EVALUATION OF INNOVATIVE LIGHT FRAMED WALL BRACING OPTIONS

Prepared for
NAHB

Prepared by
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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Let-in bracing has been a viable option for bracing of conventional construction for many years. Recent testing conducted by the NAHB Research Center under conditions of both full and partial restraint reconfirmed that let-in bracing continues to be an acceptable method of bracing [1]. The renewed interest in let-in bracing is triggered by the increasing demand from builders for cost-effective energy-efficient construction. Technological barriers to the use of let-in bracing include (1) the limitations on the flexibility of placing of doors and windows where a let-in brace is installed because of the requirements for a wide uninterrupted wall and (2) the need for notching of studs. In addition, the 2009 IRC bracing provisions increased the required amounts of diagonal bracing. For these reasons, the utility of traditional let-in braces and similar alternative bracing methods have become challenged and are in need of innovation to meet the demands of current code provisions.

The objective of this research effort was to conduct exploratory testing to determine the performance of several innovative residential wall bracing options that provide improved strength and versatility over conventional let-in bracing methods or that expand builder choice. The focus of the testing was on wind bracing solutions in low seismic areas. Performance results are evaluated against baseline test results[1] as well as the upper bound wind bracing strength[2] used in the *2009 International Residential Code for One and Two Family Dwellings (IRC)*[2] for panel bracing methods other than gypsum board. The results of this testing program are expected to provide the basis for the selection and further qualification testing of a small number of these wall bracing options.

The specific objectives and scope of this study are to:

1) Evaluate the performance of typical let-in bracing augmented with several options to improve strength.
2) Evaluate the performance of alternate or innovative metal strap bracing methods.
3) Evaluate the effects of spray foam insulation (SPF) infill on the performance of walls sheathed with Thermo Ply® structural sheathing.

METHODS AND MATERIALS

General

Testing was conducted at the NAHB Research Center Laboratory Facility located in Upper Marlboro, MD. All specimens were constructed in the laboratory and the lumber, gypsum board, spray foam insulation and fasteners were purchased through local suppliers. The POSI-STRUT® metal truss webs were donated by Mitek Industries, Inc. USP Structural Connectors donated the metal strap bracing products and Berry Plastics Building Products™ donated the Thermo Ply® structural sheathing.

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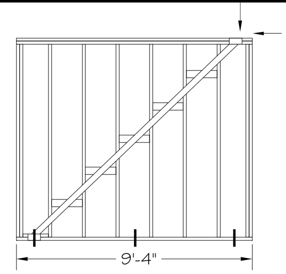
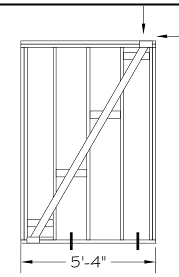
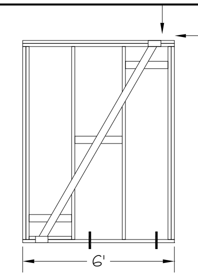
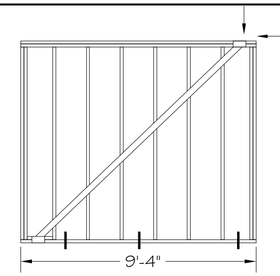
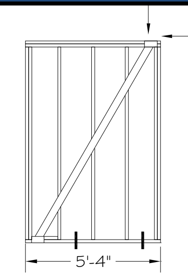
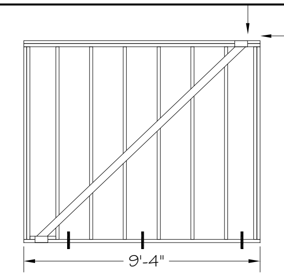
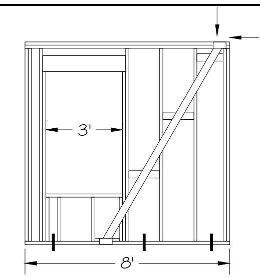
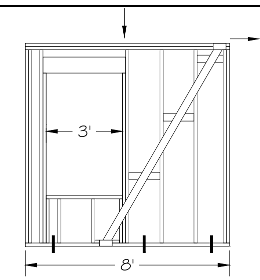
[1] Baseline test results are obtained either from single baseline tests conducted as part of the current testing program or previous testing outlined in the 2008 NAHBRC Report *Evaluation of the Lateral Performance of Let-in Bracing and Mixed Bracing Systems* [1].

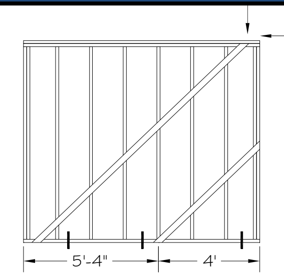
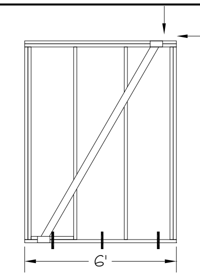
[2] The upper bound peak strength currently used in the IRC is 700 plf as outlined in *The Story Behind the 2009 IRC Wall Bracing Provisions (Part 2: New Wind Bracing Requirements)* [3].

Tables 1, 2, and 3 summarize the test matrix with purpose statements and details specific to each individual test specimen (refer to Tables 4 and 5 in the next section for additional assembly information). Specimens A through J were designed to evaluate the performance of typical let-in bracing augmented with various improvements including alternative connection details and layouts. Specimens K through O were designed to evaluate the performance of several innovative light gauge metal bracing methods including a vertical truss configuration. Specimens P through S were designed to evaluate the contribution of spray foam insulation to the racking strength of Thermo Ply® sheathing attached to 24-inch on center framing.

Table 1 – Test Matrix – Wood Let-in Bracing Options

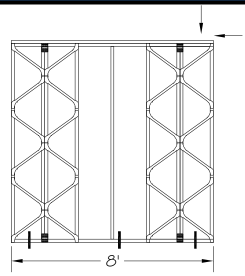
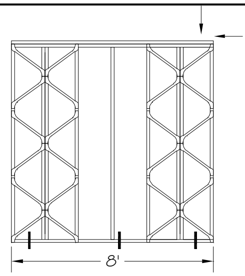
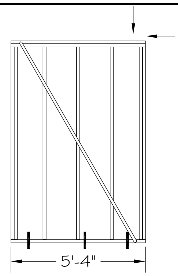
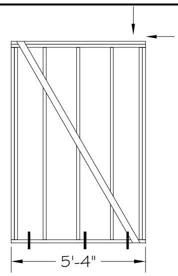
Specimen	Description	Framing Spacing	Brace to Stud Attachment	Brace to Plates Attachment	Interior Finish	Purpose	Diagram[1]
A	1x4 wood let-in brace at 45° w/ mending plates and blocking between stud bays	16” o.c.	(5) 8d smooth shank nails ea. stud; (2) 8d smooth shank nails ea. block	(18) 8d smooth shank nails w/ metal mending plate; (12) thru brace & plate & (6) into plates only	Gypsum installed horizontally, fully attached with mudded joints	Evaluate contribution of mending plates, additional nailing and blocking	
B	1x4 wood let-in brace at 60° w/ mending plates and blocking between stud bays	16” o.c.	(5) 8d smooth shank nails ea. stud; (2) 8d smooth shank nails ea. block	(16) 8d smooth shank nails w/ metal mending plate; (12) thru brace & plate & (4) into plates only	Gypsum installed horizontally, fully attached with mudded joints	Same as A with 60° brace	
C	1x4 wood let-in brace at 60° w/ mending plates and blocking between stud bays	24” o.c.	(5) 8d smooth shank nails ea. stud; (2) 8d smooth shank nails ea. block	(16) 8d smooth shank nails w/ metal mending plate; (12) thru brace & plate & (4) into plates only	Gypsum installed horizontally, fully attached with mudded joints	Same as B with 24” stud spacing	
D	1x4 wood let-in brace at 45° w/ mending plates and ring shank nails	16” o.c.	(4) 10d ring shank nails ea. stud	(16) 8d smooth shank nails w/ metal mending plate; (12) thru brace & plate & (4) into plates only	Gypsum installed horizontally, fully attached with mudded joints	Evaluate contribution of mending plates, additional nailing and ring shank nails	

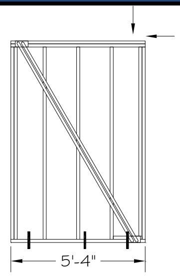
Specimen	Description	Framing Spacing	Brace to Stud Attachment	Brace to Plates Attachment	Interior Finish	Purpose	Diagram[1]
E	1x4 wood let-in brace at 60° w/ mending plates and ring shank nails	16” o.c.	(4) 10d ring shank nails ea. stud	(16) 8d smooth shank nails w/ mending plate; (12) thru brace & plate & (4) into plates only	Gypsum installed horizontally, fully attached with mudded joints	Same as D with 60° brace	
F	1x6 wood let-in brace at 45° w/ mending plates and ring shank nails	16” o.c.	(4) 10d ring shank nails ea. stud	(16) 8d smooth shank nails w/ mending plate; (12) thru brace & plate & (4) into plates only	Gypsum installed horizontally, fully attached with mudded joints	Evaluate wider brace with mending plates, additional nailing and ring shank nails	
G	1x4 wood let-in brace at 60° in compression w/ mending plates, blocking between stud bays and opening	16” o.c.	(5) 8d smooth shank nails ea. stud; (2) smooth shank nails ea. block	(16) 8d smooth shank nails w/ mending plate; (12) thru brace & plate & (4) into plates only	Gypsum installed horizontally, fully attached with mudded joints	Evaluate let-in brace in compression extending below window	
H	1x4 wood let-in brace at 60° in tension w/ mending plates, blocking between stud bays and opening	16” o.c.	(5) 8d smooth shank nails ea. stud; (2) smooth shank nails ea. block	(16) 8d smooth shank nails w/ mending plate; (12) thru brace & plate & (4) into plates only	Gypsum installed horizontally, fully attached with mudded joints	Evaluate let-in brace in tension extending below window	

Specimen	Description	Framing Spacing	Brace to Stud Attachment	Brace to Plates Attachment	Interior Finish	Purpose	Diagram[1]
I	(2) 1x4 wood let-in braces at 45°	16” o.c.	(3) 8d smooth shank nails ea. stud	(3) 8d smooth shank nails ea. plate	Gypsum installed horizontally, fully attached with mudded joints	Evaluate contribution of second brace	
J	5/4” wood let-in brace at 60° with 2x6 framing	24” o.c.	(5) 10d smooth shank nails ea. stud	(16) 8d smooth shank nails w/ mending plate; (12) thru brace & plate & (4) into plates only	Gypsum installed horizontally, fully attached with mudded joints	Evaluate thicker let-in brace in combination with 2x6 framing	

1. The vertical arrow at top of wall indicates location of tie-rod overturning restraints per ASTM E 72. The horizontal arrow at the top wall corner indicates direction and location of loading.

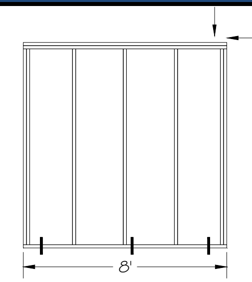
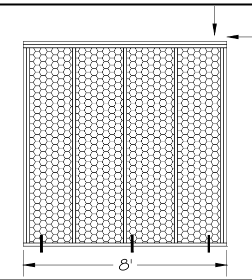
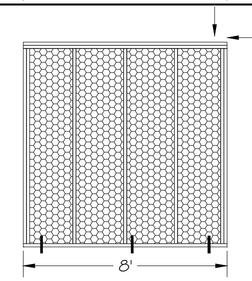
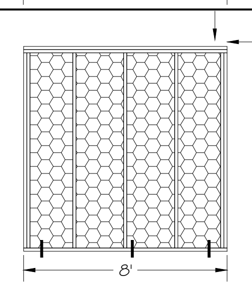
Table 2 – Test Matrix – Metal Bracing Options

Specimen	Description	Framing Spacing	Brace to Stud Attachment	Brace to Plates Attachment	Interior Finish	Purpose	Diagram[1]
K	Vertical truss system using POSI-STRUT® metal truss webs & truss plates	15.5” o.c. in trussed bays; 17” o.c. all other bays	Integrated truss plates	Integrated truss plates	Gypsum installed horizontally, fully attached with mudded joints	Evaluate performance of trussed wall panels	
L	Vertical truss system using POSI-STRUT® metal truss webs & truss plates	15.5” o.c. in trussed bays; 17” o.c. all other bays	Integrated truss plates	Integrated truss plates	Gypsum installed horizontally, fully attached with mudded joints	Same as K without truss plates between double center studs and wall plates	
M	1.25” metal strap at 60°	16” o.c.	(1) smooth shank nail ea. stud	(4) smooth shank nails ea. plate	Gypsum installed horizontally, fully attached with mudded joints	Establish baseline for metal strap bracing	
N	3” metal strap at 60°, wrapped around top and bottom plates	16” o.c.	(2) smooth shank nails ea. stud	(6) smooth shank nails ea. plate; (2) thru front, (2) thru face & (2) thru back of ea. plate	Gypsum installed horizontally, fully attached with mudded joints	Evaluate performance of large metal strap	

Specimen	Description	Framing Spacing	Brace to Stud Attachment	Brace to Plates Attachment	Interior Finish	Purpose	Diagram[1]
O	(2) 1.25” metal straps at 60° w/ mending plates	16” o.c.	(2) smooth shank nail per strap, ea. stud	(14) smooth shank nails w/ mending plate; (4) thru brace & (10) into plates	Gypsum installed horizontally, fully attached with mudded joints	Evaluate contribution of second strap, metal mending plates and additional nailing	

1. The vertical arrow at top of wall indicates location of tie-rod overturning restraints per ASTM E 72. The horizontal arrow at the top wall corner indicates direction and location of loading.

Table 3 – Test Matrix – Thermo Ply® sheathing and Spray Foam Insulation

Specimen	Description	Framing Spacing	Brace to Framing Attachment	Interior Finish	Purpose	Diagram
P	Thermo Ply® sheathing	24” o.c.	Staples at 3” o.c. around the edge and in the field	None	Establish baseline for spray foam insulation options	
Q	Thermo Ply® sheathing w/ closed cell SPF, full cavity application	24” o.c.	Staples at 3” o.c. around the edge and in the field	None	Evaluate contribution of full cavity high density SPF insulation	
R	Thermo Ply® sheathing w/ closed cell SPF, flash and batt application	24” o.c.	Staples at 3” o.c. around the edge and in the field	None	Evaluate contribution of “flash & batt” high density SPF insulation (3/4” avg. thickness in cavity)	
S	Thermo Ply® sheathing w/ open cell SPF, full cavity application	24” o.c.	Staples at 3” o.c. around the edge and in the field	None	Evaluate contribution of full cavity low density SPF insulation	

1. The vertical arrow at top of wall indicates location of tie-rod overturning restraints per ASTM E 72. The horizontal arrow at the top wall corner indicates direction and location of loading.

Specimen Construction

Tables 4 and 5 summarize the materials and fastener schedule, respectively, used in construction of the specimens. Specimens ranged in length from 5-feet 4-inches to 9-feet 4-inches. In all cases, a stud height of 91.5 inches was used in combination with a double top plate and a single bottom plate for an overall specimen height of 8 feet.

Nominal 1x4 and 1x6 lumber is not commercially available in structural grade. The specific gravity (SG) of the bracing lumber used in this testing program was evaluated to provide a reference benchmark of mechanical properties. Appendix B provides a summary of specific gravities for the lumber of the specimen braces tested. The wood let-in braces were installed flush with the bottom plate and allowed to bear on the base of the test setup. At the double top plate, each brace was installed approximately 4 inches from the corner and extended only into the first (lower) member of the double top plate.

The interior gypsum board nailing schedule was selected from Table R702.3.5 of the 2009 IRC [2]. The gypsum board sheathing was installed horizontally and raised approximately 1/4-inch up from the bottom of the wall to allow for initial rotation. The Thermo Ply® sheathing in Specimens P through O was installed flush with the bottom of the wall, and a 3.5-inch wide base plate was added below the wall specimen to insure the sheathing did not bear against the base of the racking apparatus. The load distribution beam at the top of the specimen was always installed such that it did not interfere with the sheathing materials during testing.

The spray foam insulation (Specimens Q-S) was installed by local contractors with the walls in the horizontal position. The closed-cell type foam had a specified density range of 2.1 – 2.3 pcf and the open-cell type foam had a specified density range of 0.6 – 0.8 pcf according to manufacturer’s specifications. The installed density of both types of spray foam was determined by measuring the mass and volume of several samples taken from the tested specimens. (The volume of the samples was obtained by measuring the amount of water displaced by the sample). The measured mass, volume, and density of samples of both foam types are listed in Appendix C. The measured density of closed-cell type foam ranged from 2.3 – 2.5 pcf and the measured density of open-cell type foam ranged from 0.6 – 0.9 pcf.

All framing nails were installed using a pneumatic nail gun, except for the nails through the mending plates on specimens A through H which were installed using a typical framing hammer. (The nails through the mending plates on Specimen O were installed using a pneumatic nail gun, indicating that either installation method is feasible.) The gypsum sheathing nails were installed using a typical framing hammer and the Thermo Ply® sheathing staples were installed using a pneumatic staple gun. The POSI-STRUT® metal truss webs were installed by hand using a 5 lb sledge hammer and the truss connector plates in Specimen K were installed using a portable hydraulic truss plate press.

Further discussion of the construction and bracing details of the various specimens is included in the results section of this report.

Table 4 – Materials and Wall Construction

Wall Height:	8 feet
Wall Length:	Per test matrix (Tables 1, 2, & 3)
Openings:	Window: 32 inches x 54 inches rough opening per test matrix (Table 1)
Framing Lumber:	2x4 SPF STUD Grade studs, plates, blocking, and headers (2) 2x4 top plates 2x4 bottom plate 2x4 blocking per test matrix (Table 1) (2) 2x4 end studs (2) 2x12 headers with 1/2-inch OSB Spacer
Stud Spacing:	Per test matrix (Tables 1, 2, & 3)
Bracing Materials:	Wood – 1x4, 1x6, or 5/4-inch (nominal 7/8-inch) thick #1 Pine brace (unless otherwise specified in text) (grade is non-structural, structural grade not assigned), recessed into framing except upper top plate Metal – USP RWB96 strap (1.25 inches x 16 gauge) or USP CMSTC strap (3 inches x 16 gauge), per test matrix (Table 2) – POSI-STRUT® metal truss webs (20 gauge)
Attachment Components:	Simpson Strong-Tie TP37 metal mending plate (7 inches x 3 inches x 20 gauge) or truss plate (5 inches x 3 inches x 20 gauge), per test matrix (Tables 1 & 2)
Interior Sheathing:	1/2-inch regular gypsum wallboard per test matrix (Tables 1, 2, & 3) installed horizontally, unblocked, joints tapped & mudded
Exterior Sheathing:	Thermo Ply® Blue Structural panels per test matrix (Table 3) installed vertically, overlapped at center joint
Anchor Bolts:	1/2-inch diameter bolts with round cut washers 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 Thermo Ply®: 1/2-inch
Spray Foam Insulation:	Demilec HEATLOK SOY® closed-cell spray polyurethane foam insulation (specified density of 2.1 – 2.3 pcf) or Demilec *SEAL*ECTION Agribalance open-cell spray polyurethane foam insulation (specified density of 0.6 – 0.8 pcf) (see Appendix C for sample densities from test walls)

Table 5 – Fastener Schedule

Connection	Fastener	Spacing
Top plate to top plate (face-nailed)	(1) 16d pneumatic (3.25" x 0.131")	At framing spacing
Top/bottom plate to stud (end-nailed)	(2) 16d pneumatic (3.25" x 0.131")	Per connection
Stud to stud (face-nailed)	(1) 10d pneumatic (3" x 0.128") (unless otherwise noted in text)	24 inches on center
Double header with spacer	(2) 16d pneumatic (3.25" x 0.131")	16 inches on center along each edge
Blocking (end-nailed)	(2) (unless otherwise noted in text)16d pneumatic (3.25" x 0.131")	Per connection
Let-in brace @ studs	Smooth Shank: 8d pneumatic (2.5" x 0.113") or 10d pneumatic (3" x 0.128")[1] Ring Shank: 10d pneumatic (3" x 0.131")	Per test matrix (Tables 1, 2, & 3)
Let-in brace @ top and bottom plates	8d pneumatic (2.5" x 0.113")	Per test matrix (Tables 1)
Metal strap brace @ top and bottom plates	8d common (2.5" x 0.131")	Per test matrix (Tables 2)
Gypsum	13 gauge drywall nail (1.625" x 0.095")	8 inches on center, all studs and plates
Thermo Ply®	16 gauge staple (1" crown x 1.25")	3 inches around the edges and in the field

1. 10d pneumatic nails used only in Specimen J.

Test Set-up and Protocol

Testing was conducted in accordance with the general provisions of ASTM E 72-05 *Standard Test Methods of Conducing Strength Tests of Panels for Building Construction* [4] using a racking shear test apparatus controlled via a computer-based control system. Testing in accordance with ASTM E 72 provided a consistent basis for comparison of results with historical test data. All specimens were fully restrained against uplift using ASTM E 72 type restraints. Specimens were anchored to the base of the racking apparatus using 1/2-inch diameter bolts. Tables 1, 2, and 3 provide the approximate location of the anchor bolts with respect to the ends of the wall and the wall brace.

Specimens A through O were tested monotonically using a hydraulic actuator to apply load to the top of the wall at a constant rate of 1.0-inches per minute until failure. This loading rate is based on the recommendations of the IRC Wall Bracing Task Group[3] and allowed for direct comparison to previous test results [1].

Specimens P through S were tested using the loading protocol outlined in Section 14.4 of ASTM E 72. The specimen was displaced at a constant rate of 0.06-inches per minute until an initial load of 790 lb was reached. The specimen was then unloaded and the set deflection was recorded. This loading and unloading process was repeated for load levels of 1,570 lb and 2,360 lb. Finally, the specimen was displaced until either failure or 4 inches of total displacement occurred. This loading procedure is consistent with the requirements of ICC Evaluation Service *AC269 Acceptance Criteria For Racking Shear Evaluation of Proprietary Sheathing Materials Attached to Light-Frame Wall Construction or Code-Complying Sheathing Attached to Light-Framed Walls With Proprietary Fasteners; Approved October 2009* [5].

Loading was applied at the top of all specimens using a 4-inch x 4-inch steel box beam along the entire length of the wall and attached to both top plates with a minimum of (4) 1/2-inch bolts at approximately 2 feet on center. Tables 1, 2, and 3 provide the direction of loading for each specimen tested.

Instrument readings including load and deflection measurements were recorded using a computer-based data acquisition system. Load was measured using an electronic load cell located between the cylinder and the steel load distribution beam. Displacement at the top of wall relative to the setup base was measured using an electronic string potentiometer. The following displacements were measured using Linear Variable Differential Transformers (LVDTs) relative to the base of the racking apparatus:

1) Slip at the bottom plate
2) Compression at the specimen corner studs
3) Uplift at the specimen corner studs

Figure 1 shows the schematic of the test set up used with Specimen A to illustrate the location of the instrumentation and loading apparatus. Figure 2 provides a photograph of the test setup for Specimen D.

[3] The IRC Wall Bracing 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.

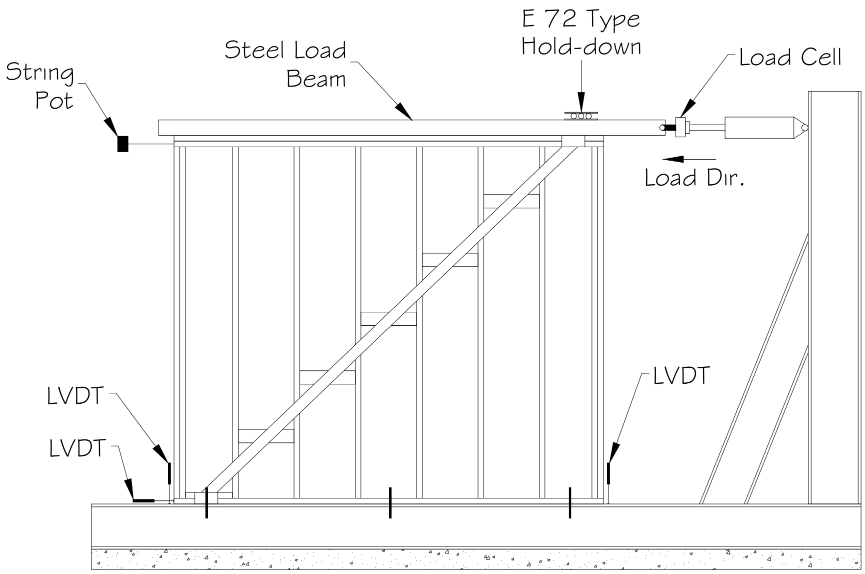


Figure 1 – Instrumentation of test set-up
(E 72 type hold-down shown for Specimen. A - See Tables 1, 2, & 3 for approx. location of hold-down in other configurations)

Figure 2 – Shear wall test specimen
(Specimen D)

RESULTS

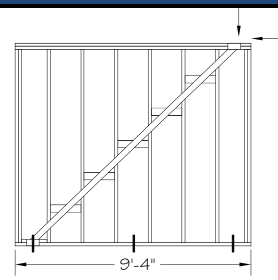
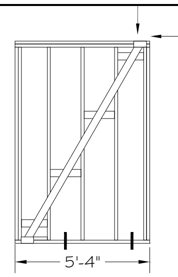
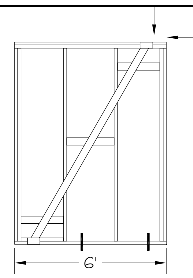
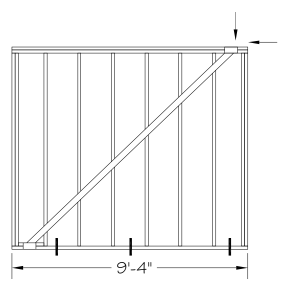
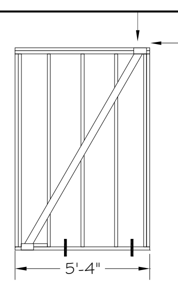
Wood Let-in Bracing Options

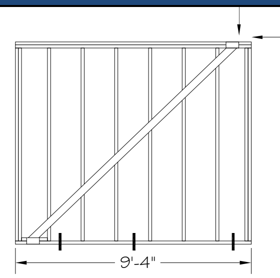
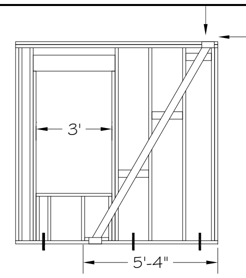
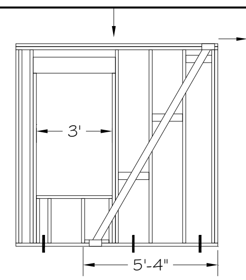
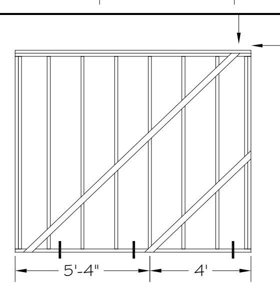
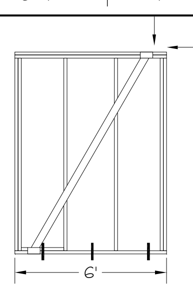
The results of the testing of wood let-in bracing options are summarized in Table 6 including the peak load for the entire wall and the unit peak capacity on a per linear foot basis. Appendix A provides the load vs. deflection behaviors for each test. A comparison to baseline wall capacities from previous test results of a typical let-in brace conducted in 2008 [1] is also included in Table 6. The 2008 study evaluated the performance of a let-in brace in either compression or tension. The specimens consisted of non-structurally graded 1x4 nominal lumber braces installed at a 45° angle and attached with (2) 8d common nails at the top and bottom plates, as well as at each stud. The following is a brief summary of the results of that testing:

- Typical 1x4 let-in brace in compression (w/o gypsum): 341 lb/ft
- Typical 1x4 let-in brace in tension (w/o gypsum): 166 lb/ft

The contribution of gypsum sheathing was added to the above baseline results in order to enable direct comparison to the results of the current testing program. The gypsum sheathing was assumed to contribute 200 lb/ft. This value is in accordance with the unit shear capacity of an unblocked shear wall with gypsum attached using nails at 7 inches on center per the *2005 AF&PA Special Design Provisions for Wind and Seismic* [6]. The same value was used as a basis for the contribution of gypsum wall board (interior finish) to bracing methods in the 2009 IRC [2].

Table 6 – Test Results – Wood Let-in Bracing Options

Specimen	Description	Interior Finish	Diagram[1]	Peak Load (lb)	Unit Peak Load (lb/ft)[2]	Ratio Relative to Baseline[3]
A	1x4 wood let-in brace at 45° w/ mending plates and blocking between stud bays	Gypsum fully attached		8,956	1,119	2.1
B	1x4 wood let-in brace at 60° w/ mending plates and blocking between stud bays	Gypsum fully attached		5,675	1,218	2.3
C	1x4 wood let-in brace at 60° w/ mending plates and blocking between stud bays	Gypsum fully attached		5,295	1,136	2.1
D	1x4 wood let-in brace at 45° w/ mending plates and ring shank nails	Gypsum fully attached		8,429	1,054	1.9
E	1x4 wood let-in brace at 60° w/ mending plates and ring shank nails	Gypsum fully attached		3,977	854	1.6

Specimen	Description	Interior Finish	Diagram[1]	Peak Load (lb)	Unit Peak Load (lb/ft)[2]	Ratio Relative to Baseline[3]
F	1x6 wood let-in brace at 45° w/ mending plates and ring shank nails	Gypsum fully attached		9,131	1,141	2.1
G	1x4 wood let-in brace at 60° in compression w/ mending plates, blocking between stud bays and opening	Gypsum fully attached		6,035	1,295	2.4
H	1x4 wood let-in brace at 60° in tension w/ mending plates, blocking between stud bays and opening	Gypsum fully attached		2,439	523	1.4
I	(2) 1x4 wood let-in braces at 45°	Gypsum fully attached		5,068	608	1.1
J	5/4" wood let-in brace at 60° with 2x6 framing	Gypsum fully attached		3,837	823	1.5

1. The vertical arrow at top of wall indicates location of tie-rod overturning restraints per ASTM E 72. The horizontal arrow at the top wall corner indicates direction and location of loading.
2. Unit peak load calculated based upon nominal brace lengths of 8 feet (45° brace) or 4.67 feet (60° brace).
3. Baseline test results obtained from previous testing conducted at the NAHB Research Center [1] and comparisons are made on a per linear foot basis to results in compression or tension as appropriate.

Specimens A through C were designed to evaluate the contribution of blocking and end nailing details to the strength of a typical wood let-in brace at various angles and stud spacing. The ends of the braces in Specimens A through C were reinforced with mending plates (Figure 3) and 2x4 blocking at the compression end to provide an additional nailing surface. Blocking was also installed in Specimens A through C at the mid-span of each brace between studs to reduce the un-braced, out-of-plane buckling length of the brace. The 2x4 blocking was installed using (2) 16d pneumatic nails through the studs and into each end of the blocking. The let-in brace was attached to the blocking using (2) 8d pneumatic nails at the mid-span of the stud bay (Figure 4). The brace was also attached to each stud with (5) 8d pneumatic nails; five nails being the maximum number achievable without splitting either the brace or the stud.

The mending plates in Specimen A were installed using a total of (18) hand-driven 8d box nails; (12) nails through the mending plate, brace, and top (or bottom) plate of the wall and (6) through only the mending plate into the top (or bottom) plate. This attachment schedule is the practical upper limit on the number of nails that can be installed in the field. Specimen A exhibited a peak test load of 8,956 lb (or peak unit shear of 1,119 lb/ft) with a primary failure mode of buckling between the stud and the additional blocking (Figure 5). (Note that the unit shear capacity is based upon the let-in brace's nominal length of 8 feet). This peak load capacity is 2.1 times greater than the peak load achieved in the baseline tests [1].

Since the mending plates did not fail in Specimen A, the number of nails used to attach the mending plate and brace in Specimen B (and all subsequent specimens utilizing a mending plate and wood let-in brace) were reduced to (16) to improve constructability. The angle of the brace in Specimen B was increased to 60°. Specimen B achieved a peak capacity of 5,675 lb (1,218 lb/ft), or 2.3 times greater load than the baseline results [1] and the primary failure mode of Specimen B was a splitting of the brace in the last bay at the compression end of the wall (Figure 6). The construction of Specimen C was similar to Specimen B except that the spacing of the wall framing was increased to 24" on center. Specimen C reached a peak load of 5,295 lb (1,136 lb/ft) and failed in a fashion similar to Specimen A.

Figure 3 – Reinforcing mending plate and blocking of wood let-in brace

Figure 4 – Out-of-plane blocking of wood let-in brace

Figure 5 – Buckling failure of wood brace (Specimen A)

Figure 6 – Splitting failure of wood brace (Specimen B)

In summary, the addition of mending plates and additional nailing at each end of the let-in braces, in combination with the addition of blocking in the stud bays increased the overall strength of the wall by factors of 2.1 – 2.3 over the baseline results [1].

Specimens D through F were designed to evaluate the use of ring shank nails to attach the let-in braces to the intermediate wall framing in lieu of additional blocking. The number of nails at each brace to stud connection was reduced to four because of the larger shank diameter of the 10d ring shank compared to the 8d smooth shank nail. By observation, the ring shank nails appeared to provide a greater level of joint fixity (compared to smooth shank nails) and thus greater restraint against out-of-plane rotation of the braces at the stud to brace intersections. This greater fixity, in turn, would tend to reduce the effective buckling length of the brace[4]. A

[4] Buckling strength is inversely correlated with the effective length of the member in compression. The effective length is equal to the length measured between brace points multiplied by the buckling length coefficient, K_e, which is an approximate measure of the end fixity and typically ranges between 0.5 and 1.2. Therefore, any decrease of the

total of (4) 10d pneumatic ring shank nails were installed at each brace to stud connection. Specimens D through F also incorporated the end reinforcement of the mending plates consistent with Specimens B and C.

Specimens D and E were constructed with 1x4 let-in braces at angles of 45° and 60°, respectively. Specimen D reached a peak unit shear of 1,054 lb/ft while exhibiting a brace buckling failure mode at the mid-span of the center stud bay (Figure 7). Comparing to the Specimen A test that reached a peak unit shear of 1,119 lb/ft, the Specimen D results were only slightly less (about 6%), indicating that the ring shank nailing schedule provides sufficient end fixity to be used as an alternative bracing option in lieu of 2x4 blocking for a 1x4 brace at 45° and 16-inch on center framing.

Specimen E achieved a peak unit shear of 854 lb/ft with a combined failure mode of shear plug failure at the compression end of the wall and significant out-of-plane bending of the brace (Figure 8) It should be noted that the bracing material used in Specimen E had an SG well above the average SG of the bracing material used in this testing program (SG of 0.62 compared to the average SG of 0.48).

The size of the brace in Specimen F was increased to a 1x6 nominal member at 45° with the same attachment details as the two previous specimens. Specimen F exhibited another shear plug failure at the compression end of the wall at a unit peak shear capacity of 1,141 lb/ft.

The next two specimens evaluated the performance of a reinforced 1x4 let-in brace located so that the bottom end of the brace extended beneath a window opening (Figure 9). This option allows for greater versatility in the placement of let-in bracing. Specimen G was tested in compression and Specimen H was tested in tension. Specimen G exhibited a brace buckling failure mode at the blocking in the center stud bay and diagonal cracking of the gypsum around the opening (Figure 10). The specimen reached a peak unit shear of 1,295 lb/ft, a capacity 2.4 times greater than the baseline [1] and a 6% increase over the Specimen B results, indicating that the placement of an opening above the end of a reinforced let in brace has negligible impact on the strength of that brace in compression. Specimen H achieved a peak unit shear capacity of 523 lb/ft, an increase of 43% over the baseline results of a 1x4 brace in tension [1]. The primary failure mode of Specimen H was nail withdrawal at the connection of the brace and mending plate to the bottom plate of the wall (Figure 11). Significant cracking of the gypsum sheathing was also observed at the corners of the opening (Figure 12), as well as at the horizontal joint between gypsum panels (Figure 13). This amount of cracking is similar to the gypsum sheathing damage observed in previous testing of conventional let-in bracing near window openings [1]. The average peak unit shear capacity of the brace in compression (Specimen G) and the brace in tension (Specimen H) was 907 lb/ft. This unit shear capacity exceeds the current upper bound wall strength of 700 lb/ft used in the development of the 2009 IRC [2]. However, it is clear that the strength of these braces is asymmetric and, if the average of the tension and compression strength is to be used as a basis for design, the braces should be applied in opposing pairs. Otherwise, the bracing strength in compression and tension

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effective length of a member either by a reduction in span length or increase in end fixity will consequently increase the buckling strength of that member.

should be separately used for each brace, whether in tension or compression depending on orientation and loading direction.

Specimen I was tested to evaluate the performance of a system of two 1x4 let-in braces without any reinforcing details. Both braces were installed at a 45° angle with (3) 8d pneumatic nails at each end and every intermediate stud. The primary brace was in the typical location, beginning approximately 4 inches from the leading edge of the wall. The second brace began at mid-height of the leading edge of the wall (Figure 14) and was let into both end studs and the bottom plate of the wall. The peak test load for this specimen was 5,068 lb (608 lb/ft), a 12% increase over the baseline let-in brace strengths [1] and failed by buckling of the primary brace. Thus, the addition of a partial length brace provided only marginal benefits.

The last wood let-in bracing option, Specimen J, evaluated the performance of a nominal 5/4-inch board let-in to 2x6 framing at 24 inches on center and reinforced with mending plates. The use of the deeper 2x6 framing allows for a deeper notch (per Section R602.6 of the 2009 IRC [3]) and consequently a thicker bracing member that will provide increased buckling performance (in the weak axis direction compared to nominal 1x bracing) without requiring additional blocking or ring shank nailing. The 5/4-inch brace was installed at a 60° angle with (5) 10d pneumatic nails at each end and every intermediate stud. Specimen J achieved a peak unit shear of 823 lb/ft and underwent a brace buckling failure at the mid-span of the center stud bay. This peak capacity is a modest increase of 50% over the baseline test results [1], but it should be noted that the 5/4-brace member was low density material with an SG of 0.31 compared to the average SG of 0.48 for all other let-in braces in the current testing program.

Figure 7 – Buckling failure of wood brace (Specimen D)

Figure 8 – Out-of-plane bending of wood brace (Specimen E)

Figure 9 – Specimen G wall construction

Figure 10 – Buckling failure of wood brace (Specimen G)

Figure 11 – Withdrawal failure of wood brace (Specimen H)

Figure 12 – Diagonal cracking of gypsum at opening (Specimen H)

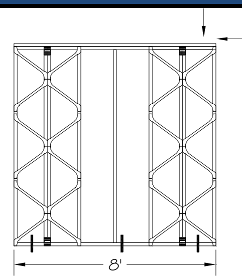
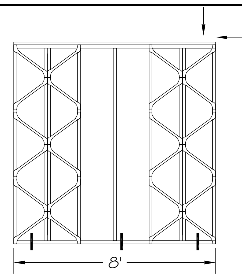
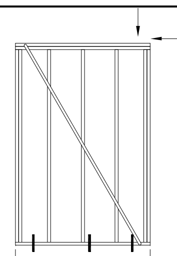
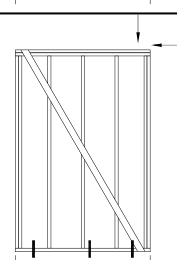
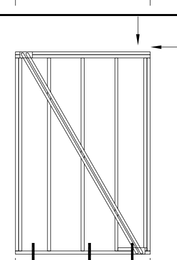
Figure 13 – Cracking of gypsum at horizontal joint (Specimen H)

Figure 14 – Specimen I wall construction

Metal Bracing Options

The results of testing of the metal bracing options are summarized in Table 7 including peak load for the entire wall and the unit peak load on a per linear foot basis. Appendix A provides the load vs. deflection behaviors for each of the tests. A comparison to baseline specimen strength (Specimen M) is made where appropriate and is also included in Table 7.

Table 7 – Test Results – Metal Bracing Options

Specimen	Description	Interior Finish	Diagram[1]	Peak Load (lb)	Unit Peak Load (lb/ft)[2]	Ratio Relative to Baseline[3]
K	Vertical truss system using POSI-STRUT® metal truss webs & truss plates	Gypsum fully attached		4,511	777	N/A
L	Vertical truss system using POSI-STRUT® metal truss webs & truss plates	Gypsum fully attached		4,247	725	N/A
M	1.25" metal strap at 60°	Gypsum fully attached		1,990	427	N/A
N	3" metal strap at 60°, wrapped around top and bottom plates	Gypsum fully attached		3,192	685	1.6
O	(2) 1.25" metal straps at 60° w/ mending plates	Gypsum fully attached		3,749	804	1.9

1. The vertical arrow at top of wall indicates location of tie-rod overturning restraints per ASTM E 72. The horizontal arrow at the top wall corner indicates direction and location of loading.
2. Unit peak load calculated based upon nominal brace lengths of 5.05 feet (POSI-STRUT®) or 4.67 feet (60° brace). Unit peak load for Specimens K and L neglects the contribution of the middle 3 feet of gypsum wall board between trussed stud bays.
2. Baseline test results are results of Specimen M testing with prescribed nailing per USP product literature [7].

Specimens K and L resist shear forces through vertical trusses constructed using POSI-STRUT® metal truss web members (Figure 15). Each specimen includes two 32-inch wide bracing units. The POSI-STRUT® product is a V-shaped stamped metal web member intended to connect the top and bottom chords of a Warren type, parallel chord wood floor or roof truss. The metal web member is connected to wood studs through integrated truss plates (Figure 16). The web members were installed only at the exterior face of the wall. The trussed stud bays were reduced by 3/4 of an inch to a 15.25-inch on center spacing and a double stud member was required in the middle of the truss bracing unit to accommodate the web members (note that off-the-shelf metal web members were configured for floor truss applications). These double stud members were spliced at 12 inches on center using (2) 16d pneumatic framing nails. This nailing schedule was increased from the (1) 10d nail at 24-inch on center required in the 2009 IRC in order to provide greater shear load transfer capacity between the studs and prevent slippage of the studs relative to each other. Specimen K also included additional rectangular truss plates at the top and bottom of the double studs to reinforce the connection of the bracing unit to the top and bottom plates of the wall (Figure 17).

Specimen K attained a peak load of 4,511 lb (or peak unit shear of 777 lb/ft over the 5 feet 1 inch length of trussed stud bays). The primary failure mode was a buckling of the web members and withdrawal of the integrated truss plates at the top and bottom plates (Figures 18 and 19). Some splitting of the single studs was observed in locations where web members were spaced apart from each other as shown in Figure 20. Specimen L was tested without the additional truss plate connection between the double studs and the wall plates. This specimen reached a peak load of 4,247 lb (or peak unit shear of 725 lb/ft, over the 5 feet 1 inch length of trussed stud bays) with a primary failure mode of integrated truss plate withdrawal along the top plate of the wall (Figure 21). Both Specimen K and Specimen L exceeded the 700 lb/ft upper bound strength of the IRC bracing methods [2] demonstrating viability of truss walls for wall bracing applications.

Figure 15 – Specimen L wall construction

Figure 16 – POSI-STRUT® web member

Figure 17 – Additional truss plates between double studs and top plate (Specimen K)

Figure 18 – Combined buckling and withdraw failure at leading edge of wall (Specimen K)

Figure 19 – Combined buckling and withdraw failure at trailing edge of wall (Specimen K)

Figure 20– Splitting failure of stud (Specimen K)

Figure 21 – Withdrawal failure of web members (Specimen K)

The purpose of Specimen M was to establish baseline performance for a typical diagonal metal strap brace. A basic 1.25-inch, 16-gauge pre-cut strap manufactured by USP Structural Connectors was installed per the manufacturer's instructions [7] at a 60° angle. The strap was attached using (4) 8d common nails at the top and bottom plates and a single 8d common nail at each intermediate stud. This baseline specimen was tested in tension and reached a peak unit shear of 427 lb/ft with a nail withdrawal primary failure mode at the strap ends as shown in Figure 22.

In an effort to preclude this failure mode, Specimen N was constructed using a longer and wider metal strap supplied in a coil. The strap was cut to length to allow the brace to be wrapped around the top and bottom plates of the wall specimen as shown in Figure 23. The brace was attached to wall framing at each end with a total of (6) 8d common nails: (2) nails into the interior face of the plate, (2) nails into the wide face of the plate, (1) nail into the exterior face of the plate, and (1) nail into the exterior face of the double end stud. (2) 8d common nails were also installed at each intermediate stud. The peak unit shear in tension for this wrapped metal strapping was 685 lb/ft, a 60% increase in capacity over the baseline metal strap capacity. The primary failure mode was a flexural and cross-grain bending failure of the bottom plate in the stud bay where the brace was attached (Figure 24). This bracing option, however, proved difficult from a constructability standpoint due to the heavier gauge of the product and its resistance to bending around the plates of the wall. The cross-grain bending induced by wrapping the brace around the plates is also a concern.

Specimen O was tested to evaluate the performance of two 1.25-inch straps installed side by side and reinforced at each end with mending plates and additional nailing. The straps were installed with a total of (14) 8d common nails at each end: (4) nails through the mending plate and each brace into the top (or bottom) plate of the wall and (6) nails through only the mending plate into the top (or bottom) plate (Figure 25). The braces were also attached to each intermediate stud with (2) 8d common nails per brace. Specimen O reached a peak unit shear in tension of 804 lb/ft and displayed nail withdrawal at the bottom end of the brace as its primary failure mode (Figure 26). Some degradation of the gypsum sheathing connections was also observed at the bottom edge of the wall. The peak unit shear of Specimen O was an increase of 90% over the baseline strap results and also exceeds the 700 lb/ft upper bound shear strength in the current IRC [2].

Figure 22 – Withdrawal failure of metal brace (Specimen M)

Figure 23 – Installation of metal brace (Specimen N)

Figure 24 – Flexural and cross grain failure of bottom plate (Specimen N)

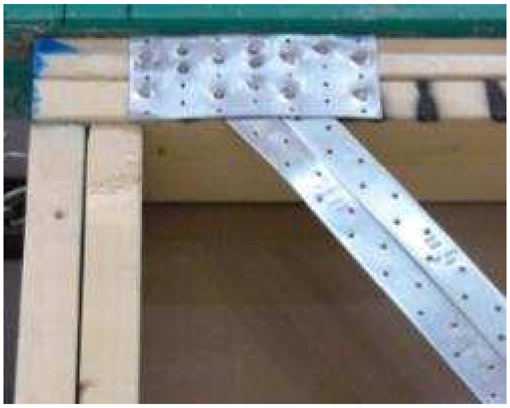


Figure 25 – Installation of metal brace (Specimen O)

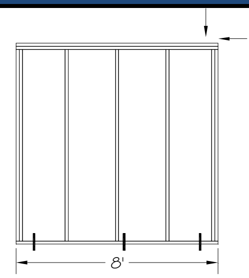
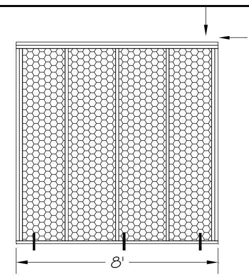
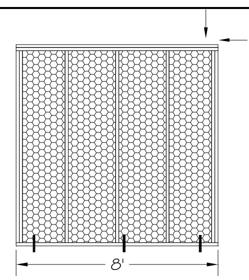
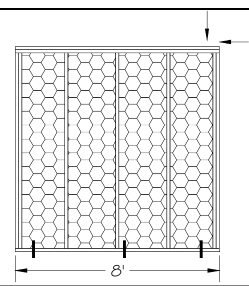
Figure 26 – Withdrawal failure of metal brace (Specimen O)

Combination of Thermo Ply® sheathing and Spray Foam Insulation

Specimens P through S were tested to evaluate the contribution of spray foam insulation (SPF) to the shear performance of Thermo-Ply® sheathing. Because the typical shear response mode of Thermo-Ply® sheathing panels involves wrinkling (i.e., diagonal tension buckling) of the panel (Figure 27) due to its limited resistance to out-of-plane buckling forces, the spray foam was identified as a potential method for improving the Thermo-Ply® shear response. Spray foam installed in the wall cavity adheres to Thermo-Ply® sheathing, increasing its out-of-plane stiffness and minimizing or suppressing the buckling response mode.

The test results are summarized in Table 8 including peak load for the entire wall and the peak load on a per linear foot basis. Appendix A provides the load vs. deflection behaviors for each of the tests. A comparison to baseline performance (Specimen P) is also included in Table 8.

Table 8 – Test Results –Thermo Ply® sheathing and Spray Foam Insulation

Specimen	Description	Interior Finish	Diagram[1]	Peak Load (lb)	Unit Peak Load (lb/ft)	Unit Ratio Relative to Baseline[2]
P	Thermo Ply® sheathing - Baseline	None		4,687	586	N/A
Q	Thermo Ply® sheathing w/ closed cell SPF, full cavity application	None		8,881	1,110	1.9
R	Thermo Ply® sheathing w/ closed cell SPF, flash and batt application	None		6,358	795	1.4
S	Thermo Ply® sheathing w/ open cell SPF, full cavity application	None		4,980	622	1.1

1. The vertical arrow at top of wall indicates location of tie-rod overturning restraints per ASTM E 72. The horizontal arrow at the top wall corner indicates direction and location of loading.
2. Baseline test results are results of Specimen P testing with prescribed nailing per ICC-ES ESR-1122 [8].

Specimen P was tested to provide the baseline performance of the Thermo Ply® sheathing attached to 24-inch on center framing without the SPF insulation in the cavities. It should be noted that Thermo Ply® sheathing is currently qualified as an alternative bracing option per ICC-ES Evaluation Report ESR-1122 [8] for use with wall framing at 16 inches on center or less. The purpose of this testing was to evaluate the 24-inch on center configuration due to its improved thermal characteristics. The Thermo Ply® sheathing was fastened to framing per the manufacturer's instructions using 16 gage staples spaced at 3 inches on center around the panel perimeter and in the panel field. Specimen P attained a peak load of 4,687 lb (586 lb/ft) and displayed sheathing buckling as its primary failure mode (Figure 27).

Specimen Q was tested to measure the contribution from a full cavity application of closed-cell, high-density SPF insulation. Each stud bay was completely filled with SPF insulation and any excess was removed using a hand saw to keep the interior surface of the insulation flush with the interior face of the wall framing (Figure 28). Specimen Q achieved a peak load capacity of 8,881 lb (1,110 lb/ft), an increase of 89% over the baseline (Specimen P). The primary failure mode of Specimen Q was fastener tear through the sheathing along the top of the wall (Figure 29). There was also some slight separation of the SPF insulation from the studs (Figure 30). No fastener failure was observed at the bottom of the wall, indicating that the insulation added sufficient strength and stiffness to the wall to force an isolated shear failure of the connection between the sheathing and the top plate of the wall. Future efforts on further optimization of this system for IRC applications would include increasing fastener spacing to 4 or 6 inches on center.

The next test (Specimen R) evaluated the contribution of the same closed-cell, high density SPF insulation applied using the “flash and batt” method. Figure 31 shows Specimen R after the application of the SPF insulation. The “flash and batt” method of application consists of a thinly applied layer of spray foam over the entire surface of the stud bays. This layer of SPF is meant as an air sealer as opposed to the primary insulating material. The majority of the insulating value of the wall comes from the batt insulation that is installed in the cavity over the SPF (note: the batt insulation was not installed in the tested specimen to allow for visual observation of the SPF during the testing). In the case of Specimen R, the layer of SPF between the studs ranged from 1/8-inch up to 1.5-inches in depth, with an average depth of 3/4-inch. Specimen R reached a peak load of 6,358 lb (795 lb/ft) with sheathing buckling, followed by fastener pull-through and pull-out failure modes (Figures 32 and 33). This failure behavior was similar to the failure behavior of the baseline test wall; however, Specimen R achieved a 36% increase in peak load compared to the baseline wall. The difference in failure modes between Specimen Q and Specimen R indicates that there may be a minimum depth of SPF insulation less than 3.5 inches that causes the failure mode of Thermo Ply® sheathing to change from panel buckling to fastener failure. (A fastener failure mode is assumed to be the strongest limit state for this type of sheathing and thus presumably would yield the highest capacity without increasing fastener spacing). This minimum depth could be found through a small number of additional walls tests at various SPF insulation depths.

Specimen S was tested to evaluate the contribution of low density, open-cell SPF insulation applied to the full depth of the wall cavity. As with the closed-cell SPF, each stud bay was completely filled with the foam and the excess trimmed using a hand saw. The open-cell specimen reached a peak load of 4,980 lb (622 lb/ft), a 6% increase over the baseline test results, indicating that the application of open-cell SPF insulation has a negligible effect on the shear strength of Thermo Ply® sheathing. The primary failure mode of Specimen S was also similar to the baseline test failure mode, i.e., sheathing buckling followed by fastener degradation (Figure 34). The SPF foam did not separate from the studs as seen in the previous full cavity specimen. Instead, separation occurred between the foam and the sheathing in the first bay of the wall (Figure 35). This change in behavior is attributed to the lower stiffness and tensile strength of the open-cell foam which allowed it to deform as the wall deformed, but prevented it from restraining the sheathing from out-of-plane buckling.

Figure 27 – Buckling failure of sheathing (Specimen P)

Figure 28 – Full cavity SPF application (Specimen Q)

Figure 29 – Fastener failure of sheathing (Specimen Q)

Figure 30 – Separation of SPF from studs (Specimen Q)

Figure 31 – Flash & batt application of SPF (Specimen R)

Figure 32 – Buckling failure of sheathing (Specimen R)

Figure 33 – Fastener withdrawal failure (Specimen R)

Figure 34 – Buckling failure of sheathing (Specimen S)

Figure 35 – Separation of SPF from sheathing (Specimen S)

SUMMARY AND CONCLUSIONS

This testing program was designed to evaluate the performance of several innovative residential wall bracing options in resisting in-plane shear loads due to wind. The results of this study provide information towards evaluating the viability of these innovative wall bracing options for future equivalency testing and application in residential construction. Based on the testing, the following conclusions can be made:

Wood Let-In Bracing Options

1) The tested peak unit shear capacity of 1x4 let-in wood braces in compression with mending plates and blocking in the stud bays averaged 1,158 lb/ft, a 116% increase over baseline 1x4 wood let-in brace test results. There was no reduction in capacity (on a per foot basis) going from a 45° brace to a 60° brace. There was also no reduction in capacity when greater stud spacing was used.

2) The tested peak unit shear capacity of 1x4 let-in wood braces in compression with additional mending plates and ring shank nail connections averaged 954 lb/ft, a 76% increase over previous 1x4 wood let-in brace tests. A 19% reduction in capacity relative to the 45° specimen was observed when the bracing angl e was increased to 60° (despite the reduction, the 60° specimen capacity still exceeded the baseline by 60%)The primary failure mode also changed from a buckling failure mode with the 45° brace to a shear plug failure mode with the 60° brace.
3) Increasing the size of the let-in brace from 1x4 to 1x6 nominal lumber with the same mending plates and ring shank connection details increased the peak load capacity in compression by 8%.
4) Testing of a 1x4 brace reinforced with mending plates and blocking in the stud bays, and ending below a window opening resulted in a peak unit shear capacity of 1,295 lb/ft in compression, a 6% increase over the Specimen B results of a similarly detailed brace without an opening. This indicates that the placement of a window opening above the end of a reinforced 1x4 brace has a negligible effect on the strength of that brace in compression.
5) Testing of the same reinforced 1x4 brace and window configuration in tension resulted in a peak unit shear capacity of 523 lb/ft, a 43% increase over previous 1x4 wood let-in brace test results.
6) The average unit shear capacity of 1x4 reinforced braces in compression and in tension was 907 lb/ft; this capacity exceeds the upper bound bracing strength of 700 lb/ft used for the 2009 IRC wind wall bracing methods.
7) The addition of a second un-reinforced 1x4 brace at mid-wall to the typical un-reinforced 1x4 brace provided only a 12% increase in peak load capacity over previous let-in brace test results.
8) A 5/4-inch nominal lumber brace with 2x6 framing at 24-inches on center achieved a peak unit shear capacity of 823 lb/ft, a 50% increase over previous 1x4 wood let-in brace testing. However, the difficulty in obtaining nominal 5/4-inch lumber for this application may factor into its viability as an improvement option over conventional let-in bracing.
9) Overall, the use of 1x4 let-in wood braces augmented with mending plates and ring shank nailing (without additional blocking) is the most advantageous wood let-in brace improvement option given its increase in strength over typical let-in bracing and ease of constructability in comparison to other wood bracing improvement options. Further testing is recommended to determine if the number of fasteners in the end-brace connections can be reduced without losing performance, particularly in tension.

Metal Bracing Options

10) The average peak unit shear capacity of a vertical truss wall configuration using POSI-STRUT® metal truss web members was 751 lb/ft. The removal of the truss plate connection between the wall plates and the built-up stud members resulted in only a 6% reduction in capacity, and both specimens exceeded the 2009 IRC upper bound bracing strength of 700 lb/ft. The dimensional limitations of the off-the-shelf POSI-STRUT® web members pose difficulties for applying this bracing method to a typical stud layout. Coordination with the product manufacturer to develop a wall bracing specific product would be necessary for wide-spread implementation.
11) The use of a 3-inch wide metal strap brace at 60° that was wrapped around both the top and bottom wall plates increased the peak unit shear capacity by 60% over the baseline

1.25-inch diagonal metal strap, to 685 lb/ft. Significant constructability issues arose regarding the larger strap and the ability to wrap it around the top and bottom plates of the wall, as well as concerns about cross-grain bending induced in the bottom plate.

12) Testing of two side-by-side 1.25-inch metal strap braces at 60° and reinforced at each end with mending plates resulted in a 90% increase over the baseline metal strap results. This double strap option exceeded the 700 lb/ft upper bound bracing strength.
13) The side-by-side 1.25-inch strap braces with end reinforcing proved to be the most advantageous metal bracing improvement option given its superior unit shear strength and ease of construction.

Combination of Thermo Ply® sheathing and Spray Foam Insulation

14) Application of high density, closed cell spray foam insulation in combination with Thermo Ply® sheathed wall greatly increases the unit shear capacity compared to a similarly sheathed wall with no SPF insulation. Test specimens with closed cell SPF in a full cavity application achieved 89% higher unit shear capacities (1,110 lb/ft) versus the baseline Thermo Ply® sheathed specimen (586 lb/ft). The failure mode was also altered compared to the baseline test; the baseline test exhibited sheathing panel buckling, whereas the full cavity SPF insulated specimen exhibited fastener failure along the entire top plate.
15) Reducing the amount of closed cell SPF insulation to an average depth of 3/4-inch in each stud cavity by using the “flash and batt” application method resulted in a 36% increase in capacity over the baseline while displaying a sheathing panel buckling failure mode.
16) Comparison of the two closed cell test specimens indicates that a minimum depth of SPF insulation which prevents a buckling failure mode may exist and may be less than the full 3.5-inch depth. This minimum SPF insulation depth could be found through a small number of additional wall tests using various depths of insulation.
17) The addition of low density, open cell SPF insulation applied to the full depth of the stud cavity provided only a marginal 6% improvement over the baseline tests and did not change the failure mode of the specimen.
18) The full cavity and “flash and batt” applications utilizing closed-cell spray foam show the greatest potential as bracing improvement options because of their increased performance and change in response behavior compared to walls with only Thermo Ply® sheathing.

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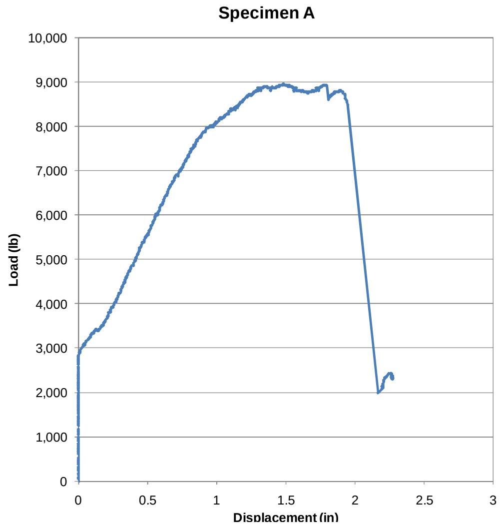
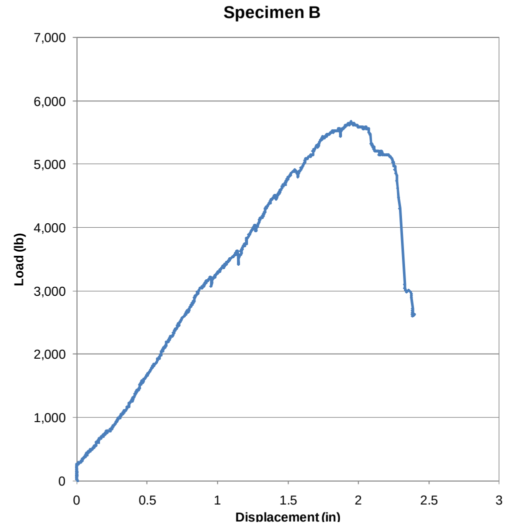
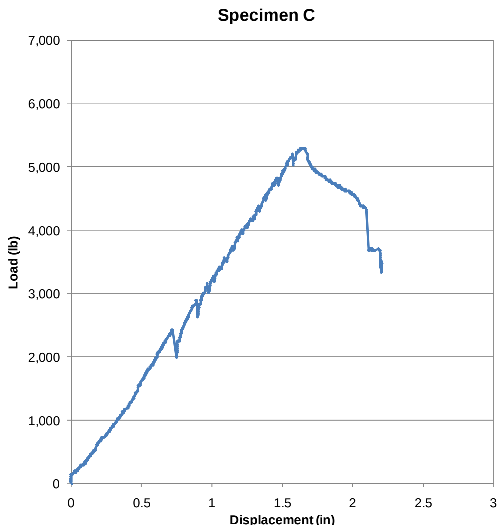
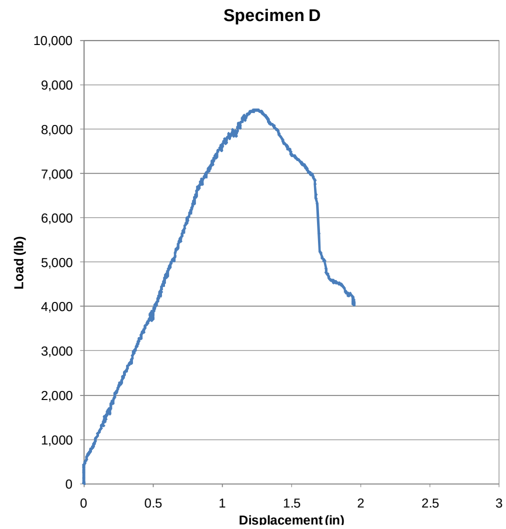
APPENDIX A

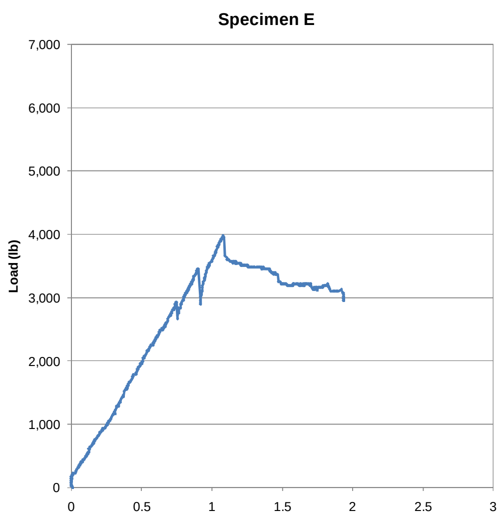
Table A1 – Wood Let-in Bracing Options Load vs. Deflection Relationships

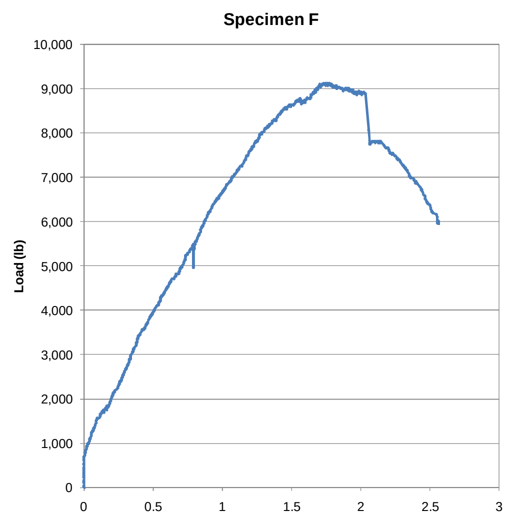


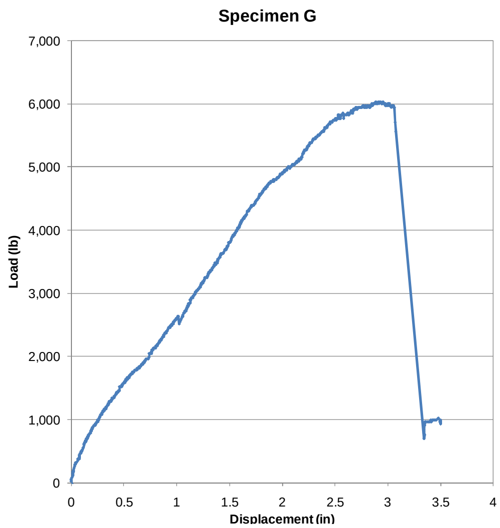


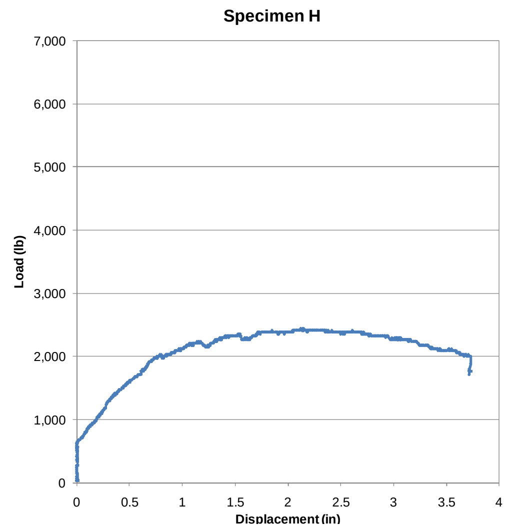


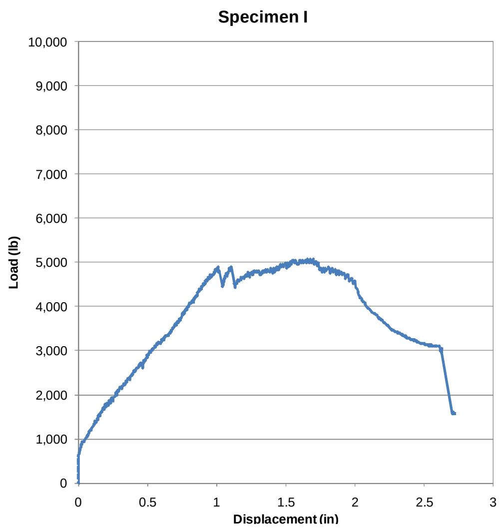







Specimen G
Load (lb)
Displacement (in)


Specimen H
Load (lb)
Displacement (in)


Specimen I
Load (lb)
Displacement (in)

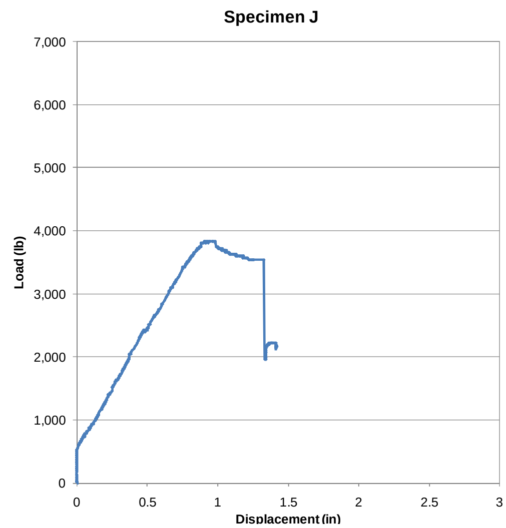
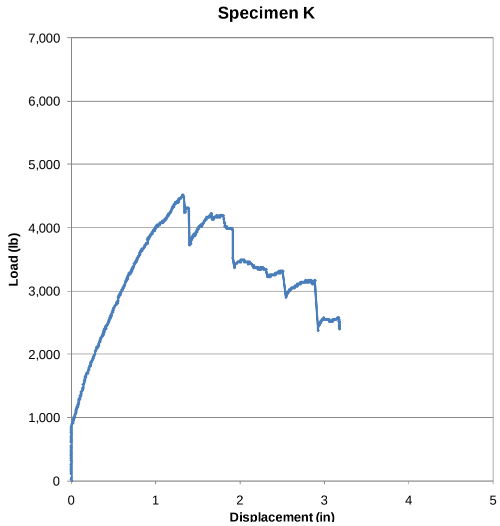
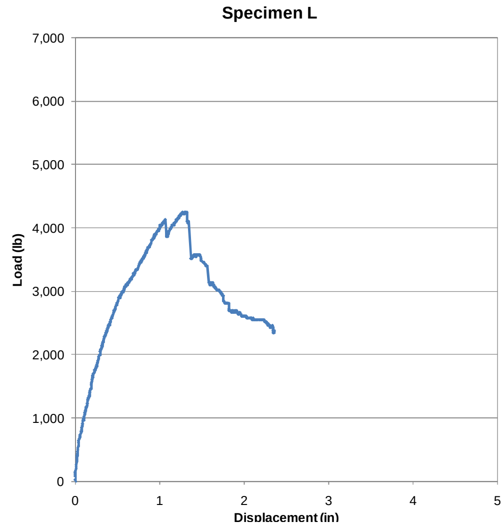
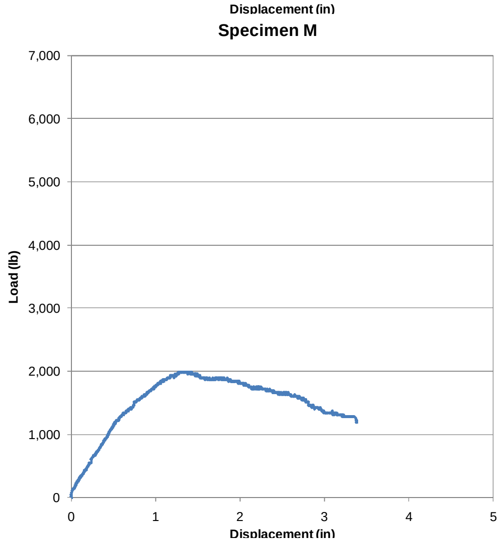
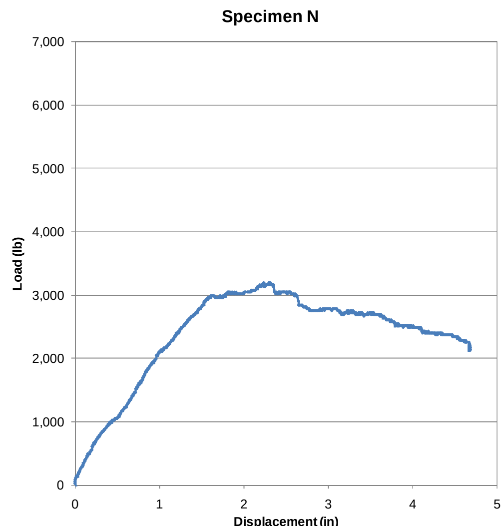

Specimen J
Load (lb)
Displacement (in)

Table A2 – Steel Bracing Options Load vs. Deflection Relationships









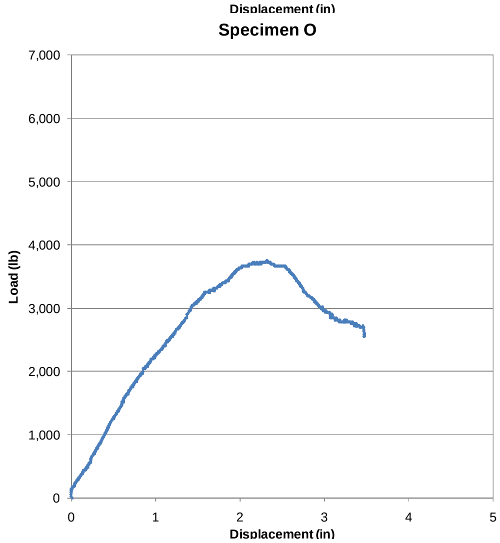
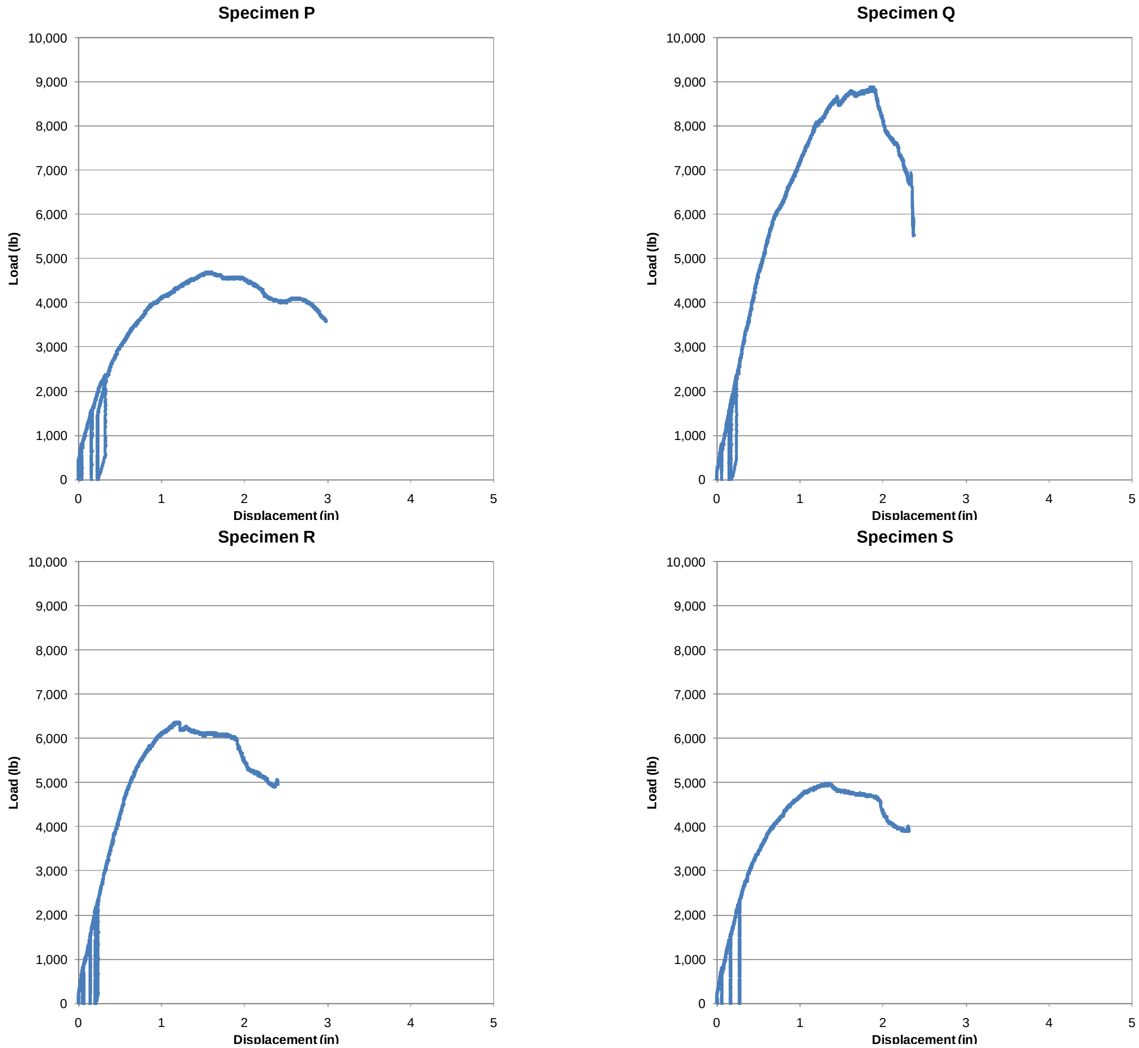


Table A3 – Spray Foam Insulation Options Load vs. Deflection Relationships



APPENDIX B

Table A4 – Specific Gravities of Selected Wood Let-in Braces

Specimen	Specific Gravity
A	0.43
B	0.42
C	0.46
D	0.48
E	0.62
F	0.52
G[1]	0.53
G[2]	0.52
H	0.30
Average	0.48

1. Long brace of Specimen G
2. Short brace of Specimen G

APPENDIX C

Table A5 – Spray Foam Insulation Density Test Results

Specimen	SPF Product Name	SPF Type	Mass (g)	Volume (ml)	Density (g/ml)	Density (lb/ft^3)
A-1	Demiliec HEATLOK SOY®	Closed Cell	1.706	42.5	0.0401	2.50
A-2			1.4588	40	0.0365	2.28
A-3			1.779	45	0.0395	2.47
A-4			1.598	40	0.0400	2.49
B-1	Demilec *SEAL*ECTION Agribalance	Open Cell	0.6662	47.5	0.0140	0.88
B-2			0.5106	52.5	0.0097	0.61
B-3			0.562	52.5	0.0107	0.67
B-4			0.6122	60	0.0102	0.64