Wind Load Design Considerations for Out-of-Plane Loading

White Paper

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April 9, 2010

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INTRODUCTION

The residential building code provisions continue to evolve with new design and construction requirements introduced every code update cycle. These new requirements are typically the result of one of the following:

- A product innovation that leads to a new method of construction that has not been previously included in the prescriptive building code requirements
- A system innovation that leads to the use of existing materials in new applications or new configurations
- A re-evaluation of conventional practices based on engineering or changed performance expectations

Innovation in construction technology has been often driven by a desire to improve performance (e.g., reduction in energy use) and/or to gain efficiency in the construction process (e.g., garage portal frames, SIP construction). On the other hand, a re-evaluation of existing code provisions is often prompted by a desire to align conventional practices more closely with engineering estimates (e.g., wall bracing provisions of the International Residential Code (IRC)[1]). Because conventional practices have a history of successful field performance, a re-evaluation task typically involves (1) development of analytical methods that are representative of the actual system performance, and (2) establishment of appropriate applicability limits on the prescriptive requirements (e.g., wind speeds less than 100 mph).

This white paper explores issues related to exterior wall resistance to wind pressure – an area of residential building design where additional building code development efforts are expected in response to both continued innovation and an evolving understanding of performance. The paper focuses on two residential technologies:

1) Rigid exterior foam sheathing attached directly to studs
2) Residential garage doors

The performance and design considerations for both systems are discussed, gaps in knowledge are identified, and recommendations for research are provided for both technologies in support of the building code development process. First, the paper provides an overview of the upcoming changes to wind hazard maps.

ASCE 7-10: UPDATE TO WIND HAZARD MAPS

The forthcoming 2010 edition of ASCE 7 will include a new format for wind design maps. The main changes include: (1) alignment of the mapped wind speed return period with the strength design basis (700-year return period design basis), (2) development of occupancy category (now called "risk category") specific wind speed maps (a total of three maps), and (3) generation of updated wind speeds using the latest understanding of hurricane behavior, additional historical storm track data, and improved modeling capabilities. The new format establishes a more uniform return period for the design wind speed across the country at the strength design limit state. For the Allowable

[1] International Residential Code (IRC) for One- and Two-Family Dwellings, 2009, International Code Council, Country Club Hills, IL.

Stress Design (ASD) load combinations, a reduction factor of 0.6 is used to provide consistency between the LRFD and ASD design methods.

As a coordinated change in the International Building Code, the deflection design requirements for components and cladding are under revision. The current code provisions allow for reducing the 50-year return period components and cladding wind loads by 30% (0.7 multiplier) for deflection design checks (IBC Table 1604.3[2]). A new reduction factor of 0.42 is proposed to replace the 0.7 factor in the IBC to maintain a consistent design basis for serviceability performance. When used with the new 700-year wind map, the 0.42 factor provides designs aligned with the previous 50-year map format.

In addition, the commentary of ASCE 7-10 will include a set of four additional maps with contours at shorter return periods: 10-year, 25-year, 50-year, and 100-year return period wind speeds. This set of maps is provided for serviceability design checks and will provide a more accurate tool for designers to analyze the performance of systems for non-life safety criteria. The commentary language recognizes the use of wind speeds at a 700-year return period recurrence interval for serviceability design checks is excessively conservative. The four new maps are intended to represent a range of return periods appropriate for performing serviceability checks. The ASCE 7-10 commentary states that selection of a return period is a matter of engineering judgment in discussion with the building client. It further recognizes that deformation limits should apply to the structural assembly, i.e., the contribution of finish materials can be included in the analysis. The use of the reduction factor for components and cladding (0.7 current or 0.42 new) approximately corresponds to a return period of 10 years[3]. Therefore, the new 10-year map provides wind loads that align with the loads calculated using the 700-year map with the new 0.42 factor.

PERFORMANCE OF WALL SYSTEMS WITH RIGID FOAM PLASTIC INSULATION

Building Code Requirements

Wall systems with exterior rigid foam insulation attached directly to wall studs have been common residential construction practice in many parts of the country for many years. While this practice is permitted by the 2009 IRC prescriptive provisions of Chapter 7 Wall Covering, at this time there are no established consensus-based test methods or engineering design procedures for determining the capacity of this type of wall system to resist wind loads. Recent debates at the ICC code development forum have raised questions regarding the wind pressure resistance of wall systems with exterior rigid foam attached directly to studs, and the possible need for appropriate limitations on this technology. The 2009 IRC performance requirements in terms of negative wind pressures for wall design with 8'-0" high studs spaced 16 or 24 inches on center are summarized in Table 1.

[2] International Building Code (IBC), 2009, International Code Council, Country Club Hills, IL.
[3] The approximate return period was calculated using the equation referenced in Section C6.5.4 of the ASCE 7-98 commentary.

Table 1. Design negative wind pressures (psf)[1]

Wind Exposure	Zone	Wind Speed (3-second gust), mph				
		90	100	110	120	130
B	Within 4 feet of corner (Zone 5)	18.1	22.4	27.1	32.3	37.8
	Away from corner (Zone 4)	15.1	18.7	22.5	26.8	31.5
C[2]	Within 4 feet of corner (Zone 5)	25.3	31.4	37.9	45.2	52.9
	Away from corner (Zone 4)	21.1	26.2	31.5	37.5	44.1

1. Wind pressures for 8'-0" high walls with 16" or 24" on center stud spacing based on an effective tributary area of 21.3 feet^2 determined as the height of the stud times wind area width calculated as (1/3) the stud length.
2. Calculated using an adjustment coefficient of 1.40 from 2009 IRC Table R301.2(3).

For wood structural panels, Section R602.3 of Chapter 6 provides a prescriptive method for compliance with the wind pressure requirements – Table R602.3(3) "Requirements for Wood Structural Panel Wall Sheathing Used to Resist Wind Pressures". These requirements were developed assuming that 100 percent of the wind pressure is resisted by the wood structural panel sheathing. Although this assumption is conservative (based on results of limited testing described later in the report), the capacities and thicknesses of typical wood structural panels used in residential construction are sufficient to satisfy these requirements. Therefore, there is no incentive to improve the accuracy of the analysis for wall configurations with wood structural panels.

For walls with foam sheathing attached directly to studs, a better understanding of the actual response of the wall is needed to reasonably correlate the historic performance of these wall systems and the design wind loads. While limited in scope, the results of existing testing of walls with rigid foam attached to studs suggest for these systems that the wind pressure experienced by the foam sheathing is less than the total wind pressure. This behavior is a result of pressure equalization that occurs across a multi-layered system.

Pressure Equalization Effects – General

The wind design provisions of ASCE 7-05 "Minimum Design Loads for Buildings and Other Structures"[4] allow for reduced loads for air-permeable cladding based on approved test data or recognized literature (ASCE 7-05 Section 6.4.3). This reduction in load is the result of **pressure equalization** – a reduction in net pressure across the cladding material due to the counterbalancing pressure on the opposite face. This air pressure acting on the opposite face is the result of air entry/exit behind the cladding layer. The air entry can be specifically controlled through designated perforations (e.g.,

[4] Minimum Design Loads for Buildings and Other Structures ASCE/SEI 7-05, American Society of Civil Engineers, Reston, VA.

PER[5] systems) or can be the result of the inherent cladding configuration (e.g., lap siding that permits air passage between the siding strips, or veneer cladding with a gap – also referred to as drained/back-ventilated (DBV) walls). The basic concept of pressure equalization across an exterior cladding layer is illustrated in Figure 1 for a PER system and for a veneer cladding system. It should be noted that PER systems are not common in low-rise residential applications and are presented here for background purposes as accepted systems with a good history of performance.

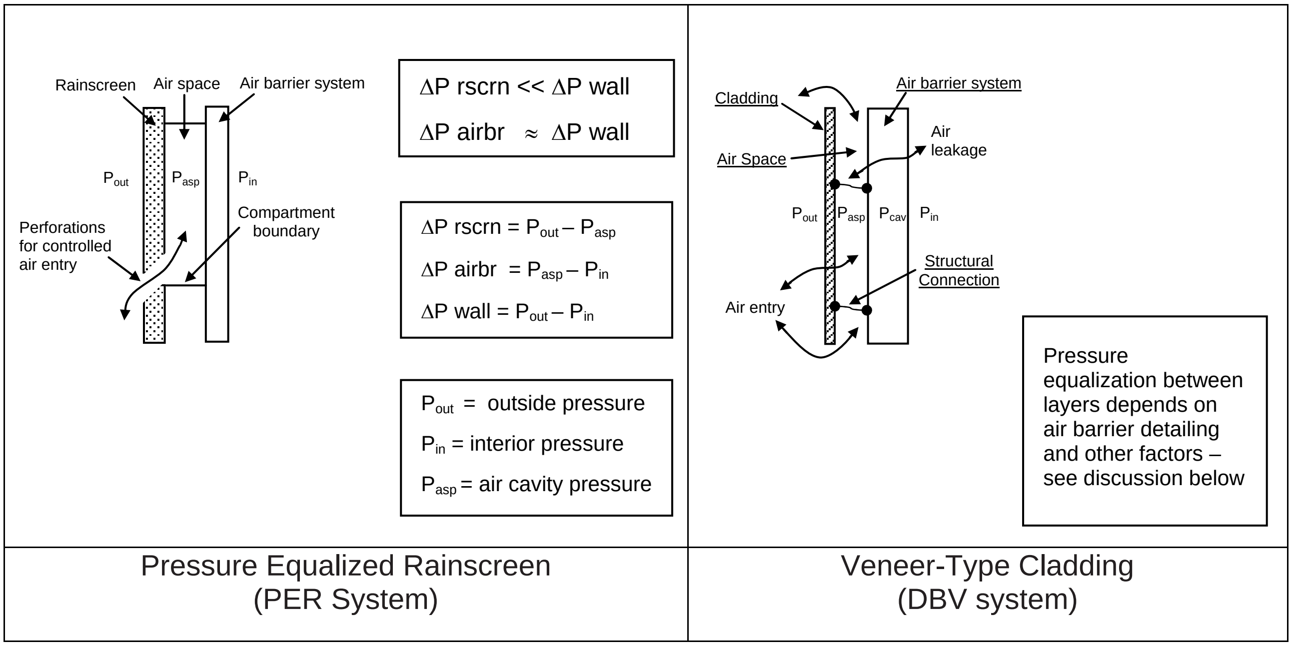

Figure 1. Cladding pressure equalization mechanism in PER and DBV Systems

As a result of pressure equalization across the exterior cladding, the net pressure acting on the cladding is substantially less than the total wind pressure:

$$\Delta P\ rscrn << \Delta P\ wall$$

Where:

$\Delta P\ rscrn$ = *pressure gradient across rainscreen*
$\Delta P\ wall$ = *pressure gradient across the entire wall system, i.e., total pressure*

The degree of pressure equalization is often expressed in terms of the pressure equalization factor (PEF) defined as follows:

$$PEF = \frac{pressure\ gradient\ across\ layer}{total\ \ pressure\ gradient} = \frac{pressure\ at\ \ face\,1 - pressure\ at\ \ face\ 2}{total\ \ pressure\ gradient}$$

[5] Pressure equalized rainscreen (PER) systems are common in commercial applications and are designed to minimize the bulk water intrusion behind the primary cladding layer by reducing the pressure gradient across the cladding.

$$0 \leq PEF \leq 1.0$$

Because wall systems are not completely air-tight, the concept of pressure equalization is also applicable to other layers of a wall system. Although limited in scope at this time, both laboratory testing and field measurements support the observation that the exterior sheathing does not experience the full wind pressure. This observation is particularly important for walls with rigid foam sheathing attached directly to studs because the foam sheathing layer may not always have the design capacity to resist the full pressure on its own. Yet, because the exterior sheathing does not experience the full pressure, the design methodology should allow design for the wind pressures that are actually expected. The key to such design is the knowledge of the pressure equalization factors across each wall layer for the various wall systems. The design principle for a wall layer subject to pressure equalization can be formulated as follows:

$$P_{layer} = (P_{total})(PEF) \leq R_{layer}$$

Where:

P_{layer}	- Pressure acting on the wall layer
P_{total}	- Total wind pressure across the entire wall system
PEF	- Pressure equalization factor
R_{layer}	- Resistance of the wall layer including applicable safety margin

Light-frame Wall Systems

The design of a wall system must ensure that all wall layers and their connections are adequate to resist the appropriate pressure differential. Figure 2 (based on the proposed commentary to ASCE 7-10 and provided courtesy of Jay Crandell) shows the typical layers involved in defining the pressure profile across a light-frame wall system.

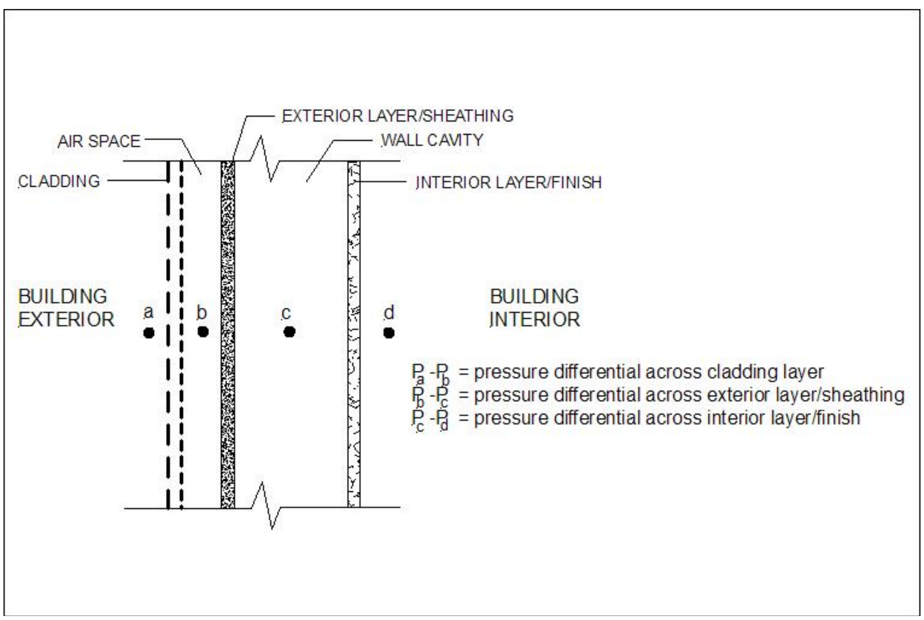

Figure 2. Pressure gradient in a light-frame wall system (courtesy of Jay Crandell).

Two typical light-frame system designs incorporating exterior foam sheathing are discussed below to illustrate the difference in their response to wind pressures: exterior rigid foam attached to wood structural panels (Table 2) and exterior rigid foam attached to studs (Table 3). Each table is followed by a discussion of the performance of the layers of the system.

Table 2 - Exterior Rigid Foam Attached to Wood Structural Panels

Layer	Pressure Resistance	Enclosure Function	Discussion
Siding	Designed to resist partial wind pressure	Bulk water control	Because the air flows through the joints and behind the siding, pressure equalization occurs across the siding such that the siding pressure is less than the total pressure gradient across the wall. Previous testing conducted by Architectural Testing, Inc (ATI) measured a maximum pressure equalization factor of 0.18 for vinyl siding[6].
WRB[a]	Flexible membrane with no resistance to pressure	Bulk water control and air control	May or may not be included in system.
Rigid Foam	Pressure primarily resisted by the wood structural panel	Thermal transfer control and air control	
Wood structural panel (WSP)	Designed as the primary wind pressure resisting element	Air barrier and secondary moisture control through storage and release	Previous testing conducted by ATI measured the pressure equalization factor ranging from 0.2 to 0.75[2] for exterior plywood sheathing (walls tested without exterior foam).
Framing	Transfers wind pressures to floor and roof diaphragms and foundation	N/A	Provides support for WSP sheathing and attachment for fasteners.
Interior gypsum panels	Resists a portion of the overall wind pressure	Air barrier	The amount of pressure on the interior gypsum depends on the air leakage into the wall cavity. The WSP is designed as the primary wind pressure resisting element, but testing indicates that the interior gypsum resists significant pressure in walls with WSP sheathing. Previous testing conducted by ATI measured a pressure equalization factor ranging from 0.2 to 0.8[b] for interior gypsum sheathing (walls tested without exterior foam).

a. If rigid foam sheathing joints are taped, it is common practice not to install a separate WRB layer. The WRB function is provided by the system of rigid foam panels and taped joints.

b. Pressure equalization factors (PEF) for exterior and interior sheathings were determined based on visual analysis of plots provided in the ATI report. Therefore, the pressure equalization factors provided in this study for exterior and interior sheathings represent estimates rounded to the closest 0.05, not the actual measured data. The ATI report provides calculated PEF values only for vinyl siding.

Where rigid foam sheathing is installed over and in direct contact with wood structural panels (e.g., OSB), the wind pressure is assumed to be primarily resisted by the wood

[6] Pressure Equalization Factor Project, Report No. 01-40776.01, Research Project Report rendered to Vinyl Siding Institute, September 5, 2002, Architectural Testing, Inc., York, PA.

structural panel. Because the stiffness of the wood structural panel is substantially higher than that of the rigid foam, the foam does not resist substantial loads in these types of assemblies. If an air gap were introduced between the rigid foam and the wood structural panel, the load sharing mechanism would change and the force exerted on the foam sheathing could increase.

There is always some air leakage into the wall cavity (i.e., system porosity) that results in some degree of pressure equalization across the wood structural panels. However, it is typical design practice to assume that the wood structural panels resist the full wind pressure, because the capacity of commonly used wood structural wall panel sizes (i.e., 7/16 inch OSB or ½ inch plywood) typically exceeds the required wind pressure loads.

Siding is a part of the wall system and must resist forces resulting from wind pressure. Because air can penetrate through the joints of lap siding, the pressure gradient across lap siding is substantially lower than the total wind pressure gradient across the wall. The magnitude of the wind pressure resisted by the siding depends on the stiffness of the siding, the air gap between the siding and the adjacent air barrier, the stiffness of the air barrier, and air leakage through the air barrier. All of these factors affect the pressure because they affect the airflow characteristics. The laboratory testing conducted by Architectural Testing, Inc. (ATI) on walls with vinyl siding indicated a maximum pressure equalization factor of 0.18[7], i.e., vinyl siding only experiences 18% or less of the total wind pressure. The significantly lower pressure is the result of airflow behind the siding that equalizes the pressure exerted by the airflow over the siding's exterior surface. Therefore, even though it is not designed as a PER system, the vinyl siding exhibits pressure equalization characteristics across its pressure profile. (Note that these results are limited to unbacked vinyl siding. Foam-backed vinyl siding responds differently and resists higher forces due to the increased stiffness of the siding element.) Similar testing would be of value for systems with brick veneer cladding and other types of siding and installation, to better understand the behavior of such wall systems.

A study conducted by the Forest Product Laboratory[8] measured pressures across the wall in two single-story wood-frame buildings located in southern Florida. The wind speeds observed at the test sites ranged below 18 mph. Both buildings used wood lap siding. The study concluded that the wood lap siding experienced substantial air pressure equalization. The study also indicated that due to leakage of air into the wall cavity, the pressure drop across the interior drywall was of similar magnitude as the pressure drop across the sheathing and the siding. While these observations were made at low wind pressures, the above-mentioned ATI testing suggests that for a given wall system the pressure equalization profile is maintained across a wide range of pressures.

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[7] Pressure Equalization Factor Project, Report No. 01-40776.01, Research Project Report rendered to Vinyl Siding Institute, September 5, 2002, Architectural Testing, Inc., York, PA.

[8] Air Pressures in Wood Frame Walls, Anton TenWolde, Charles G. Carll, Vyto Malinauskas, Forest Product Laboratory, USDA Forest Service, Madison, WI. Published in Conference Proceedings, Buildings VII, December 6-10, 1998, Clearwater Beach, FL. (http://www.fpl.fs.fed.us/documnts/pdf1998/tenwo98a.pdf)

Table 3 - Exterior Rigid Foam Attached Directly to Framing

Layer	Pressure Resistance	Enclosure Function	Discussion
Siding	Designed to resist partial wind pressure	Bulk water control	Because the air flows through the joints and behind the siding, pressure equalization occurs across the siding such that the siding pressure is less than the total pressure gradient across the wall. Previous testing conducted by Architectural Testing, Inc (ATI) measured a maximum pressure equalization factor of 0.18 for vinyl siding.
WRB[a]	Flexible membrane with no resistance to pressure	Bulk water control and air control	May or may not be included in system.
Rigid Foam	Resist a significant amount of wind pressure	Thermal transfer control and air control	Without WSP, the rigid foam becomes the primary exterior air barrier and wind pressure resisting component. Previous testing conducted by ATI measured a pressure equalization factor ranging from 0.17 to 0.5[b] for ½-inch exterior rigid foam sheathing[c].
Framing	Transfers wind pressures to floor and roof diaphragms and foundation	N/A	Provides support for rigid foam sheathing and attachment for sheathing and siding fasteners.
Interior gypsum panels	Resists a portion of the overall pressure	Air barrier	The amount of pressure on the interior gypsum depends on the air leakage into the wall cavity. Previous testing conducted by ATI measured a pressure equalization factor ranging from 0.5 to 0.85[b] for interior gypsum sheathing.

a. If rigid foam sheathing joints are taped, it is common practice not to install a separate WRB layer. The WRB function is provided by the system of rigid foam panels and taped joints.

b. Pressure equalization factors (PEF) for exterior and interior sheathings were determined based on visual analysis of plots provided in the ATI report. Therefore, the pressure equalization factors provided in this study for exterior and interior sheathings represent estimates, not the actual measured data. The ATI report provides calculated PEF values only for vinyl siding.

c. Where the rigid foam relies on the siding attachments to secure the foam sheathing, these attachments must be designed to resist the combined pressure differential across the siding and foam sheathing layer (i.e., 0.18 + 0.5 = 0.68 as a worst case combination of PEF factors determined for the individual siding and sheathing layers per ATI testing).

Where the rigid foam is the primary exterior sheathing (without wood structural panel backing), it resists a substantial portion of the pressure exerted by the airflow. Because the wall system has a certain degree of leakage (i.e., system porosity), the wall cavity will in turn be either pressurized or depressurized, leading to some level of pressure equalization across the rigid foam. The degree of pressure equalization depends on the air leakage into the wall cavity, as well as the stiffness of air barriers and the cavity volume. The wall cavity pressure leads to pressure exerted on the interior air barrier covering, typically gypsum wallboard. Therefore, the pressure is "shared" between the interior and exterior air barriers. However, the fraction of the pressure resisted by each layer may vary in time such that different layers may experience their peak pressures at different times. The degree of pressure sharing between the rigid foam and the gypsum is difficult to accurately predict using available engineering methods. Laboratory and/or field testing are the only options available for accurate evaluation of pressure equalization across multiple air barrier systems.

The wall system variables that affect the pressure equalization characteristics include:

- Stiffness of rigid foam insulation
    - XPS, EPS, ISO
    - Thickness
    - Facings
- Air permeability of the exterior air barrier (i.e., air barrier system porosity)
    - Taped joints vs. untapped joints
    - Air sealing details at top and bottom plates, rim joists, adjacent studs, etc
    - Penetrations from installation of fasteners into the framing
    - Penetrations at mechanical and plumbing entries, and air sealing at such locations
    - Permeability of insulation material
    - Permeability of the facing materials
- Cladding material, its stiffness, attachments, and air permeability
    - Lap siding
    - Insulation-backed vinyl siding
    - Brick veneer
    - Stucco
    - Other
- Gap between the cladding and the exterior air barrier
- Connections of the cladding to backing/framing
- Wall cavity material
    - Spray foam
    - Blown-in insulation
    - Batt insulation
    - Other types of insulation
- Permeability of the interior air barrier
    - Fastening schedule of gypsum (gypsum often not attached at top and bottom plates for crack control)
    - Air sealing at top and bottom plates
    - Penetrations at mechanical and plumbing entries, and air sealing at such locations
- Direction of loading
    - Positive pressure (towards wall) vs. negative pressure (away from wall)

The degree to which these variables affect pressure equalization needs to be better quantified and explained based on an enhanced physical analysis of the entire wall system. In general, the stiffer and less permeable the exterior air barrier is, the lower the pressure equalization will be across the rigid foam sheathing (i.e., higher design pressure). A typical practice in energy-efficient construction is to air-seal the house to reduce air leakage. Different strategies are possible to achieve this goal with layers on both sides of the wall cavity acting as an air barrier. Therefore, test specimens should have air-sealing characteristics typical of the wall construction in the field. In addition, testing a broader range of air-sealing options can be beneficial in understanding the impact of air-sealing practices on pressure equalization effects in light-frame construction.

Direction of loading is another design and testing consideration. Negative wall pressures are always higher than positive wall pressures. For example, in Zone 5 (the first 4 feet from building corners, also see Table 1), negative pressures are about 25% higher than positive pressures and typically control design. However, the wall response is different in the two directions and should be considered separately. In the negative direction, some of the load resisted by the siding is transferred from the siding to the siding fasteners and directly to the framing members, bypassing the sheathing material. In the positive direction, the load transfer mechanism depends on the stiffness of the cladding system. For flexible claddings such as unbacked vinyl siding, the load resisted by the siding is transferred to the sheathing through contact, in addition to the load resisted by the sheathing directly. For more rigid claddings such as brick veneer or foam-backed vinyl siding, some or a significant portion of the positive pressure load is transferred directly from the cladding to the framing through the framing fasteners. For most wall configurations, negative pressure is expected to govern design of the sheathing materials.

Current Design Procedures and Laboratory Test Results

At this time, the only accepted design methodology that includes pressure equalization considerations is the design procedure for vinyl siding covered under ICC-ES AC37 "Acceptance Criteria for Vinyl Siding"[9]. The design procedure is limited to wall configurations with vinyl siding installed over solid sheathing (i.e., wood structural panel), with the solid sheathing resisting the full positive and negative design wind pressures. The AC37 test procedure requires the specimen to be constructed with oriented strand board (OSB) sheathing. The allowable design pressures for vinyl siding are determined in accordance with the design procedure in Annex A1 of ASTM D 3679-09 "Standard Specification for Rigid Poly (Vinyl Chloride) (PVC) Siding"[10] as follows:

$$P_{D-VS} = \frac{P_{Test\,D5206}}{(0.36)(1.5)}$$

Where:

P_{D-VS}	- Allowable design pressure for vinyl siding for direct comparison with wind pressures in Table 1 (i.e., IRC Table R301.2(2))
$P_{Test\,D5206}$	- Direct test pressure applied to vinyl siding measured in accordance with ASTM D5206 (without pressure equalization)
(0.36)	- Pressure equalization factor
(1.5)	- Allowable stress design (ASD) safety factor for vinyl siding

[9] Acceptance Criteria for Vinyl Siding, AC37, July 1, 2009, ICC Evaluation Service, Whittier, CA.
[10] Standard Specification for Rigid Poly(Vinyl Chloride) (PVC) Siding, ASTM D3679, 2009, ASTM International.

The pressure equalization factor in ASTM D3679 is a product of two inputs:

(0.18)	- Maximum pressure equalization factor measured through testing for vinyl siding installed over wood structural panel or rigid foam sheathing (ATI Report No. 01-40776.01, September 5, 2009)
(2.0)	- Safety factor on the pressure equalization effect recommended by ATI and included in ASTM D3679

The ATI report suggested a safety factor of 2.0 with the maximum measured pressure equalization factor for use in the design of vinyl siding. The basis for this safety factor is unclear and it is likely an interim measure put in place at the time to facilitate the adoption of the approach. When combined with the ASD safety factor of 1.5, the total safety factor for the system is 3.0. Such practice of using a separate safety factor for one of the physical characteristics of the assembly is not common in engineering design. A more appropriate method is to establish a pressure equalization property based on statistical analysis of data and apply a single safety factor for the design of an entire assembly or its layers. Therefore, the basis for the current ASTM D3679 approach should be reassessed and re-aligned with the accepted engineering design practices.

The pressure equalization factor (PEF) of 0.18 represents the highest value measured by ATI in a testing program that included a total of 24 wall configurations and three incremental levels of pressure. The test variables are summarized in Table 4. Three repetitions of all 72 unique combinations of test variables were tested for a total of 216 tests. The specimens were tested in a chamber designed to simulate a wind pulse by creating a sudden pressure drop on the exterior side of the specimen. The pressure equalization factors for vinyl siding ranged from 0.03 to 0.18. At the highest pressure drop level (105 psf[11]), the pressure equalization factors ranged between 0.03 and 0.12. For specimens with foam sheathing, the PEF ranged between 0.05 and 0.18. For specimens with plywood sheathing, the PEF ranged between 0.03 and 0.16, indicating no detectable difference in the siding pressure between the two sheathing materials.

[11] The reference pressure drop represents the pressure generated in an auxiliary chamber of the test apparatus. The pressure experienced by the specimen is typically 2 to 5 times lower due to an increase in the total air volume after the auxiliary chamber is open to the test chamber in order to generate a pressure drop across the specimen.

Table 4 – Test Variables (ATI testing program for pressure equalization factors)

Test Variable	Range
Vinyl siding	0.048" thick, double 3 0.048" thick, double 4 0.048" thick, double 5 0.038" thick, double 3 0.038" thick, double 4 0.038" thick, double 5
Sheathing	½ plywood or ½ polystyrene sheathing
Water Resistive Barrier	Installed (*<u>note:</u> the test report does not specify whether it was taped*) Not Installed
Vacuum Chamber Pressure	Level 1: 50 psf (low pressure) Level 2: 75 psf (medium pressure) Level 3: 105 psf (high pressure)

Because the purpose of the ATI report was to measure pressure equalization across vinyl siding, the ATI report does not provide the PEFs for the interior and exterior sheathing layers. Using the reported wall cavity pressure, the ranges of PEFs for the exterior sheathing are summarized in Table 5. There is a wide range of PEFs for both plywood and ½-inch polystyrene sheathing. The highest PEF observed for plywood is 0.76, whereas the highest PEF for ½-inch polystyrene sheathing is 0.44. In both walls with plywood sheathing and ½-inch polystyrene sheathing substantial pressure was imposed on the gypsum wallboard.

The ATI report includes limited analysis of results and does not attempt to explain the reason for such a significant dispersion within configurations (approaching a factor of 3 for plywood without water resistive barrier). Under each of the four configurations summarized below, six different types of vinyl siding were tested. However, analysis of the results as part of this review did not reveal a correlation or a trend between the exterior sheathing PEF and vinyl siding PEF. Therefore, the difference in vinyl siding by itself does not suggest an explanation for the observed ranges in the sheathing PEFs. Other reasons may include air leakage into the wall cavity. It is interesting to note that the variability between the three replicas tested under each of the 24 unique wall configurations was substantially less than the variability between the configurations. This observation suggests that the observed wide range of PEFs may not be all due to random variability.

Table 5 – PEFs for Plywood and ½-inch Rigid Foam Insulation based on ATI Testing

Group	Exterior Sheathing and WRB	PEF Range Across Exterior Sheathing[a]
1	½" Plywood w/o WRB	0.2 – 0.75
2	½" Polystyrene foam sheathing w/o WRB	0.15 – 0.35
3	½" Plywood with WRB	0.45 – 0.75
4	½" Polystyrene foam sheathing with WRB	0.2 – 0.45

a. Pressure equalization factors (PEF) for exterior sheathings were determined based on visual analysis of plots provided in the ATI report. Therefore, the pressure equalization factors provided in this study for exterior and interior sheathings represent estimates rounded to the nearest 0.05, not the actual measured data. The ATI report provides calculated values only for PEFs for vinyl siding.

While 2009 IRC contains prescriptive provisions for walls with foam plastic sheathing (Section R703.11.2) that are based on the pressure equalization effects, there is no generally accepted engineering design methodologies for exterior foam sheathing or other types of sheathing for reduced pressures due to pressure equalization. A design of foam sheathing for the full pressure would not be representative of the system's response and would result in uneconomical solutions for the rigid foam products available on the market today.

A comprehensive design methodology acceptable for application under the IRC and other building codes needs to include:

1) A standardized and appropriately calibrated testing procedure for measuring PEFs for a variety of wall systems
2) A design procedure for wall sheathing layers using PEFs that is coordinated with application of results from the standardized PEF test method and standardized methods for determining static wind pressure resistance of the sheathing and/or siding
3) Performance criteria (strength and deformation) and safety factors for the sheathing materials and the system overall
4) For IRC applications, prescriptive solutions for typical wall systems.

Envelope Performance Design Considerations

Although this paper focuses on structural performance considerations with regard to wind pressure, wall systems also perform enclosure functions including:

- control of bulk-water intrusion
- control of water vapor drive
- control of heat transfer
- control of air movement

In wall assemblies with wood structural panel sheathing, the exterior foam sheathing is primarily performing an enclosure function. In wall assemblies with exterior rigid foam attached directly to studs, the foam sheathing panels perform both structural (wind pressure resistance) and envelope functions. Therefore, the foam sheathing should be designed to maintain its envelope functionality under serviceability levels of structural loading. Performance-based design (PBD) provides a framework and a format that can be used for defining the appropriate design criteria for wall systems. The basic concept of the PBD relevant to this discussion is the definition of clear performance objectives, typically in terms of specific limit states.

Table 6 illustrates the PBD format for design of wall systems for wind pressure. The 10-year and 700-year wind hazard levels correspond to the code minimum design requirements at the serviceability and life-safety levels, respectively. The appropriate return period for enclosure performance design has not been standardized. For the purpose of this white paper, a 50-year wind event is selected as the appropriate hazard level for ensuring uninterrupted performance of the building enclosure. Other return periods should be considered in the future based on specific considerations for building enclosure performance. Table 6 also provides description of each performance level in terms of observed system response and the applicable measure of performance that can be used as pass/fail criteria.

Table 7 compares wind pressures for different wind return periods. The pressure values allow for a more direct comparison of load magnitude between the limits states (as compared to the mapped wind speed values). Review of the results from the ATI testing did not suggest a correlation between the measured PEFs and the absolute pressure (see section *Current Design Procedures and Laboratory Test Results* for more details). Therefore, based on this limited test data it can be suggested that a single PEF factor is appropriate for design of a given assembly at all performance levels. It further can be suggested that the cumulative damage occurred to walls during the first two loading stages did not alter the pressure distribution profile, i.e., there was not a substantial change in air leakage to change the structural response. Additional research is needed to confirm this observation and to understand whether this conclusion can be extended to building enclosure response (i.e., water and air tightness) and to other wall configurations.

Table 6. Performance-based wind pressure design format for wall systems

Performance Level	Performance Criteria	Wind Load Return Period			Description	Design Performance Measure
		10 years	50 years	700 years		
Operational	Deflection	√			All structural and non-structural elements of the wall systems are fully operational. Little or no repair to non-structural elements needed.	Max deflection (L/120 – L/360 depending on type of construction)
Immediate Occupancy	Enclosure functionality		√		The wall envelope elements are functional and building can be continually occupied. Some repair to wall finish elements may be needed.	Systems' ability to maintain air tightness and water tightness
Life Safety	Structural Capacity			√	The wall system is capable of sustaining the load. The envelope function can be compromised. Damage to non-structural elements and some damage to structural elements is expected.	System's ability to sustain load

Table 7. Comparison of wind pressure loads at different performance levels

	Wind Load Return Period		
	10 years	50 years	700 years
Wind speed (non-hurricane prone areas)	75 mph	90 mph	115 mph
Example of components and cladding wind pressure	-13.5 psf	-19.5 psf	-31.8 psf
Wind pressure as a fraction of 700-year event	0.43	0.61	1.0

Summary

The practice of using rigid foam insulation attached directly to studs has been successfully used to improve energy efficiency of walls in many parts of the country. This paper discusses the structural performance aspects of such wall systems in resisting wind pressure. One of the key performance characteristics that should be considered in order to accurately model out-of-plane wall response in wind events is pressure equalization across multiple wall layers. While the concept of pressure equalization is not new, its use for design of wall systems with foam sheathing is in its infancy.

Although the prescriptive provisions of 2009 IRC Chapter 7 Wall Covering continue to allow the practice of using foam as the primary wall sheathing material, debate in the code development forums is expected to continue with regard to the limitations of such wall systems to resist wind pressure. The understanding of the pressure equalization mechanism is important in order to avoid imposing overly restrictive limitations on the use of foam sheathing technology. Limited testing is available to date on such systems with the previous studies focusing primarily on the performance of vinyl siding. The existing data suggests a wide range of pressure equalization profiles across the exterior and interior sheathing panels. Additional laboratory testing is needed to better understand the performance of walls with exterior rigid foam sheathing and to attempt to rationalize the observed range of the responses.

A design method with appropriate performance criteria and a standardized testing methodology are ultimately needed to enable a broad acceptance of the technical justification for the wind pressure resistance profiles. In addition, a long-term research agenda should include validation of laboratory test results through wind tunnel testing and full-size field monitoring studies.

WIND DESIGN CONSIDERATIONS FOR GARAGE DOORS

Issue

In accordance with Figure 6-11 of ASCE 7-05, the magnitude of the external pressure coefficient for components and cladding (GC_p) depends on the *effective wind area*. In turn, the *effective wind area* depends on the size of the component. However, delineating a “component” in a system is not always a straightforward task. If a system is effective in distributing the load between its elements and connections, the *effective wind area* is more accurately represented by the area of a system of multiple components. This increase in the *effective wind area* is justified because the system will be able to redistribute the load from the area where a localized peak pressure occurs to the adjacent areas where the time-correlated pressures are lower, resulting in a satisfactory performance of the overall system. Current methods of applying a uniform pressure to determine strength of a system of components do not provide a means of addressing this issue.

Current Wind Tunnel Test Data

The pressure coefficients in ASCE 7-05 were developed from small-scale wind tunnel tests (see ASCE 7-05 Commentary). Because of components’ small area, pressure fluctuations are highly correlated over the effective area of a component. The induced localized pressures are also highly dependent on the location in the building, height above ground level, exposure, and location of the element relative to the boundaries of the building surface (e.g. building corner). All of these factors are considered in the ACSE 7-05 external pressure coefficients for components and cladding.

The pressure measurements used to develop the coefficients are based on aerodynamic data sets from tests in the University of Western Ontario's Boundary Layer Wind Tunnel Laboratory. The datasets are available in electronic format and the test methods are documented in two reports:

- T.C.E Ho, D. Surry, and D. Mossris. NIST/TTU Cooperative Agreement – Windstorm Mitigation Initiative: Wind Tunnel Experiments on Generic Low Buildings. BLWT-SS20-2003, May 2003. The University of Western Ontario, London, Ontario, Canada.

- T.C.E Ho, D. Surry, and D. Nywening. NIST/TTU Cooperative Agreement – Windstorm Mitigation Initiative: Further Experiments on Generic Low Buildings. BLWT-SS21-2003, September 2003. The University of Western Ontario, London, Ontario, Canada.

Table 8 summarizes tested building configurations and research variables.

Table 8. Wind Tunnel Data Sets

	Plan dimensions, ft x ft	Heights, ft	Roof Slope	Scale
1	125 x 80	16, 24, 32, 40	1:12	1:100
2	125 x 80	16, 24, 32, 40	3:12	1:100
3	125 x 80	12, 18, 24, 32, 40	1:48	1:100
4	62.5 x 40	12, 18, 24, 40	1:12	1:100
5	250 x 160	12, 18, 24, 40	1:12	1:100
6	45x30	13	1:48	1:50
7	45x30	13	1:48	1:100

Suggested Testing Approach for Comparative Performance Using Uniform Loads

Testing is needed to measure the response and failure modes of residential garage doors under a static loading gradient representative of dynamic wind pressure profiles observed in wind tunnel tests. The primary purpose of the testing is to evaluate the load distribution mechanism rather than the peak resistance of the system. Two different loading patterns are suggested to compare the response of the garage door system:

Phase I – Uniform load applied only to the effective wind area of a structural component as defined in accordance with ASCE 7-05 commentary provisions.

Phase II – Uniform load applied over the entire door.

The load distribution profiles can be determined based on the UWO datasets, selected for applicability to residential construction and the objectives of the study. It is important to evaluate pressure gradients over the wall surfaces representative of the area and the location of residential garage doors. A range of garage door variables encompassing a wide range of door sizes are summarized in Table 9. Testing to a selection of door sizes and locations is needed to assess the pressure gradients and their sensitivity to the relevant variables (e.g., building configuration, door size, proximity to building corners).

Table 9. Garage Door Variables

Proximity to building corner, ft	1, 2, 3, 4, 6, 8
Door width, ft	8 - 18
Door height, ft	6 - 9

The system's load-distribution parameter, calculated as follows, can be used to make inferences about the load sharing properties of the system:

$$f_{sys} = \frac{Phase\ I\ (peak\ \ pressure \times pressure\, area)\left(\dfrac{total\ door\ area}{Phase\ I\ \ pressure\, area}\right)}{Phase\ II\ (peak\ load)}$$

If f_{sys} is close to unity, the distribution is minimal and the load is resisted locally. If f_{sys} is greater than unity, a portion of the load is distributed away from the component. For example, if f_{sys} equals two, half of the load is resisted by the components outside of the Phase I loading area (i.e., conservative effective wind area).

The concept employed in this task is similar to the concept of "influence area" used to determine reductions in live loads.

A full-size door (e.g., 16 foot wide by 7 foot high door) should be tested as flexibility of the door system increases with size (more flexible systems typically have poorer load sharing characteristics). Based on the results of the first configuration, other door sizes/configurations may be considered to capture the range of responses as affected by the door size. Results of the positive pressure tests should be reviewed for a need to conduct tests in the negative direction to enable generalized conclusions on the system performance in both directions. Testing in both positive and negative directions may be needed depending on the door characteristics.

Summary

The current commentary language of ASCE 7-05 suggests that a garage door consists of individual components that do not act as a system. Therefore, the effective wind area is determined based on the individual component, not the entire area of the door or some significant portion of the door area. To enable an ASCE 7-05 change, structural testing of full-size garage doors is needed. A testing protocol including loading procedure and instrumentation needs to be designed to evaluate the garage door's ability to effectively redistribute the load between its structural components and connections.

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