Evaluation of the Lateral Performance of Let-in Bracing and Mixed Bracing Systems

EG5736_052908

May 29, 2008

NAHB RESEARCH CENTER

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INTRODUCTION

This testing program is designed to measure the performance of conventional bracing systems including wood let-in bracing, gypsum wallboard, and wood structural panels. The purpose of the study is to better understand how these bracing methods work as part of a system and in combination with each other. Although these bracing methods have been studied in the past, recent re-evaluation of testing procedures and analytical approaches for establishing prescriptive wall bracing requirements raised new questions related to the interaction of these materials with each other and with the rest of the structure. Some of the new concepts that have been recently introduced include the continuous sheathing methods of wall bracing, partial restraint conditions, interaction of dissimilar materials, and contribution of finish materials to the structure's performance. This study provides information towards reconciling the traditional bracing methods, their historic use and performance, and the new approaches to analyzing prescriptive wall bracing provisions.

The specific objectives of the testing program include:

- Evaluation of the performance of let-in bracing with and without interior gypsum sheathing and with varying degrees of overturning restraint.
- Evaluation of the applicability of the perforated shear wall equations to gypsum sheathing used in combination with let-in bracing.
- Evaluation of the effect of finishes, such as interior gypsum sheathing and windows, on the performance of a single, isolated wood structural panel braced wall segment.

BACKGROUND

This section summarizes results of two studies that evaluated the performance of let-in braces.

NAHB RESEARCH FOUNDATION (1971)

The purpose of the testing conducted by the NAHB Research Foundation was to recommend performance criteria for racking resistance based on the evaluation of the performance of 11 exterior wall configurations commonly used in construction at the time. Four of these configurations included let-in bracing of various grades and species of lumber. The remaining balance of the wall configurations tested utilized different thicknesses of exterior fiberboard sheathing. Stud sizes and spacing varied throughout the wall configurations. All walls were sheathed on the interior with gypsum wall board nailed at 8 inches on center with joints fully taped and mudded. Testing was done in accordance with ASTM E 72. The tested strength of the exterior wall configurations with a single let-in brace ranged from 3,560 lbs to 4,920 lbs.

The Research Foundation also submitted a series of recommendations/criteria for the acceptability of exterior wall configurations to be used to resist racking loads. For any proposed exterior wall configuration, 8 foot long specimens were to be tested using ASTM E 72 and required to achieve the greater of an ultimate load of 3,600 lbs or three times the design wind load. The criteria also limited the wall's deformation and deformation set (i.e., residual deformation) at two load levels: the greater of 1,200 lbs or one times the design wind load and the greater of 2,400 lbs or two times the design wind load.

TUOMI AND GROMALA (1977)

The testing done by Tuomi and Gromala investigated the effects of changes in testing procedures such as loading rate on the overall racking performance of braced walls. Tuomi and Gromala also developed various energy based equations to predict the racking strength of both sheathed walls and walls using let-in bracing.

Seven of the configurations utilized let-in bracing as the method of resisting racking forces, six where the brace was let into the top and bottom plates and tested in compression, and one where the brace was let into the end wall studs and tested in tension. The wall studs consisted of Douglas Fir No. 2 or better grade lumber and were spaced at 16 inches on center. The bracing material was 1 x 4 inch boards consisting of three different species of wood, White Pine, Southern Pine and Sugar Pine. Braces were attached at each end and at every stud with two 8d common nails. No sheathing was used in conjunction with the let-in bracing. All testing was done in accordance with ASTM E 72.

The results of the testing showed that for the configurations where the brace was subject to compression, racking strengths varied from 2,350 lbs to 4,450 lbs, with an average strength of 3,183 lbs. It should be noted that these ranges included the results from each of the three different species of bracing lumber. For the single test with the brace in tension, the racking strength was at 1,900 lbs. The authors also noted the results of unpublished previous testing of walls framed with let-in braces and sheathed with horizontal boards. Where horizontal board sheathing was installed on the same side as the brace and acted to restrain the brace against buckling, the specimen reached a peak load of 6,050 lbs. Where horizontal board sheathing was installed on the side opposite of the let-in brace, the peak load was at 5,450 lbs.

METHODS AND MATERIALS

Specimens were fabricated and tested at the NAHB Research Center Laboratory facility located in Upper Marlboro, Maryland. Lumber, gypsum board, OSB panels, fasteners, and hardware were all purchased from local suppliers.

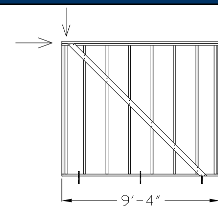
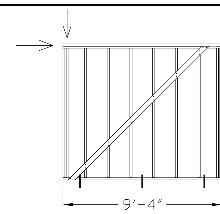
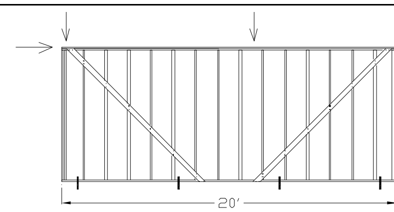
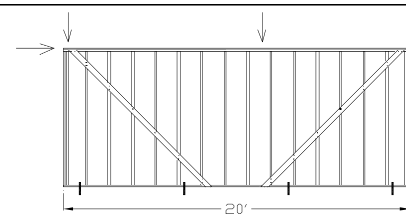
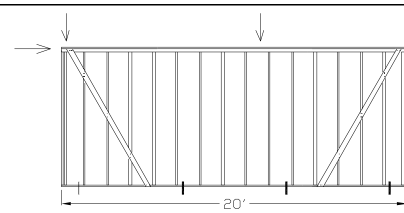
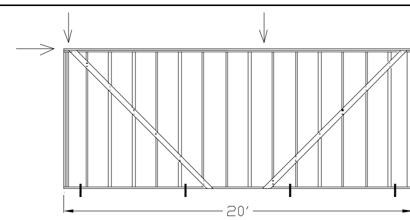
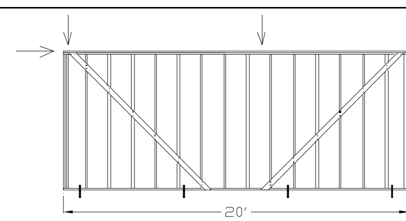
Tables 1, 2, and 3 summarize the test matrix with details specific to each individual test. A purpose statement is also included for each test configuration. Configurations 1-7 were designed to test the response of fully restrained let-in braced wall systems. Configurations 8-12 were designed to evaluate the performance of partially restrained let-in braced systems by using holddowns and stud strapping. Configurations 13 and 14 were used to evaluate the performance of perforated interior gypsum shear walls with let-in bracing. Configurations 15-18 were designed to evaluate the added contribution of finishes, such as gypsum sheathing and windows, on the performance of a single isolated wood structural panel.

All specimens were 8 feet tall and ranged in length from 9 feet 4 inches up to 24 feet. A stud height of 91.5 inches was used in combination with a double top plate and single bottom plate to obtain the overall specimen height of 8 feet. The interior gypsum board nailing schedule was selected from IRC Table R702.3.5. For Configuration 6, blocking was provided at the top plate and sides of the specimen to provide a bearing surface for the gypsum to simulate in-situ conditions. For all specimens, the bottom edge was raised from the bottom of the wall to allow rotation. Tables 4 and 5 summarize the materials and fastening schedules.

The let-in braces were installed flush with the bottom plate. At the double top plate, each let-in brace extended only into the lower plate. Gypsum sheathing was always raised by ½ inch from the bottom edge of the wall. The distribution fixtures used to apply the load onto the specimen was always installed such that it did not interfere with the sheathing materials during testing.

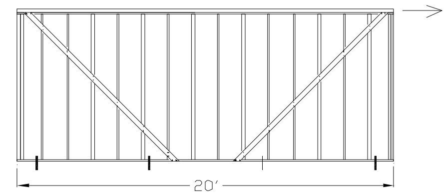
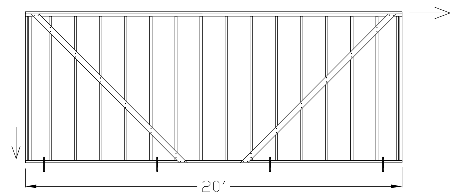
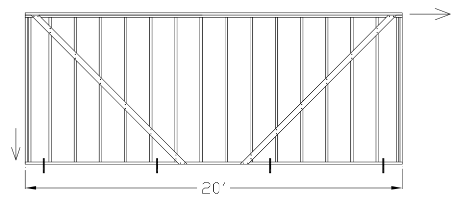
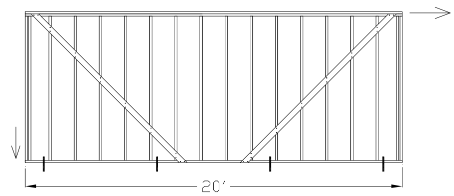
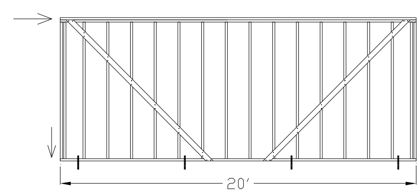
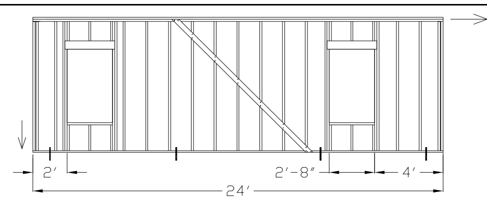
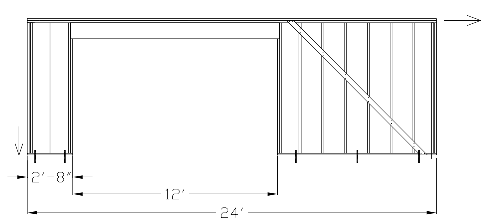
Moisture content of lumber during fabrication and testing ranged from 8 to 12%. All framing nails were installed using a pneumatic nail gun except that the let-in brace nails were installed using a handheld hammer. OSB sheathing nails were installed using a pneumatic nail gun. Gypsum board sheathing nails were installed using a handheld hammer.

Table 1 – Test Matrix—Fully Restrained Systems (Let-in Brace, Gypsum)

Conf. #	Description	Restraint[1]	Interior Finish	Purpose	Diagram[1]
1	Let-in brace @ 45° loaded in compression	Full – E72	None	Establish baseline for compression, fully restrained	
2	Let-in brace @ 45° loaded tension	Full – E72	None	Establish baseline for tension, fully restrained	
3	Let-in brace @ 45° tension and compression	Full – E72	None	Performance of combination of opposing braces	
4	Let-in brace @ 45° loaded in tension and compression with gypsum	Full – E72	Gypsum fully attached with mudded joints	Measure contribution of gypsum	
5	Let-in brace @ 60° loaded in tension and compression with gypsum	Full – E72	Gypsum fully attached with mudded joints	Effect of 60° brace	
6	Let-in brace @ 45° tension and compression with gypsum	Full – E72	Gypsum, floated, with mudded joints	Measure contribution of gypsum with floating joints	
7	Let-in brace @ 45° tension and compression with gypsum on both sides	Full – E72	Gypsum fully attached with mudded joints	Measure contribution of gypsum when installed on both interior and exterior of wall	

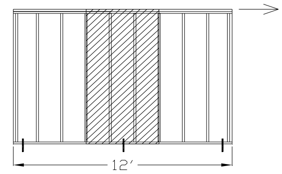
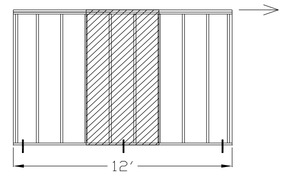
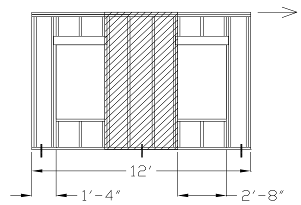
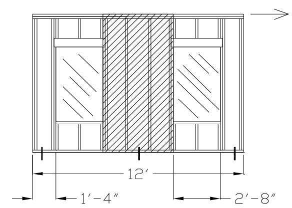
1. See Table 6 for description of restraint condition. The vertical arrows at top of wall indicate location of tie-rod overturning restraints per ASTM E72. The horizontal arrow at the top wall corner indicate direction and location of loading.

Table 2 – Test Matrix—Partially Restrained Systems and Combined Perforated Walls (Let-in Brace, Gypsum)

Conf. #	Description	Restraint[1]	Interior Finish	Purpose	Diagram[1]
8	Let-in brace @45° loaded in tension and compression	Low bound (No holddown, no strapping, no distrib. beam)	Gypsum fully attached with mudded joints	Measure the performance of combination of braced with varying degrees of restraint	
9	Let-in brace @45° loaded in tension and compression	20% (no strapping, no distrib. beam)			
10	Let-in brace @45° loaded in tension and compression	30% (strap at each stud with 1-6d nail, no distrib. beam)			
11	Let-in brace @45° loaded in tension and compression	30% (strap at every other stud with 1 drywall nail, no distrib. beam)			
12	Let-in brace @45° loaded in tension and compression	60% (strap at each stud with 2-6d nail, distrib. beam)			
13	Let-in brace @45° loaded in compression with gypsum and window openings	Full – E564 (distribution beam, no strapping)		Performance of gypsum with perforations and let-in brace in combination	
14	Let-in brace @45° loaded in compression with gypsum with door openings	Full – E564 (distribution beam, no strapping)		Performance of gypsum with perforations and let-in brace in combination	

1. See Table 6 for description of restraint condition. The vertical arrows at bottom corners indicate location of holddowns. Holddowns were not installed at openings or at the wall end subject to compression force. The horizontal arrows at the top wall corner indicate direction and location of loading.

Table 3 – Test Matrix—Isolated OSB Braced Wall Panel with Minimum Restraint – Effect of Finishes

Conf. #	Description	Restraint[1]	Interior Finish	Purpose	Diagram[1]
15	Single 4' x 8' wood structural panel	Minimum (no distrib. beam, no strapping, no HD)	Single 4' x 8' gypsum panel opposite face of wood structural panel	Baseline for isolated wood structural panel tested as part of a 12-foot framed assembly	
16	Single 4' x 8' wood structural panel with gypsum	Minimum (no distrib. beam, no strapping, no HD)	Gypsum fully attached and with mudded joints entire 12 foot length	Measure the contribution of gypsum	
17	Single 4' x 8' wood structural panel with gypsum and window openings	Minimum (no distrib. beam, no strapping, no HD)	Gypsum fully attached and with mudded joints	Measure the contribution of gypsum in a perforated wall assembly	
18	Single 4' x 8' wood structural panel with gypsum and windows installed	Minimum (no distrib. beam, no strapping, no HD)	Gypsum fully attached and with mudded joints	Measure the contribution of gypsum and windows	

1. See Table 6 for description of restraint condition. The horizontal arrows at the top wall corner indicate direction and location of loading.

Table 4 – Materials and Wall Construction

Wall height:	8 feet
Wall width:	per test matrix (Tables 1, 2, 3)
Openings:	Windows: 32 inches x 54 inches rough opening Door: 12 feet x 81-3/4 inches rough opening (garage door)
Framing lumber:	2x4 SPF STUD Grade studs, (2)-2x4 corner studs 2x4 SPF #2 Grade plates 1x4 #1 Pine brace (unless otherwise specified in text) (grade is nonstructural, structural grade not assigned), recessed into framing except upper top plate (2)-2x4 SPF #2 top plates 2x4 SPF #2 bottom plate (2)-2x6 SPF #2 headers – Configuration 13, 17, 18 (2)-2x12 SPF #2 headers – Configuration 14
Stud Spacing:	16 inches o.c.
Interior Sheathing:	1/2 inch gypsum wallboard per test matrix (Tables 1, 2, 3) installed horizontally, unblocked
Exterior Sheathing:	7/16 inch OSB panels per test matrix (Tables 3)
Anchor bolts:	1/2 inch diameter bolts with round cut washers spaced a maximum of 6 feet on center and located at 12 inches from ends of sill plate See Tables 1, 2, 3 for approximate bolt locations
Fastener edge distance:	At brace end: 3/4 inch At gypsum: 1/2 inch except 3/8 inch at butt joints At wood structural panel: 1/2 inch at top and bottom plates
Gypsum panel joints:	Taped and mudded per test matrix (Tables 1, 2, 3)
Windows	32 inch x 54 inch nominal; Single-Hung; Vinyl; EnergyStar; Manufacturer: Pella
Holddown	HTT16 where specified

Table 5 – Fastening Schedules

Connection	Fastener	Spacing
Top plate to top plate (face-nailed)	10d pneumatic (3" x 0.128")	24 inches on center
Top/bottom plate to stud (end-nailed)	(2)-16d pneumatic (3.25" x 0.131")	per connection
Stud to stud (face-nailed)	10d pneumatic (3" x 0.128")	24 inches on center
Double header with ½" spacer	16d common (3.5" x 0.135")	16 inches on center along each edge
Let-in brace	(2)-8d common (2.5" x 0.131")	Per each intersecting stud and plate
Holddown	16d common (3.5" x 0.161"), number of nails per Table 6	per holddown
Gypsum	13 gage (D=0.095"), 19/64" head diameter, 1-5/8" long, drywall nail; all joints are taped and mudded	8 inches on center, all studs and plates
Gypsum (floated)	13 gage (D=0.095"), 19/64" head diameter, 1-5/8" long, drywall nail; all joints are taped and mudded	8 inches on center (Nails at all studs except end studs, gypsum not attached at top and bottom plates)
Wood Structural Panels	8d common (2.5" x 0.131")	6 inches around the edges 12 inches in the field

Varying overturning restraint conditions were provided in accordance with Table 6. A partial degree of restraint was provided using an HTT16 holddown bracket with the number of nails installed equal in capacity to the full overturning restraint adjusted by the partial effect (20%, 30%, or 60%). The full overturning force was estimated based on the results of the baseline tests. In addition, for Configurations 10, 11, and 12 with 60% and 30% restraint, studs were tied to the top and bottom plate with a 20-gage steel strap nailed per Table 6 to simulate the local gravity load from framing members above and the stiffness of the diaphragm. For the 30% restraint condition, two attachments of the stud to plate were evaluated to measure the degree of sensitivity of the results to the effects of local gravity load and stiffness. Where full E564 restraint is specified, an HTT16 holddown bracket was installed with all nails in accordance with manufacturer's specifications. Where full E 72 restraint was used for walls longer than 8 feet, a second overturning restraint was provided at 11 feet from the specimen corner (Figure 2). Bottom plates were anchored to the setup using 1/2-inch-diameter bolts spaced not more than 6 feet on center and located 12-inches from the corners and door openings. Specimen diagrams in Tables 1, 2, and 3 show approximate locations of bolts with respect to wall ends, openings, and let-in braces.

Table 6 – Overturning Restraint Conditions

Degree of overturning restraint	Details
Full restraint – E72	4x4 steel tube loading beam (0.25-inch wall thickness) Tension rods per E72
Full restraint – E564	4x4 steel box loading beam HTT16 holddown @ uplift end, all nails per Simpson specifications
60% restraint	4x4 steel tube loading beam HTT16 holddown with only 6-16d common nails installed Each stud is attached to plates with a 20 gage metal strap nailed with two nails (D=0.113", L=2.5")
30% restraint	No loading beam Load is applied in tension with a small bracket through the double top plate HTT16 Holddown with only 3-16d common nails installed Two options for attaching studs to plates: 1) each stud attached to plates with a 20 gage metal strap nailed with one nail (D=0.113", L=2.5") 2) every other stud attached to plates with a 20 gage metal strap nailed with one gypsum nail (D=0.095", L=1-5/8")
20% restraint	No loading beam Load is applied in tension with a small bracket through the double top plate No strapping HTT16 Holddown with only 2-16d common nails installed
Minimal restraint	No loading beam Load is applied in tension with a small bracket through the double top plate No strapping No holddown (overturning resistance provided by anchors bolts only)

Testing was conducted in accordance with the general provisions of ASTM E 72-05 *Standard Test Methods of Conducting Strength Test of Panels for Building Construction* (ASTM International, 2005), or ASTM E 564-06 *Standard Practice for Static Load Test for Shear Resistance of Framed Walls for Buildings* (ASTM International, 2006), depending upon the degree of vertical restraint required per the test matrix.

Figure 1 shows a schematic of the test setup used for configurations 3-7 to illustrate the location of the instrumentation and loading apparatus. Figure 2 shows a photograph of the test setup.

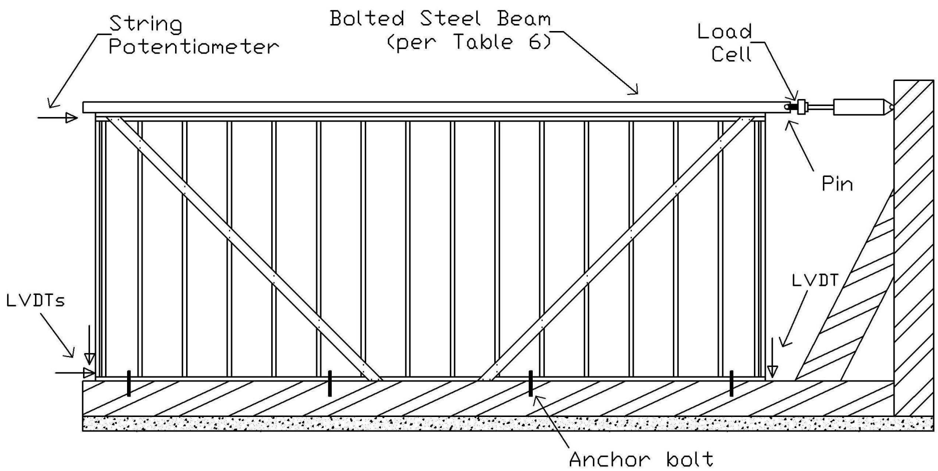


Figure 1 – Shear Wall Test Setup
(Boundary conditions not shown – see Table 6 for description of various boundary conditions)

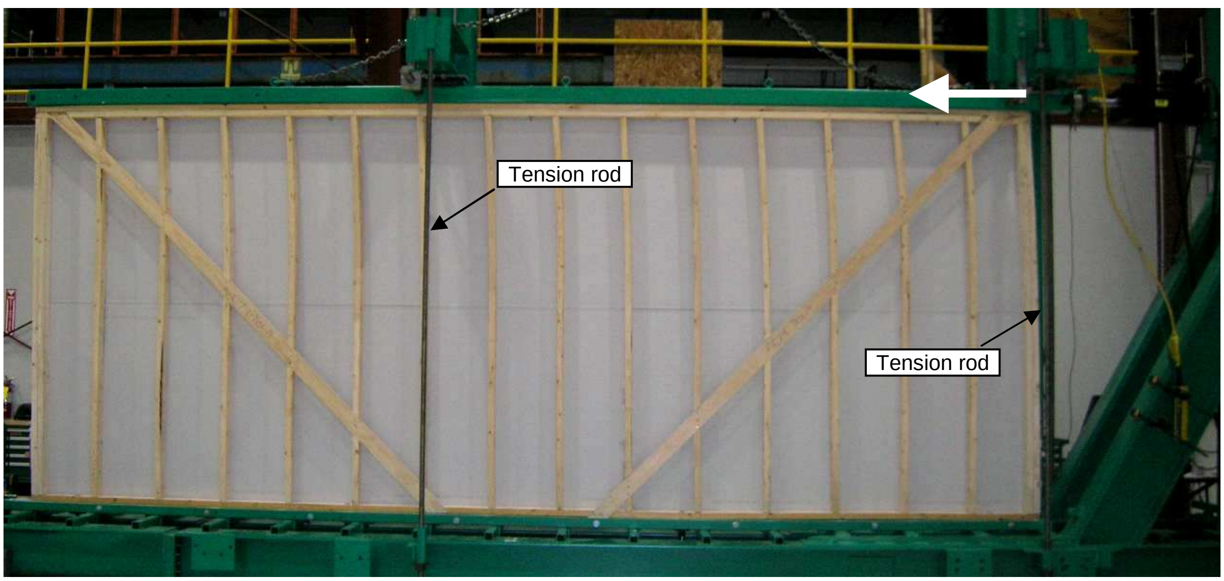


Figure 2 – Shear Wall Test Specimen
(Configuration 4, full E-72 restraint)

Testing was conducted using a racking shear testing apparatus controlled via a computer-based system. Instrument readings including load and deflection measurements were recorded using a computer-based data acquisition system.

Specimens were tested monotonically using a hydraulic actuator to apply load to the top of the wall at a constant rate of 1.0 inch per minute in a single cycle. This loading rate is based on recommendations of the IRC Sheathing Task Group[1]. Cyclic testing was not conducted because the evaluation was not intended for high seismic applications. For Configurations 1 through 7

[1] The IRC Sheathing Task Group is an ad hoc committee of industry experts that met several times in 2006, 2007, and 2008 to discuss issues related to wall bracing including testing procedures for applications with the IRC provisions. This group also provided technical advice to an ICC Ad Hoc Committee on Wall Bracing.

and 12, the load was applied in compression using a 4 inch x 4 inch steel box beam running the full length of the wall and bolted through both top plates with 1/2 inch through bolts at approximately 4 feet on center. For Configurations 13 and 14, the load was applied in tension using the same 4 inch x 4 inch box beam attached in the same fashion. For configurations 8 through 11 and 15 through 18, the load was applied in tension using a steel loading bracket attached to the top plate at the top corner of the specimens. The loading bracket consisted of a 1/4-inch-thick, 20-inch-long steel strap fastened to the specimen with wood lag screws. Testing was done to failure of the specimen, defined as a drop in capacity of the wall equal to 20% of the peak load.

Load was measured using a 20,000 lbs capacity electronic load cell located between the cylinder and either the steel distribution beam or loading bracket. The following deformations were measured using a string potentiometer and Linear Variable Differential Transformers (LVDT):

1) Displacement of the top plate relative to the setup base
2) Bottom plate slip relative to the setup base
3) Compression at the specimen corner stud relative to the base
4) Uplift at the specimen corner stud relative to the base

Anchor bolt tension forces were measured using 20,000 lbs capacity electronic compression load cells. Anchor bolts were pretensioned to 500 lbs.

Slip of the bottom plate was subtracted from the global wall deformation.

RESULTS

Fully Restrained Systems (Let-in Brace, Gypsum)

Results of the testing are summarized in Table 7 including peak load and displacement of the top of the wall at the peak load. Appendix A includes load-deflection charts for all specimens.

Configuration 1 and 2 tests were conducted to establish a baseline for let-in bracing in tension or compression without the contribution of gypsum. A total of four Configuration 1 specimens were tested with various modifications. In the first test, the let-in brace was attached to studs and plates with two 8d common nails. The primary failure mode was buckling of the brace and separation of the brace from the studs (Figures 3 and 4). It should be noted that 1 x 4 lumber is not commercially available in structural grade. The bracing material used in the first test had a specific gravity of 0.35. To investigate the performance of a system with a stronger brace, a 2 x 4 #2 Grade SPF stud was machined to the actual size of 0.75 inches and used as a brace in the second test. The strength of the system increased from 2,570 lbs to 3,170 lbs as a result of a stronger brace material; the failure mode changed to a shear plug failure at the top plate (Figure 5).

In the next test, non-structurally graded 1x4 nominal lumber from a different batch with a specific gravity of 0.44 was used. In addition, in an attempt to reduce the potential for another shear plug failure, the brace was attached to the plates with three nails instead of two nails. The peak load for this system was at 2,760 lbs with another shear plug at the top plate as the primary failure mode. In the next test, the brace was shifted 6 inches from the corner of the top plate (compared to the standard detail at 3.5 inches) to further reduce the shear plug failure potential. The system failed at 2,415 lbs due to the brace buckling out of the plane of the specimen over multiple stud bays with nails pulling out of the studs (Figure 6).

In summary for Configuration 1, the system with two nails per compression brace to framing connection can be described as balanced with each individual improvement over this baseline triggering a different failure mode with only a slight improvement in the system's capacity. It also should be noted that all specimens without sheathing showed some twisting of the studs during the tests (Figure 3). This behavior was less evident in later tests where gypsum was attached on the opposite face.

Configuration 2 tests provide a benchmark for a let-in brace in tension without gypsum sheathing. A total of three specimens were tested. The first two specimens used two 8d nails at each stud and plate. The primary failure mode was yielding of nail connections at the top and bottom plates (Figures 7 and 8). The peak load was 1,170 and 1,400 lbs In the third specimen, three nails were installed at the bottom and top plates in an attempt to strengthen this connection. The same failure mode was observed with the peak load at 1,400 lbs, which indicated that there was not a substantial improvement in performance over the configuration with two nails.

Configuration 3 was tested to evaluate the performance of a system with two opposing braces including deformation compatibility of tension and compression braces in the same braced wall line. A total of 4 specimens were tested with several modifications. The first specimen (baseline) used two nails per each brace to frame connection. The second specimen used three nails at the brace to top and bottom plate connections. For the third specimen, the brace was also shifted by 6 inches from the corner. The last specimen also used three nails at each brace-to-frame connection reaching the maximum peak load of 4,486 lbs. This peak load corresponds to a 280 lb/ft unit shear. Failure modes and general observations were similar to those for tests with single braces. Based on comparison with results from Configurations 1 and 2, it can be generalized that the resistance of a compression and a tension brace is additive for estimating the resistance of a system with two opposing braces.

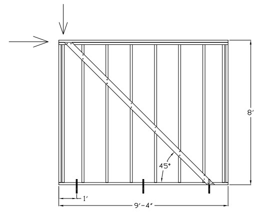
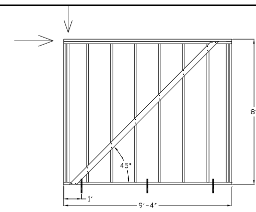
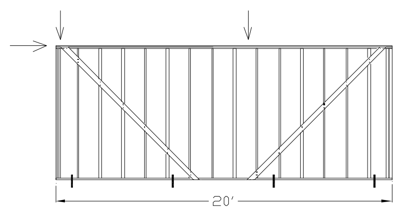
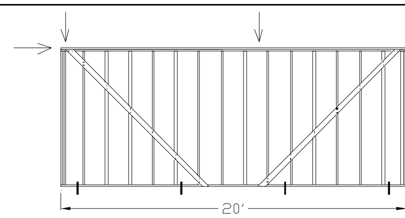
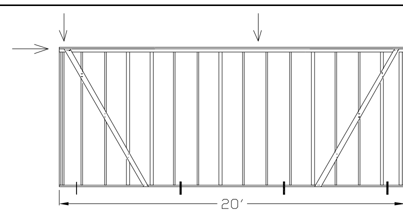
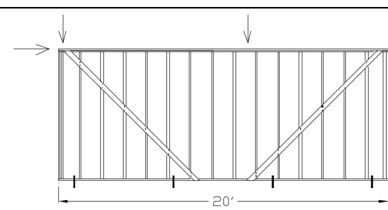
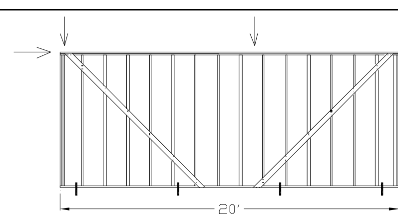
Configuration 4 measured the contribution of gypsum to the performance of the system with two opposing braces (Figure 9). A total of two identical specimens were tested with braces attached using two nails per connection. The average peak load was 8,450 lbs. The gypsum sheathing to framing connections showed degradation, particularly at the edges (Figure 10). The joints between the gypsum panels also failed (Figure 11). Comparing to the first Configuration 3 test, the contribution of gypsum was 4,550 lbs for the entire wall or 227 lb/ft. The average unit shear for a combination of two opposing let-in braces with the gypsum on the interior face was 470 lb/ft (note that this value is based on the let-in brace segment nominal width of 8 feet and is adjusted from the Configuration 4 test value to exclude the contribution of gypsum in the segment between the braces).

Configuration 5 measured the performance of a system with braces installed at a 60 degree angle and sheathed with gypsum on the opposite face. The peak load was 6,275 lbs; this is a 35% reduction compared to a system with braces at 45 degrees.

Configuration 6 measured the effect of floating joints. The gypsum was not attached around the specimen perimeter, neither at the top and bottom plates nor at the corner studs. At interior studs, the first nail was placed 8 inches inside the perimeter from the top and bottom edges. The gypsum was bearing at the top plate and corners on wood framing (Figures 12 and 14) to replicate boundary conditions from the adjacent perpendicular walls and the ceiling. The gypsum panels were raised from the edge of the bottom plate as with the previous tests. The peak load was 6,745 lbs; this is a 25% reduction compared to a system with gypsum nailed around the perimeter. As with previous tests, the failure modes included buckling of let-in brace (Figure 13) and degradation of gypsum to framing connections. At the compression corner, force was also transferred through bearing of gypsum on the boundary framing members (Figure 14).

Configuration 7 measured the performance of a system with two opposing braces and gypsum installed on both sides. The observed peak load of 15,120 lbs was 16% above the load that could be predicted solely based on doubling the performance of single-sided systems (i.e., Configuration 4). The increase in capacity for a double-sided system can be the result of the installation of the gypsum panels on the opposite face directly against the let-in brace. This installation provides additional restraint of the brace against buckling.

Table 7 – Test Results—Fully Restrained Systems (Let-in Brace, Gypsum)

Conf. #	Description	Restraint[1]	Interior Finish	Diagram[1]	Peak Load, lb	Notes
1	Let-in brace @ 45° loaded in compression	Full – E72	None		2,570	
					3,175	SPF #2 lumber (machined to 1x4)
					2,765	3-8d nails at plates
					2,415	3-8d nails; brace shifted 6 inches
2	Let-in brace @ 45° loaded tension	Full – E72	None		1,175	
					1,410	
					1,410	3-8d nails at plates
3	Let-in brace @ 45° tension and compression	Full – E72	None		3,915	None
					3,830	3x8d per brace/plate
					4,195	Brace offset 6", 3x8d at plates
					4,485	Brace offset 6", 3x8d at plates & studs
4	Let-in brace @ 45° loaded in tension and compression with gypsum	Full – E72	Gypsum fully attached with mudded joints		8,360	Brace offset 6"
					8,555	Brace offset 6"
5	Let-in brace @ 60° loaded in tension and compression with gypsum	Full – E72	Gypsum fully attached and mudded		6,275	
6	Let-in brace @ 45° tension and compression with gypsum	Full – E72	Gypsum floated, mudded, bearing at top and corners		6,745	
7	Let-in brace @ 45° tension and compression with gypsum on both sides	Full – E72	Gypsum fully attached with mudded joints		15,120	

1. See Table 6 for description of restraint condition. The vertical arrows at top of wall indicate location of tie-rod overturning restraints per ASTM E72. The horizontal arrow at the top wall corner indicate direction and location of loading.

Figure 3 – Configuration 1

Figure 4 – Configuration 1-1

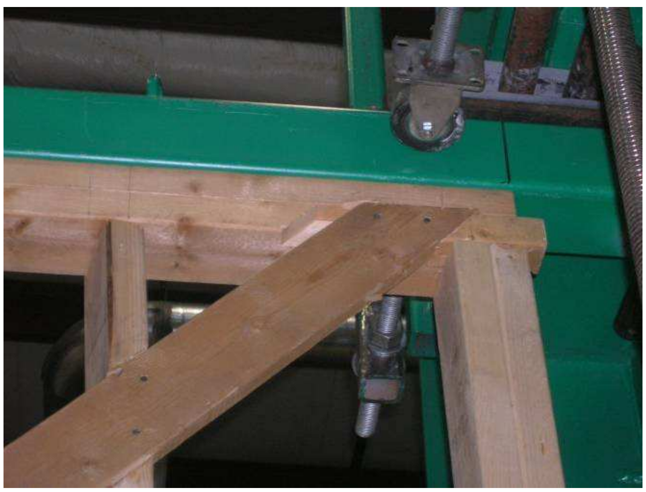


Figure 5 – Configuration 1-2

Figure 6 – Configuration 1-3

Figure 7 – Configuration 2 at Top Plate

Figure 8 – Configuration 2 at Bottom Plate

Figure 9 – Configuration 4

Figure 10 – Configuration 4 (Gypsum connections at corners)

Figure 11 – Configuration 4 (Degradation of gypsum joints)

Figure 12 – Configuration 6 (Boundary conditions)

Figure 13 – Configuration 6 (Let-in brace buckling)

Figure 14 – Configuration 13 (Contact of gypsum at the corner)

Partially Restrained Systems and Combined Perforated Walls (Let-in Brace, Gypsum)

Table 8 summarizes the test results. Configurations 8 through 12 were tested to establish the effect of partial restraint on the performance of the system. The performance was evaluated at several levels of restraint below the full restraint. Details of the boundary conditions at each level are summarized in Table 6. The average fully restrained baseline value of 8,450 lbs from Configuration 4 tests was used in the evaluation. At the minimal restraint restraint, the system developed 54% of its full capacity. At 20% of full restraint the system developed 76% of its full capacity. At 30% and 60% of full holddown restraint, the system developed 87% and 93% of its full capacity, respectively. These results indicate that let-in brace systems have significant capacity even with only a minimum overturning restraint and their performance improves significantly with partial overturning restraint that is present in a full structure. Figures 15-18 show typical failure modes for partially restrained walls.

Configurations 13 and 14 were tested to measure the effect of let-in bracing on the response of gypsum wallboard perforated walls. The peak loads for these configurations were 5,600 lbs and 3,600 lbs, respectively. Figures 19-22 show the typical failure modes. In Configuration 13, with window openings, the primary failure mode was associated with gypsum failure at the window corners due to tension or compression stress concentrations.

Based on results of Configuration 3 and 4 tests, the contribution of gypsum in a fully-restrained 20-foot wall is 227 lb/ft. This unit shear is also in general agreement with the nominal unit shear capacity of 200 lb/ft for unblocked shear walls with gypsum attached using nails at 7 inches on center (AF&PA 2005). Applying the perforated shear wall method (Sugiyama and Matsumoto, 1994) to Configuration 13 based on 227 lb/ft, the predicted capacity of the gypsum-only wall is 3,675 lbs[2]. Including the let-in brace in compression at 2,500 lbs results in a total predicted load of 6,175 lbs – 9% higher than the measured peak load of 5,620 lbs. The difference, in part, can be explained by the difference in the holddown restraint for the let-in brace located within the middle portion of the wall. This conclusion is also supported by the observed wall's response that included a noticeable uplift deformation of the wall section located between the windows (Figure 21). To achieve agreement between the predicted and the tested capacity for Configuration 13, the let-in brace compression resistance should be reduced from 2,500 lbs to 1,945 lbs – a 22% reduction (i.e., 0.78 multiplier).

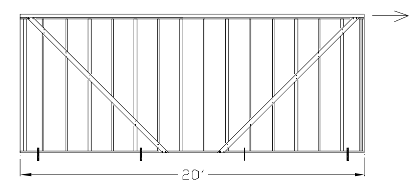
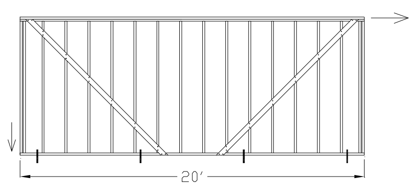
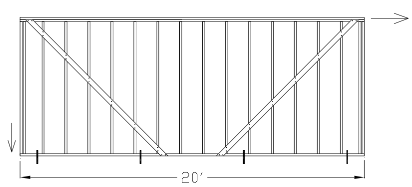
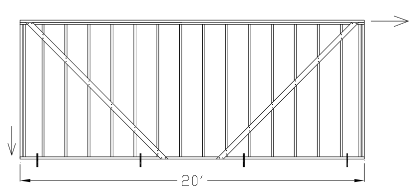
Applying the perforated shear wall method to Configuration 14, the predicted capacity of the gypsum-only wall is 1,533 lbs. With the let-in brace in compression at 2,500 lbs, the total

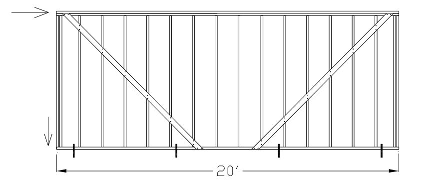
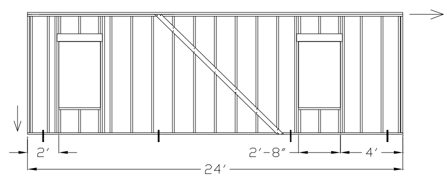
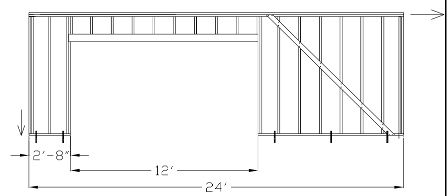
[2] Example of the perforated shear wall method calculations for Configuration 13:
Wall length: 24 ft   Wall height: 8 ft   Total area of openings: (2) (32x54) / 144 = 24 ft^2
Total length of full height segments: (24 ft) – (5.33 ft) =18.7 ft
Sheathing area ratio: (1) / (1 + 24 ft^2 / 8 ft / 18.7 ft)) = 0.86
Perforated shear wall reduction factor: (0.86) / (3-2(0.86)) = 0.68
Estimated perforated shear wall capacity: (227 lb/ft) (24 ft) (0.68) = 3,675 lbs

predicted load is 4,033 lbs – 11% higher than the measured peak load of 3,597 lbs. To achieve agreement between the predicted and the tested capacity for Configuration 14, the let-in brace compression resistance should be reduced from 2,500 lbs to 2,065 lbs – an 17.4% reduction (i.e., 0.826 multiplier).

In summary, the testing of let-in braces within perforated gypsum assemblies demonstrated that, where the brace is located away from the wall corner, an adjustment for partial restraint of that segment needs to be included to allow superposition of the two bracing methods. Analysis of the results indicates that on average a 0.80 multiplier provides a good agreement with the test data.

Table 8 – Results—Partially Restrained Systems and Combined Perforated Walls (Let-in Brace and Gypsum)

Conf. #	Description	Restraint	Interior Finish	Diagram	Peak Load, lbs	Ratio to baseline of 8,450 lbs
8	Let-in brace @45^o loaded in tension and compression	Low bound (No holddown, no strapping, no distrib. beam)	Gypsum fully attached with mudded joints		4,439 4,731	0.54
9	Let-in brace @45^o loaded in tension and compression	20% (no strapping, no distrib. beam)	Gypsum fully attached with mudded joints		6,428	0.76
10	Let-in brace @45^o loaded in tension and compression	30% (strap at each stud with 1-6d nail, no distrib. beam)	Gypsum fully attached with mudded joints		7,656 6,896	0.86
11	Let-in brace @45^o loaded in tension and compression	30% (strap at every other stud with 1 drywall nail, no distrib. beam)	Gypsum fully attached with mudded joints		7,469	0.88

Conf. #	Description	Restraint	Interior Finish	Diagram	Peak Load, lbs	Ratio to baseline of 8,450 lbs
12	Let-in brace @45^o loaded in tension and compression	60% (strap at each stud with 2-6d nail, distrib. beam)	Gypsum fully attached with mudded joints		7,750 8,030	0.93
13	Let-in brace @45^o loaded in compression with gypsum and window openings	Full – E564 (distribution beam, no strapping)	Gypsum fully attached with mudded joints		5,620	n/a
14	Let-in brace @45^o loaded in compression with gypsum with door openings	Full – E564 (distribution beam, no strapping)	Gypsum fully attached with mudded joints		3,597	n/a

1. See Table 6 for description of restraint condition. The vertical arrows at bottom corners indicate location of holddowns. Holddowns were not installed at openings or at the wall end subject to compression force. The horizontal arrows at the top wall corner indicate direction and location of loading.

Figure 15 – Configuration 8 (Gypsum uplift at bottom plate for minimum restraint conditions)

Figure 16 – Configuration 8 (Tension brace connection performance)

Figure 17 – Configuration 10 (Shearing of gypsum connections for 30% restraint conditions)

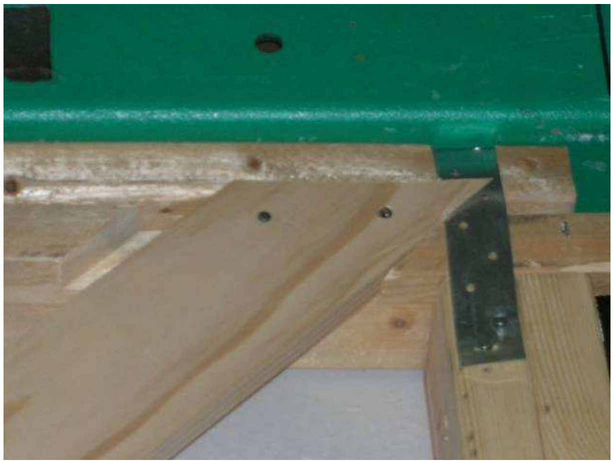


Figure 18 – Configuration 12 (Shear plug failure at compression brace)

Figure 19 – Configuration 13 (Cracks at window)

Figure 20 – Configuration 13 (Gypsum failure)

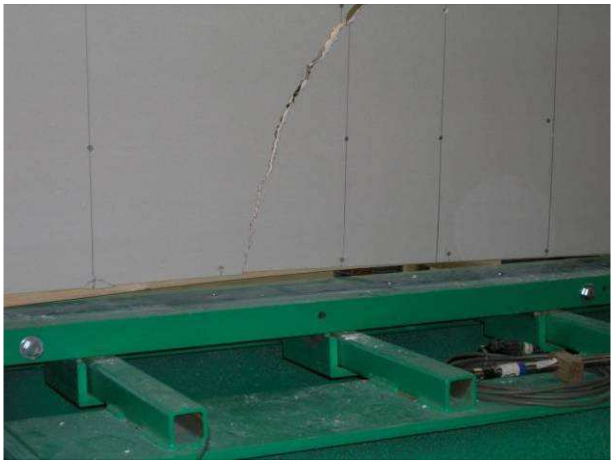


Figure 21 – Configuration 13 (Uplift at let-in brace)

Figure 22 – Configuration 14 (Uplift at let-in brace)

Effect of Boundary Conditions on an Isolated Bracing Panel

The purpose of this testing was to measure the effect of various boundary conditions on the performance of an isolated 48-inch-wide braced wall panel. The 48-inch-wide segment was constructed using wood structural panels on one side and gypsum wallboard on the opposite side. The framing was extended for 48-inches to the left and right of the braced wall panel to provide continuity of the top and bottom plates. For all tests, overturning restraint was provided only through anchorage of the bottom plate. Holddowns were not installed and load was applied in tension with a metal bracket. Table 9 summarizes the test results.

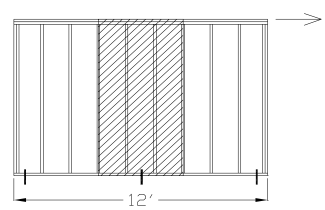
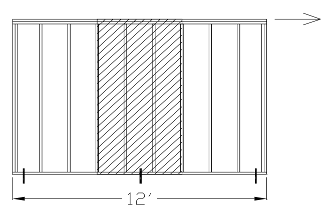
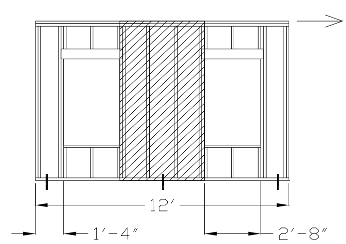
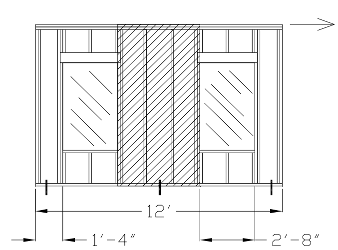
Configuration 15 (Figure 23) was tested to establish a baseline for an isolated bracing panel. Configurations 16, 17, and 18 were tested to measure the degree of impact of various adjacent framing configurations on the response of an isolated bracing panel. Based on results of Configuration 16, the addition of two gypsum panels on the interior face of the wall increases the peak capacity by a factor of 2.3. Figure 24 shows a response of the system at failure due to global overturning.

Configuration 17 with window openings located immediately adjacent to the left and right of the braced wall panel developed a peak load 1.7 times higher than the baseline. The global overturning was less pronounced as compared to Configuration 16. Instead, the window segments served more as boundary elements to the primary braced wall segment. The gypsum wallboard developed cracks at the window corners (Figures 25 and 26).

To further measure the impact of finish materials, Configuration 18 was tested with windows installed in the framed opening. The peak load increased by a factor of 2.2 relative to the baseline (Configuration 15) or a factor of 1.3 relative to the configuration without windows (Configuration 17). Figures 27 and 28 show the observed failure modes.

Results of testing Configurations 15 through 18 indicated that finish materials have an impact on the response of the primary bracing panel. This impact is a result of the finish materials resisting substantial shear forces and also acting as boundary members that provide overturning restraint for the primary bracing panel.

Table 9 – Results—Minimum Restraint OSB Panel – Effect of Varying Boundary Conditions

Conf. #	Description	Restraint	Interior Finish	Diagram	Peak Load, lb	Ratio relative to Configuration 15
15	Single 4' x 8' wood structural panel	Minimum (no distrib. beam, no strapping, no HD)	Single 4' x 8' gypsum panel behind wood structural panel		1,059	1.0
16	Single 4' x 8' wood structural panel with gypsum	Minimum (no distrib. beam, no strapping, no HD)	Gypsum fully attached and mudded entire 12 foot length		2,462	2.3
17	Single 4' x 8' wood structural panel with gypsum and window openings	Minimum (no distrib. beam, no strapping, no HD)	Gypsum fully attached and mudded		1,795	1.7
18	Single 4' x 8' wood structural panel with gypsum and windows installed	Minimum (no distrib. beam, no strapping, no HD)	Gypsum fully attached and mudded		2,310	2.2

1. See Table 6 for description of restraint condition. The horizontal arrows at the top wall corner indicate direction and location of loading.

Figure 23 – Configuration 15

Figure 24 – Configuration 16

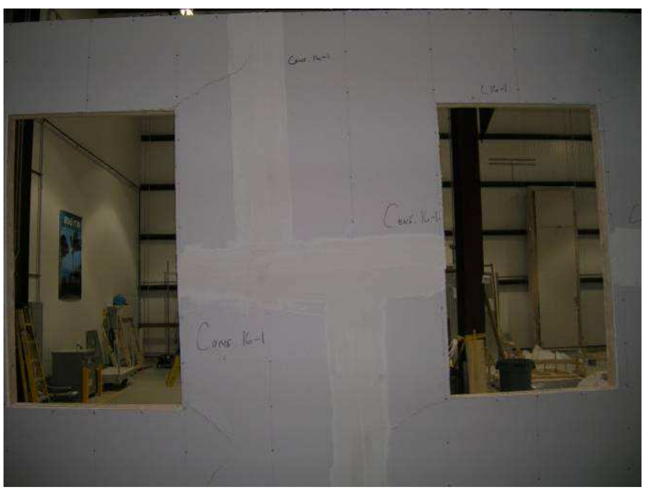


Figure 25 – Configuration 17 (Gypsum at braced wall panel)

Figure 26 – Configuration 17 (Gypsum at windows)

Figure 27 – Configuration 18

Figure 28 – Configuration 18 (Gypsum cracking)

SUMMARY AND CONCLUSIONS

This testing program was designed to measure the performance of conventional bracing systems including wood let-in bracing, gypsum board, and wood structural panels. Results of the study provide information towards understanding how these bracing methods work as part of the system and in combination with each other. Below is a summary of conclusions:

1) Testing of compression and tension let-in braces individually and in combination indicates that their capacities are additive.
2) The capacity of a system of two let-in braces (tension and compression) without interior gypsum ranged between 3,830 lbs and 4,485 lbs. Individually, the 45-deg 1x4 let-in braces provided approximately 1,200-1,400 lbs (tension) and 2,400-3,200 lbs (compression) of shear resistance.
3) The average peak load of a system with two let-in braces (tension and compression) with interior gypsum was 8,450 lbs.
4) A 35% reduction was observed for braces installed at 60 degrees in a system with interior gypsum.
5) A 25% reduction was observed where gypsum joints were floated around the entire specimen perimeter.
6) Where gypsum was installed on both faces of the wall such that it was directly against the let-in brace on one side, a 16% increase was observed in addition to the incremental increase due to additional gypsum.

7) Testing of let-in braces as part of perforated gypsum shear walls indicates that where a let-in brace is installed adjacent to an opening, the capacity of the let-in brace should be reduced by 20% to allow superposition of the two methods.

8) Results of testing of isolated bracing panels using various adjacent framing conditions indicates that finish materials have an impact on the response of the primary bracing panel. This impact is a result of the finish materials resisting substantial shear forces and also acting as boundary members that provide overturning restraint for the primary bracing panel.

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Vladimir G. Kochkin

05-29-08

Signature

Date

Reviewed by Robert Hill, PE
Director, Laboratory and Certification Services

Robert J. Hill

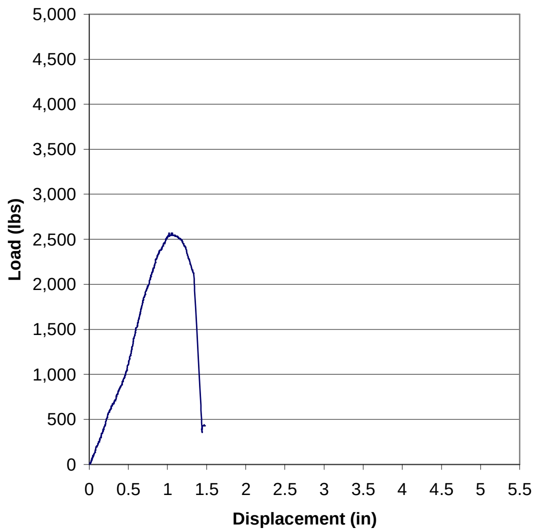
05-29-08

Signature

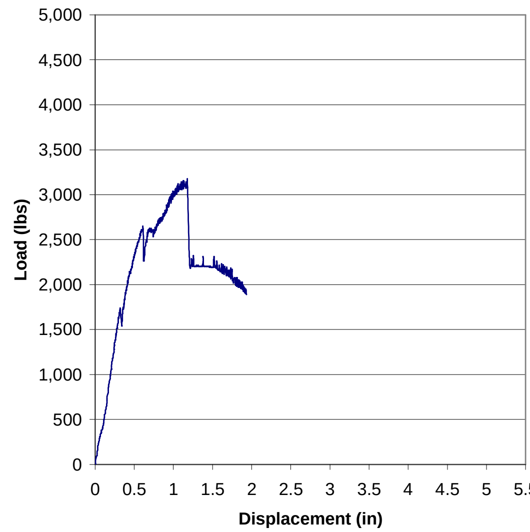
Date

APPENDIX A – LOAD VS. DEFLECTION RELATIONSHIPS

Fully Restrained Systems (Let-in Brace, Gypsum Sheathing)



Configuration 1 – Test 1



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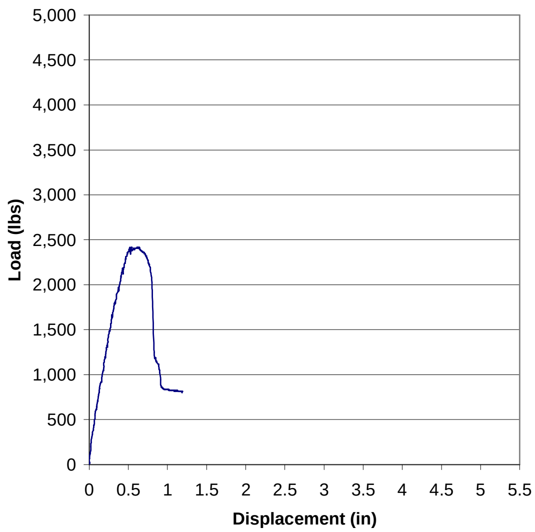

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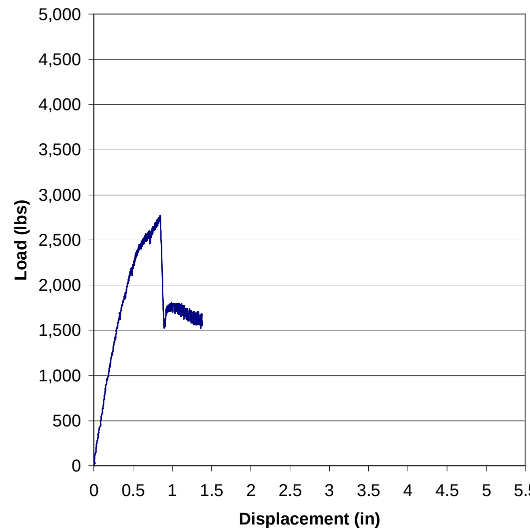

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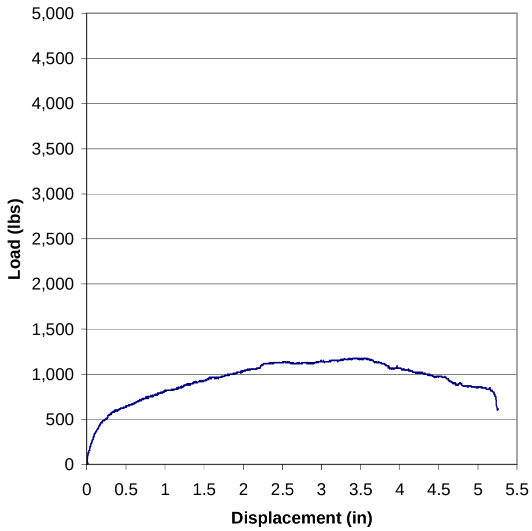

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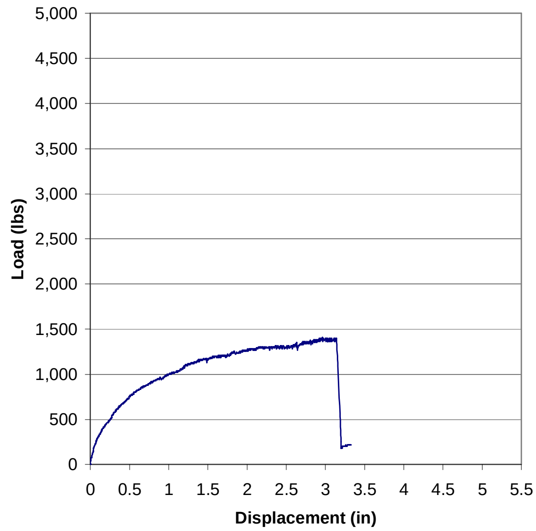

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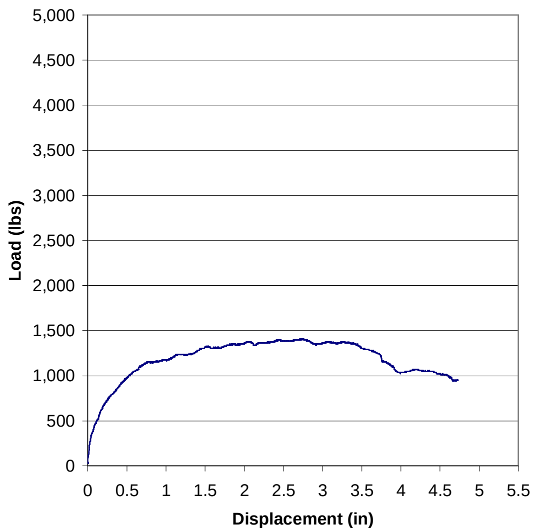

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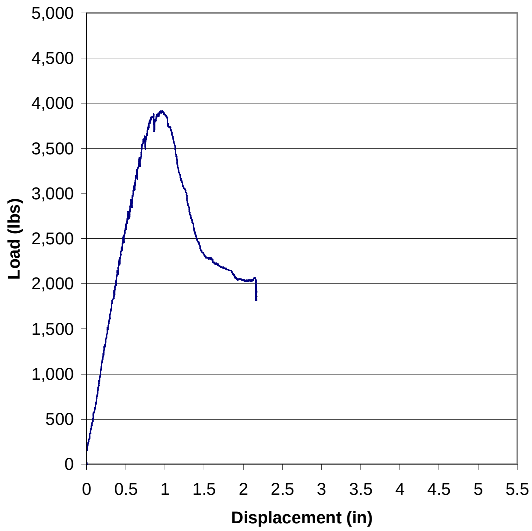

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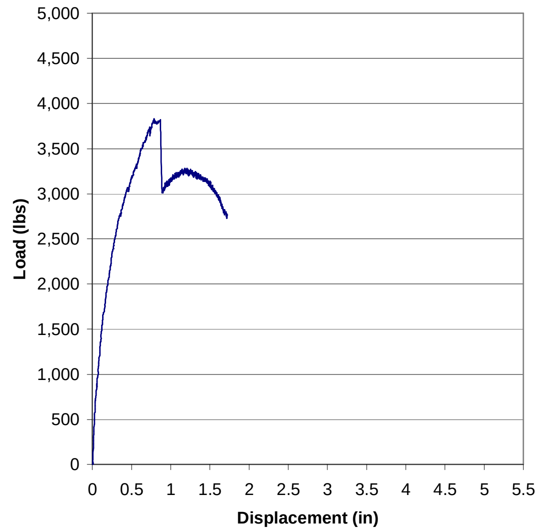

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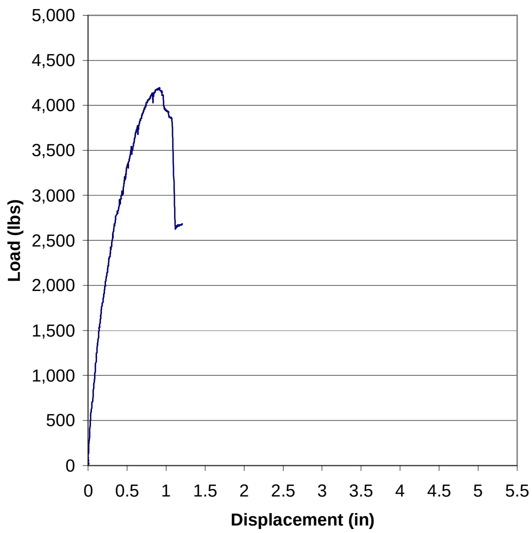

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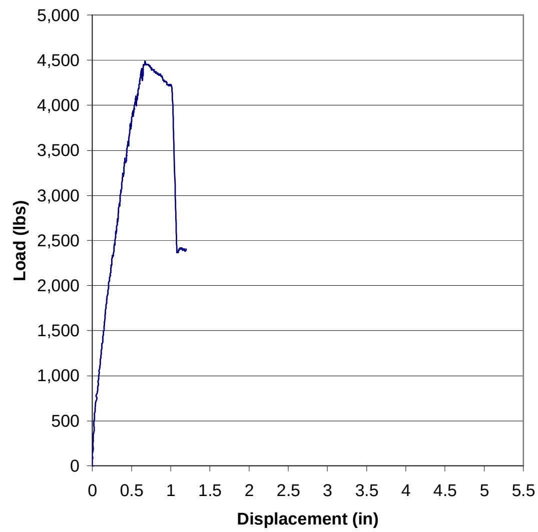

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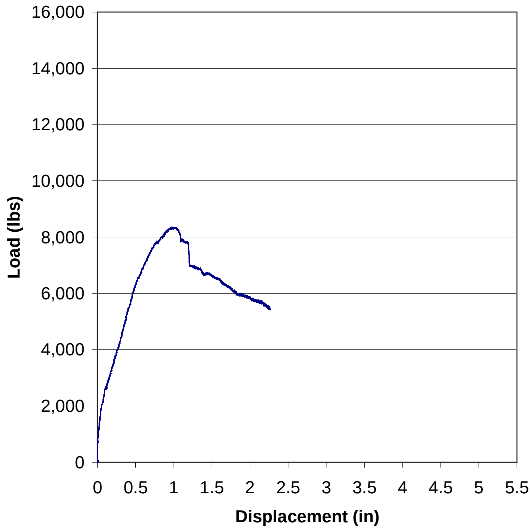

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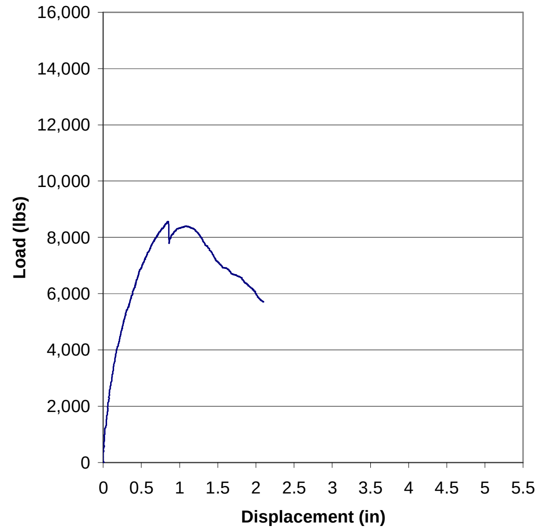
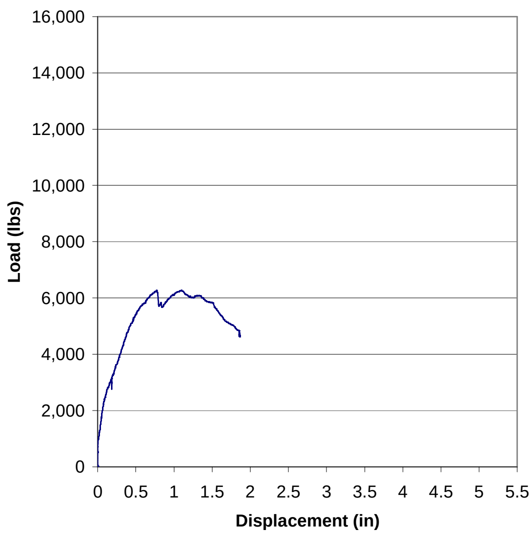
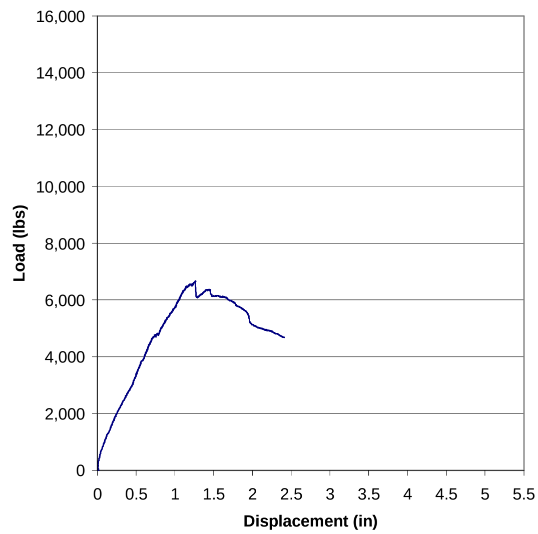


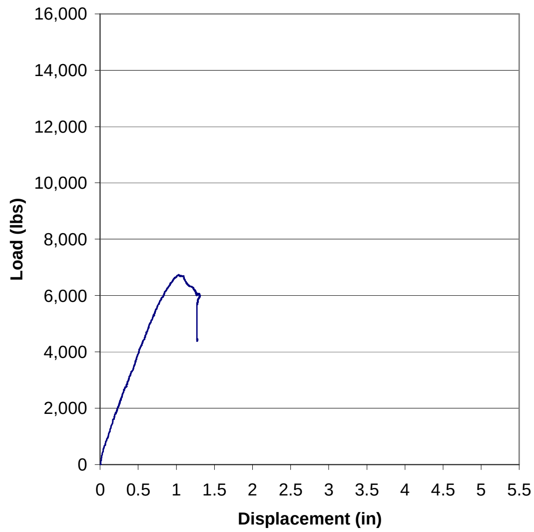
Configuration 4 – Test 2



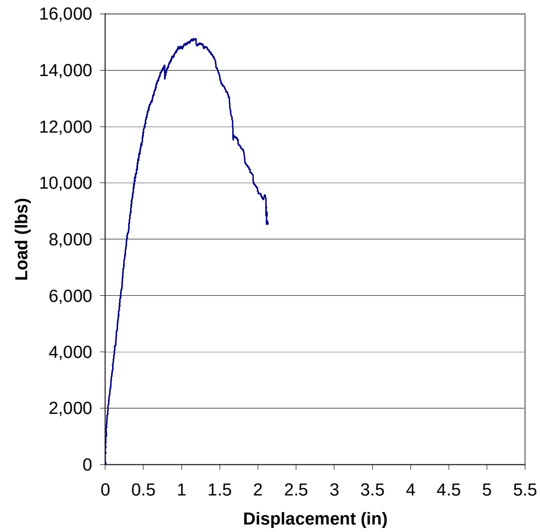
Configuration 5



Configuration 6 – Test 1

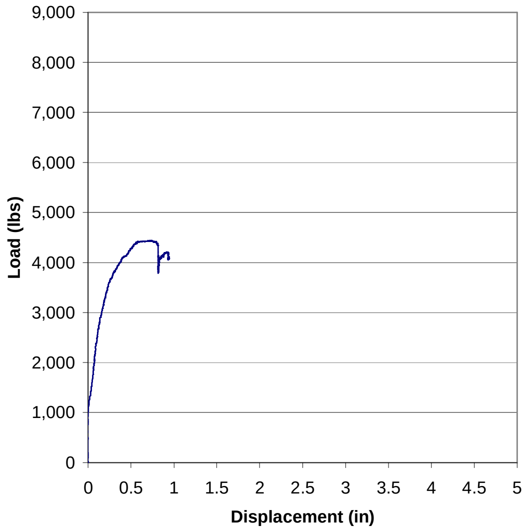


Configuration 6 – Test 2

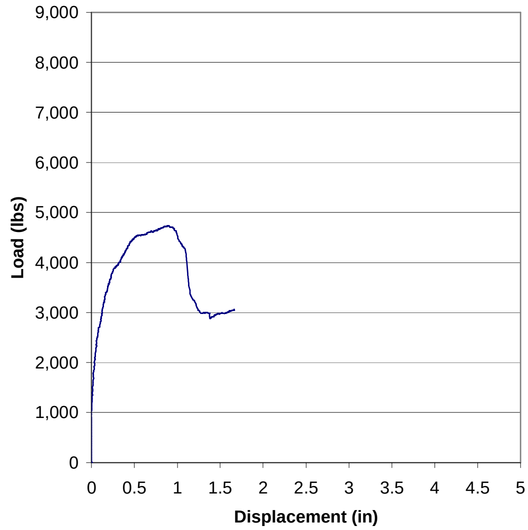


Configuration 7

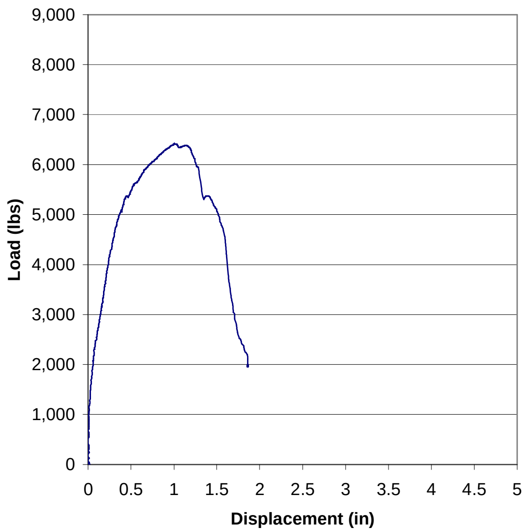
Partially Restrained Systems and Combined Perforated Walls (Let-in Brace, Gypsum Sheathing)



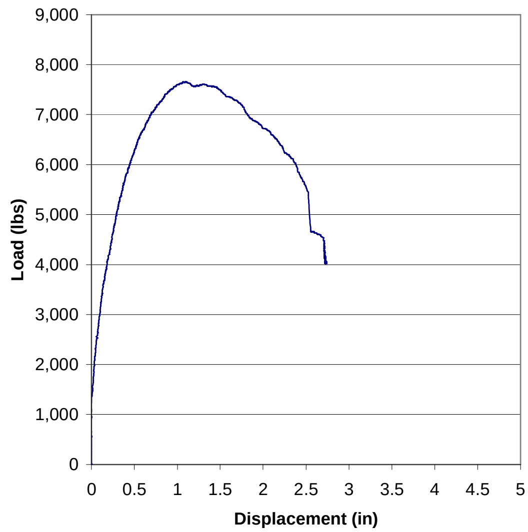
Configuration 8 – Test 1



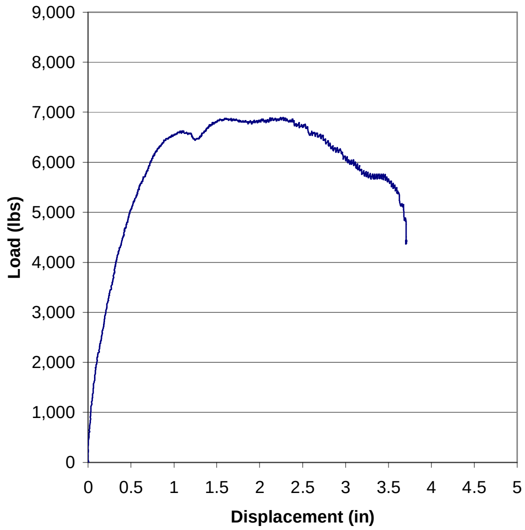
Configuration 8 – Test 2



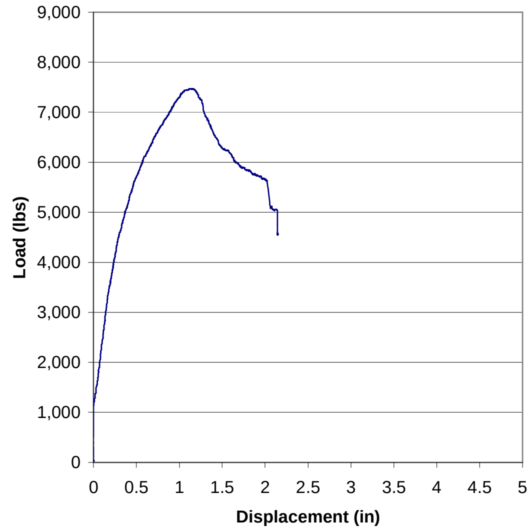
Configuration 9



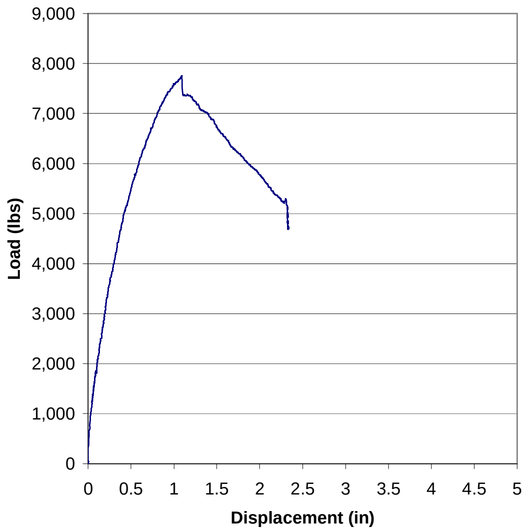
Configuration 10 – Test 1



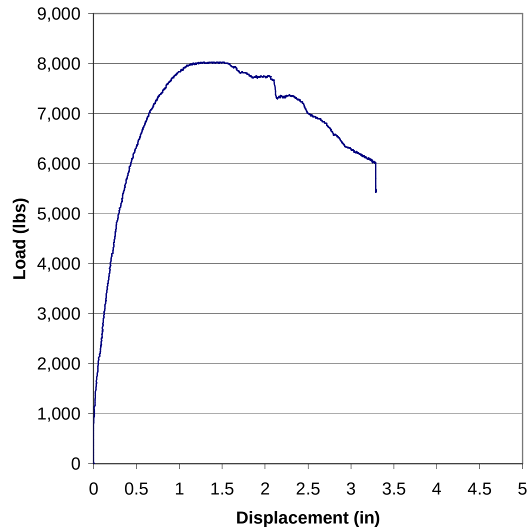
Configuration 10 – Test 2



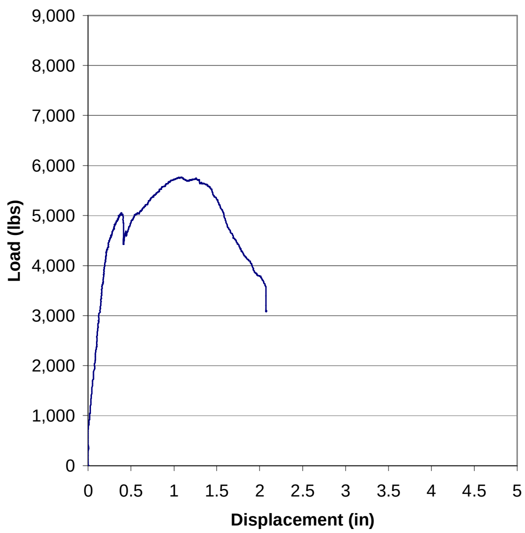
Configuration 11



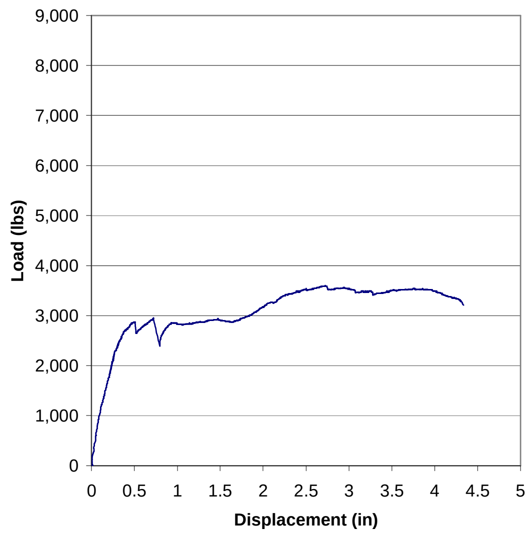
Configuration 12 – Test 1



Configuration 12 – Test 2

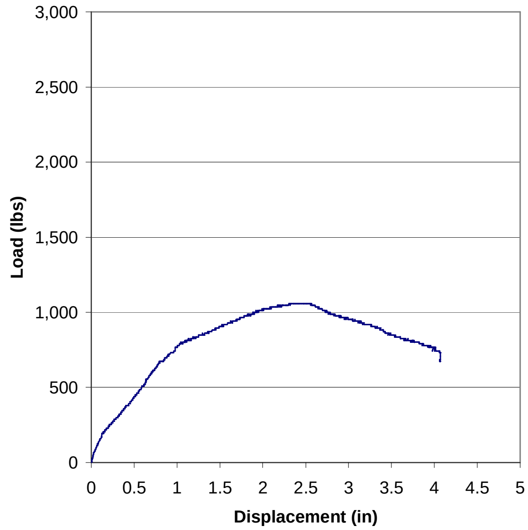


Configuration 13

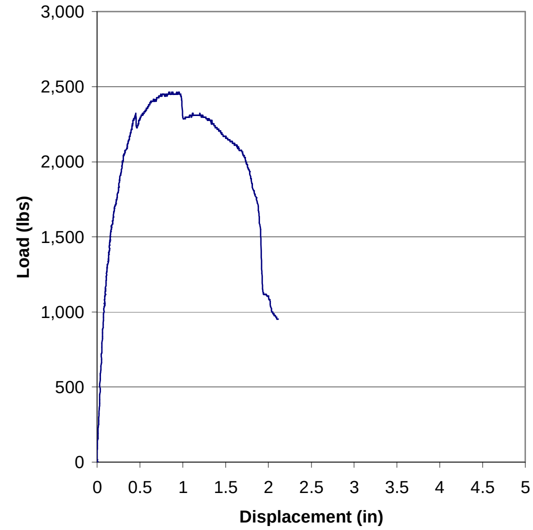


Configuration 14

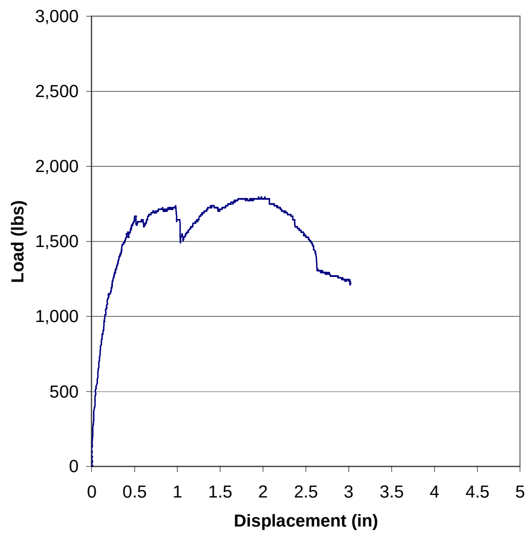
Minimum Restraint OSB Panel – Effect of Varying Boundary Conditions



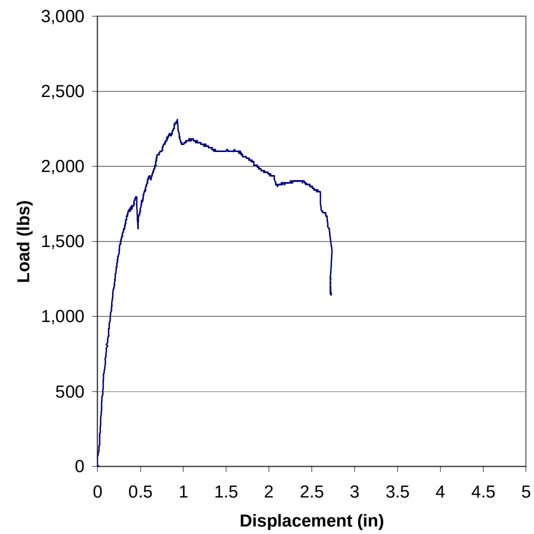
Configuration 15



Configuration 16



Configuration 17



Configuration 18