall assemblies, PEF envelope curves for each wall layer were developed as follows: (1) for each pressure trace, individual envelope curves were generated for each of the 12 pressure sensors in a wall specimen, (2) envelope curves were averaged across the 12 pressure sensors, and (3) the highest PEF factor for a given pressure was selected among all pressure traces (Figure 20b).



(a) PEF envelope curves for exterior rigid foam for 12 locations in a wall specimen

(b) Average and maximum PEF envelope curves

Figure 20. PEF analysis for rigid-foam insulation

Figure 21 plots the envelope PEFs for rigid-foam sheathing for all Group 3 configurations (full-wall assembly). For configurations with foam fully taped (configurations A, C, and D), the PEF trends for the foam sheathing ranged from 1.0 at low pressures (0 psf to 30–50 psf) to 0.55–0.70 at peak pressures (80+ psf). For configurations with foam untaped (Configuration 3B) or taped at vertical joints only (Configuration 3E), a more rapid decrease in the foam sheathing PEF was observed. Here, the PEF started at lower pressure thresholds (less than 5 psf) and reached levels below 0.2 at system capacity. For Configuration 3B, house wrap was applied as a continuous sheet and taped at the edges of the specimen. This effectively functioned as an air barrier and imposed a larger load onto the siding fasteners (refer to Figure 19b). For Configuration 3E, the gypsum sheathing resisted more than 80% of the load at pressures above 20 psf... This suggests that systems that are not fully taped respond more as untaped systems, allowing the air to move behind the foam.

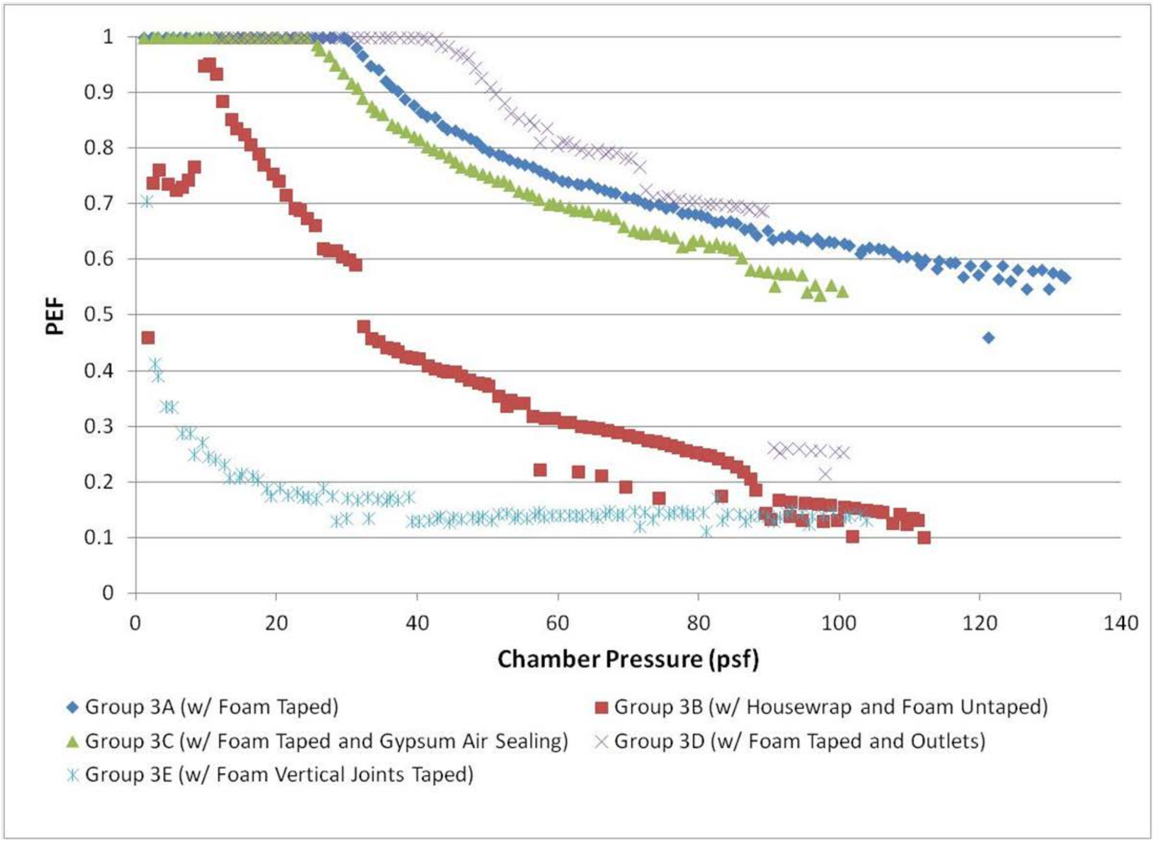


Figure 21. Envelope PEFs for rigid-foam sheathing for full-wall assemblies (Group 3 specimens)

For Group 3 specimens, Figure 22 shows the relationship between the total pressure gradient across the entire wall assembly (i.e., chamber pressure) and the pressure resisted only by the combined system of the rigid-foam sheathing, vinyl siding, and their associated fasteners. In addition, the horizontal dash line representing the capacity of the foam only (Group 1A) is included on the chart as a reference boundary. Of the five full-wall specimens of Group 3, only Configuration 3A approaches the capacity of Group 4A. This suggests that this is the only group in which the fasteners of the foam sheathing and siding system limit performance. None of the other wall systems experienced pressures approaching the capacity of the combined foam/siding system; failure in these walls, then, occurred in the framing. Because the capacities of Specimens 3B–3E were lower than the capacity for Specimen 3A, the research team concluded that the full-wall assemblies with foam sheathing are a relatively balanced system. Other factors, such as variability of lumber bending properties, have a greater impact on the overall system’s capacity than air sealing details. Configuration 3E again indicates that for systems with only vertical joints taped, the exterior assembly is resisting less than 20% of the total pressure with the majority of the load resisted by the interior gypsum.

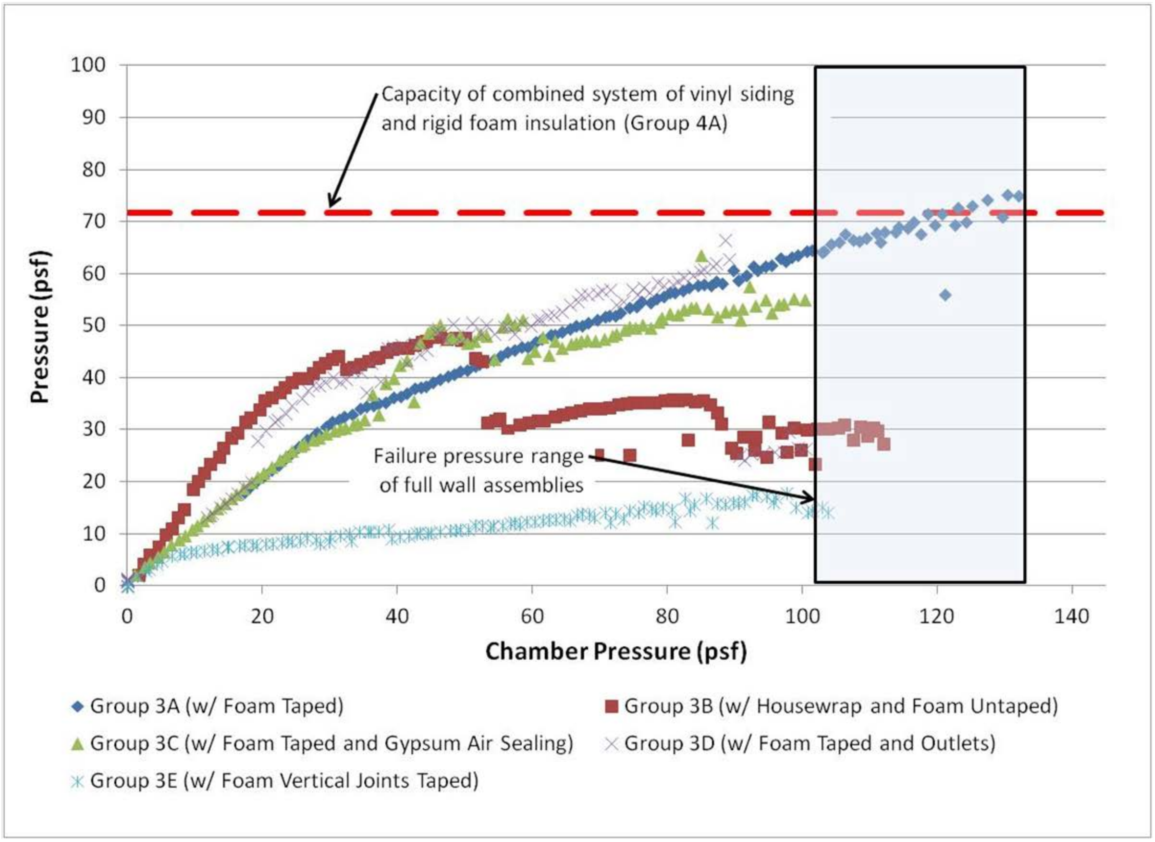


Figure 22. Calculated pressure on the combined system of rigid-foam insulation and vinyl siding versus pressures (Configuration 3)

2.4 Summary and Conclusions

This testing program was designed to evaluate the wind pressure performance of energy efficient walls constructed with exterior rigid XPS foam insulation used as the primary wall sheathing material. Several 8 ft × 12 ft wall specimens of different configurations were tested under high-frequency dynamic wind pressures traces that closely replicated the loading conditions during real-life wind events. Pressures were measured in multiple locations and at each layer in the walls to characterize the pressure distribution across the wall assembly. The results of the pressure distribution were used to characterize the behavior of each wall layer and its contribution to the system. The results also yielded pressure equalization factors for rigid-foam insulation when used as an insulating layer along with a WRB and when used solely as an insulating layer. Based on the testing, the following conclusions can be made:

- The capacity of the complete wall system (siding-foam-studs-gypsum) is five times higher than the capacity of the isolated foam sheathing (foam studs).
- Wind pressure is redistributed between the wall layers as a result of the pressure equalization effects. The degree of redistribution depends on the detailing of the exterior air barriers and, to a lesser degree, the interior air barrier (level of air sealing).

- Gypsum wall board contributes to the total wall capacity and the degree of the shared load depends primarily on the air-tightness of the exterior foam layer.
- The full-wall assembly is a relatively balanced system with failure modes ranging from failure of framing members and their connections to the failure of the exterior foam sheathing connections.
- The PEFs across the foam sheathing are a function of the total pressure applied to the wall. As the pressure increases, the PEFs decrease (i.e., a greater degree of pressure equalization occurs in the wall).
- The PEFs across the foam sheathing decrease with increased permeability of the foam sheathing layer. The walls with the foam sheathing untaped or taped only at vertical joints show an onset of equalization at low pressures (about 5 psf) and the levels of PEFs below 0.2 at higher pressures.
- In full-wall assemblies, the failure of the foam fasteners is the controlling failure mode only in the systems with the foam sheathing fully taped along all vertical and all horizontal joints. This configuration also reaches the highest overall capacity. In full-wall assemblies with the foam untaped or taped at vertical joints only, the load of the foam does not reach the levels sufficient to fail at the foam connections. In these cases, the failure is controlled by the wood framing and its connections.

2.5 Proposed Additional Testing

Further testing of other wall materials and configurations is recommended for a more complete representation of wall system PEFs. The additional testing combined with the completed testing can be used to develop more complete design guidelines for walls using foam sheathing. The recommended testing will

- Characterize the performance of a variety of plastic cap fasteners
- Determine the capacity of different field fastener spacings
- Characterize the performance of other rigid-foam insulation types (i.e., expanded polystyrene and polyisocyanurate) and brands
- Characterize the performance of 24-in. on center stud spacing.

A targeted and parallel effort is proposed to evaluate the moisture performance of high-R wall systems through laboratory testing at the Forest Products Laboratory, simulations using WUFI software, field testing of walls using the Research Center's Test Huts, and monitoring of wall moisture conditions in high performance homes.

References

IRC (2009). *2009 International Residential Code® for One- and Two-family Dwellings.* Country Club Hills, IL: International Code Council, Inc.

Kopp, G.A.; Morrison, M.J.; Gavanski, E.; Henderson, D.J.; Hong, H.P. (2010). "Three Little Pigs Project: Hurricane Risk Mitigation by Integrated Wind Tunnel and Full-Scale Laboratory Tests." *Natural Hazards Review* (11:151).

Morrison, M.J.; Kopp, G.A. (2010). "Performance of Toe-Nail Connections Under Realistic Wind Loading." *Engineering Structures* (33:2011); pp. 69–76.

NAHB Research Center (2011). *Test Plan: High-R Wall Systems – Structural Performance Testing.* Deliverable Number 2.1.1. Upper Marlboro, MD: NAHB Research Center.

NAHB Research Center (2009a). *Summary of Code and Standard Barriers to the Implementation of High Performance Home Systems Designs*. Deliverable Number 4.2.2.1 Under NREL Subcontract Number AXL-9-99208-01. Upper Marlboro, MD: NAHB Research Center.

NAHB Research Center (2009b). *Gate 1B–System Evaluations & Specifications: Advanced Header Framing Design for High-R Wall Systems*. Deliverable Number 4.2.1.2 Under NREL Subcontract Number AXL-9-99208-01. Upper Marlboro, MD: NAHB Research Center.

Appendix A Summary of Test Pressure Traces, Maximum Observed Pressures, and Observed Damage for Test Wall Specimens

Group	Configuration	Wind Speed Pressure Trace (mph)	Maximum Negative Chamber Pressure (psf)	Observed Damage/Failure
1	A	60	–21	Complete failure of the nail plastic caps in the field of the panel
2	A	73–125	–27 to –89	None
		125	–82	Complete shear failure in stud to top plate connections at two locations
	B	60	–27	None
		90	–51	Complete failure of the nail plastic caps in the field of the panel
3	A	60	–27	None
		90	–53	None
		120	–108	Slight damage around interior gypsum screw
		135	–124	Complete failure at connections of vinyl siding and rigid-foam insulation
		90	–54	None
		120	–97	None
		135	–125	Slight damage around interior gypsum screws
		145	–134	Increased damage around interior gypsum screws slight failure at connections of vinyl siding and rigid-foam insulation
3	B	90	–53	None
		120	–95	Slight damage at vinyl siding fasteners
		135	–115	Complete shear failure in stud to top plate connections at one location and stud bending failure at one location

Group	Configuration	Wind Speed Pressure Trace (mph)	Maximum Negative Chamber Pressure (psf)	Observed Damage/Failure
	C	90	–53	Slight damage around interior gypsum screw
		120	–95	Slight damage around interior gypsum screws
		135	–103	Slight shear failure in stud to top plate connections at two locations and complete bending failure in the studs at four locations
	D	90	–53	None
		120	–92	Slight failure at connections of vinyl siding and rigid-foam insulation
		135	–103	Complete bending failure at electrical wiring holes in the studs at two locations
4	A	60	–27	None
		90	–55	None
		110	–73	Failure at connections of vinyl siding and rigid-foam insulation

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