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FULL-SCALE SHEAR WALL TESTS FOR FORCE TRANSFER AROUND OPENINGS

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Abstract

Wood structural panel sheathed shear walls and diaphragms are the primary lateral-load-resisting elements in wood-frame construction. The historical performance of light-frame structures in North America are very good due, in part, to model building codes that are designed to preserve life safety, as well as the inherent redundancy of wood-frame construction using wood structural panel shear walls and diaphragms. As wood-frame construction is continuously evolving, designers in many parts of North America are optimizing design solutions that require the understanding of force transfer between load-resisting elements.

The North American building codes provide three solutions to walls with openings. The first solution is to ignore the contribution of the wall segments above and below openings and only consider the full height segments in resisting forces, often referred to as segmented shear wall method. The second approach, which is to account for the effects of openings in the walls using an empirical reduction factor, is known as the "perforated shear wall method". The final method, which has a long history of practical use with surprisingly little research and testing, is the "force transfer around openings method". This method is accepted as simply following "rational analysis". Typically walls that are designed for force transfer around openings result in the walls being reinforced with nails, straps and blocking in the portions of the walls with openings. The authors are aware of at least three techniques which fall under the definition of rational analysis. These techniques result in prediction of the internal forces in the walls as differing by as much as 800% in extreme cases. This variation in predicted forces is resulting in either some structures being over-built or some structures being less reliable than the intended performance objective.

A joint research project of APA – The Engineered Wood Association, the University of British Columbia (UBC), and the USDA Forest Products Laboratory (FPL) was initiated in 2009 to examine the variations of walls with code-allowable openings. This study examines the internal forces generated during these tests and evaluates the effects of size of openings, size of full-height piers, and different construction techniques by using the segmented method, the perforated shear wall method and the force transfer around openings method. Full-scale wall tests as well as analytical modelling were performed. The research results obtained from this study will be used to support design methodologies in estimating the forces around the openings. This paper provides test results from 2.4 m x 3.6 m (8 feet x 12 feet) full-scale wall configurations, which will be used in conjunction with the analytical results from a computer model developed by UBC to develop rational design methodologies for adoption in the U.S. design codes and standards.

1. Introduction

The North American building codes provide three solutions to walls with openings. The first solution is to ignore the contribution of the wall segments above and below openings and only consider the full height segments in resisting forces, often referred to as segmented shear wall method. The second approach, which is to account for the effects of openings in the walls using an empirical reduction factor, is known as the “perforated shear wall method”. The final method, which has a long history of practical use with surprisingly little research and testing, is the “force transfer around openings method”. This method is accepted as simply following “rational analysis”. Typically walls that are designed for force transfer around openings result in the walls being reinforced with nails, straps and blocking in the portions of the walls with openings. The authors are aware of at least three techniques which fall under the definition of rational analysis. The “drag strut” technique is a relatively simple rational analysis which treats the segments above and below the openings as “drag struts”. This analogy assumes that the shear loads in the full height segments are collected and concentrated into the sheathed segments above and below the openings. The second simple technique is referred to as “cantilever beam”. This technique treats the forces in the openings as a series of moment couples, which are sensitive to the height of the sheathed area above and below the openings. A graphical representation of these two techniques are given in Figure 1, the mathematical development of these two techniques is presented in Martin (2005).

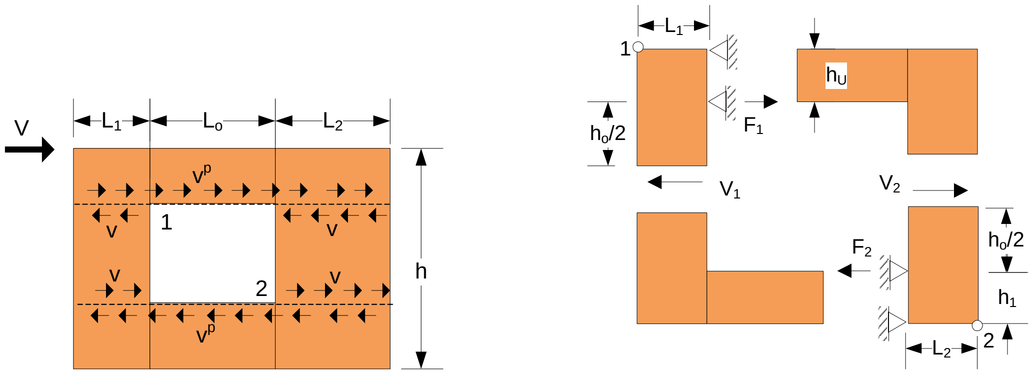

Figure 1. Representation of the drag strut technique (left), and the cantilever beam technique (right) for estimating forces around wall openings (Martin, 2005)

Finally, the more rigorous mathematical technique is typically credited to a California structural engineer, Edward Diekmann and well documented by Breyer et al. (2007). This technique assumes that the wall behaves as a monolith, and internal forces are resolved by creating a series of free body diagrams as illustrated in Figure 2. This is a common technique used by many west coast engineers in North America; however, it can become tedious for realistic walls that include multiple openings.

Of the three common techniques, the predicted internal forces can vary significantly, based on wall geometry. In extreme cases discussed below, the differences in the predicted internal forces may vary by 800%. The purpose of this research is to provide tangible data for comparison and perhaps improvement to the rational analysis methods.

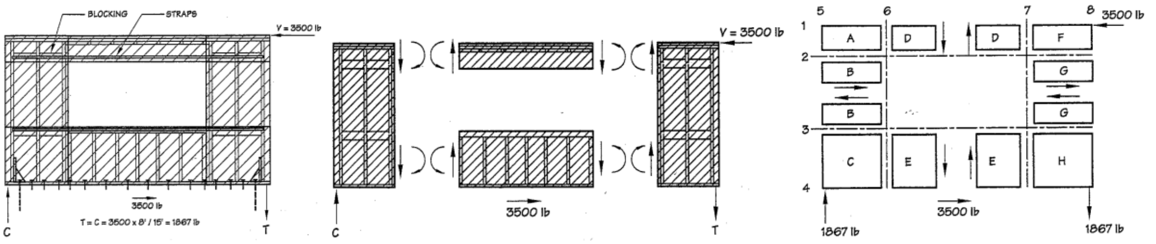

Figure 2. Representation of the Diekmann technique (1998) and drawings from Breyer et al. (2007). Global free body diaphragm of wall with openings (left), beam behaviour of various sheathed areas (center) and, horizontal and vertical cuts for establishing internal shears (right, 1 lbf = 4.45 N)

2. Test Plan

In an effort to collect internal forces around openings of loaded walls, a series of twelve walls were tested, Figure 3. This series was based on North American code permitted walls, nailed with 10d common nails (3.68 mm diameter by 76 mm long) at a nail spacing of 51 mm. The sheathing used in all cases was 12 mm (15/32-inch nominal) oriented strand board (OSB) APA STR I Rated Sheathing. All walls were 3.66 m long and 2.44 m tall. Wall 1 was based on the narrowest segmented wall (height-to-width ratio of 3.5:1) permitted by the code, with overturning restraint (hold-downs) on each end of the full height segments. The window opening of Wall 1 is common to many of the walls in this plan, at 0.91 m. Walls 2 and 3 are based on the perforated shear wall method, C_o = 0.93. Hold-downs are located on the ends of the wall and no special detailing, other than compression blocking for Wall 3, were built into the walls. Wall 4 is a force transfer around openings wall which has identical geometry to Walls 1, 2 and 3, and is to compare the various methods for designing walls with openings.

Wall 5 has the same width of piers as the first four walls; however, the opening size was increased to 1.52 m. Wall 6 was common to Wall 4, with the exception that the typical 1.2 x 2.4 m sheathing was "wrapped around" the wall opening in "C" shaped pieces. This framing technique is commonly used in North America. It is considerably more time efficient to sheath over openings, and remove the sheathing in the openings area via hand saw or router. Wall 7 is a segmented wall with height-to-width ratio of the full height segments to 2:1. Wall 8 is a match to Wall 7 but designed as a force transfer around openings wall. The window in Wall 9 is increased from 0.91 m to 1.53 m.

Walls 10 and 11 are very narrow wall segments, for use in large openings such as garage fronts. The two walls are designed with openings on either side of pier, and only on wall boundary, respectively. Finally, Wall 12 is an examination of a wall with two asymmetric openings.

Each tested wall was subjected to a cyclic loading protocol following ASTM E 2126, Method C, CUREE Basic Loading Protocol. The reference deformation, Δ, was set as 61.1 mm. The term α was 0.5, resulting in maximum displacements applied to the wall of +/- 122 mm. The displacement-based protocol was applied to the wall at 0.5 Hz, with the exception of Wall 8b, which was loaded at 0.05 Hz.

For walls detailed as force transfer around openings, two hold downs in line (facing seat-to-seat) were fastened through the sheathing and into the flat blocking (See Figure 3, Wall 4 and Figure 5 illustrating this detail). The hold-downs were intended to simulate the more typical detailed flat strapping around openings. The hold-downs were connected via a calibrated tension bolt for measuring tension forces.

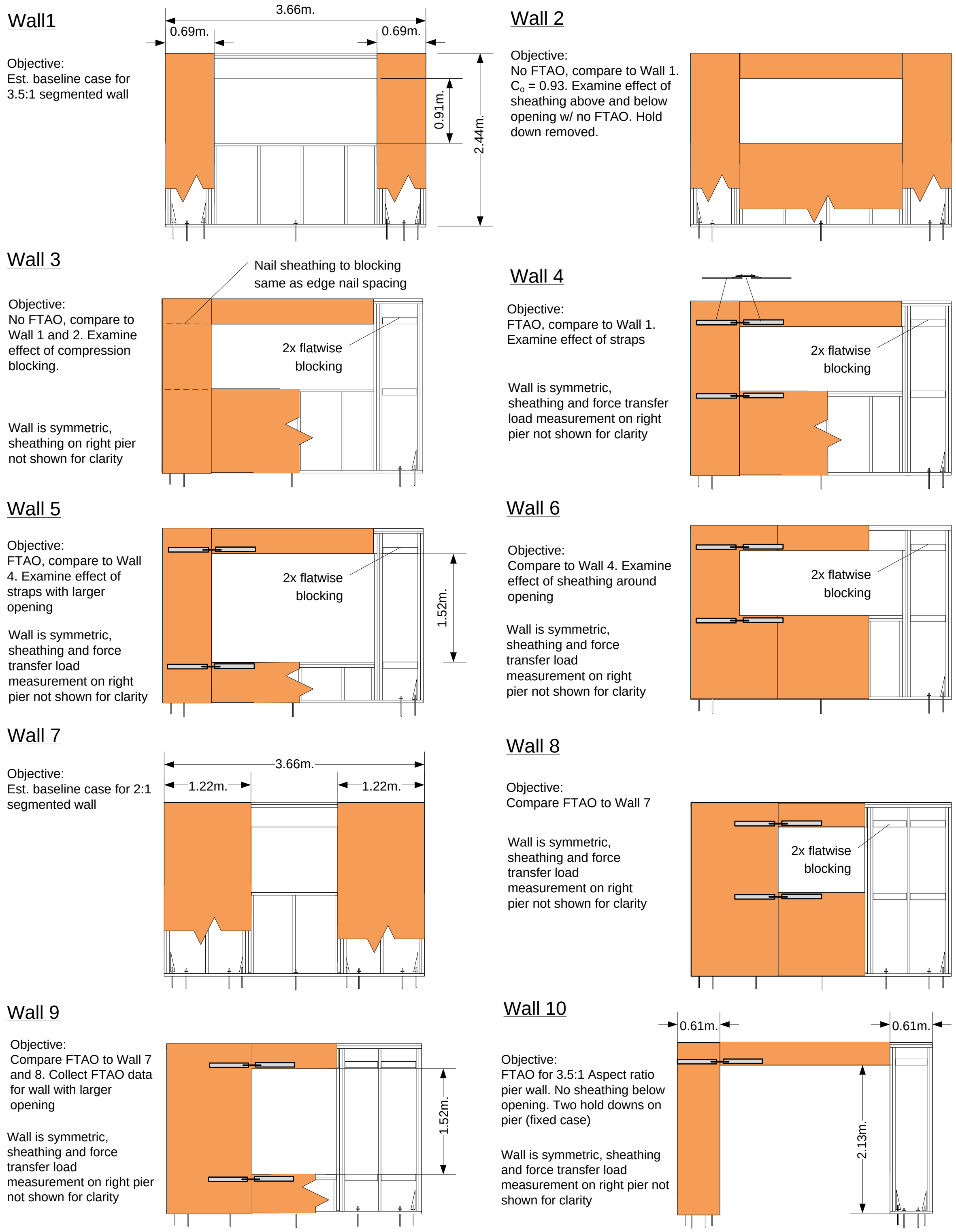

Figure 3. Test schematics for various force transfer around openings assemblies

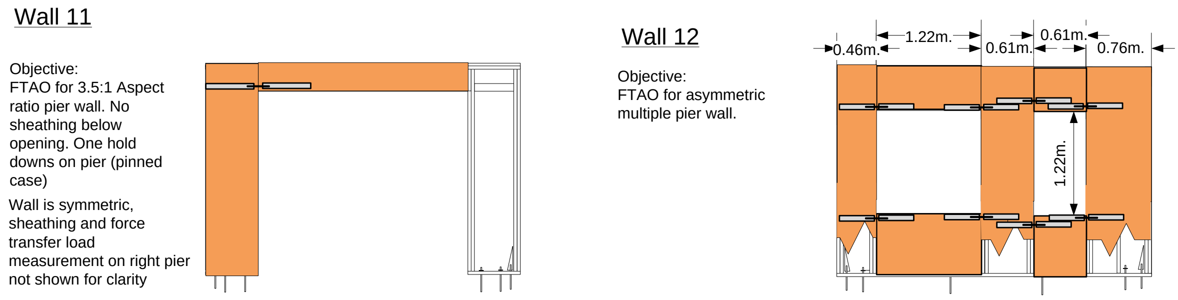

Figure 3 (continued). Test schematics for various force transfer around openings assemblies

3. Results

3.1 Global Response

Figure 4 are hysteric plots of the applied load versus the displacement of the walls. The response curves are representative for all walls tested. One can observe the relatively increased stiffness of perforated shear walls (Wall 2) versus the segmented walls (Wall 1); however, also note the relatively brittle nature of the perforated walls. As one might expect, the walls detailed for force transfer around openings (Wall 4d and 5d) demonstrated both increased stiffness and strength over the segmented walls. In addition, the response of the walls was related to opening sizes, with the larger openings resulting in both lower stiffness and lower strength.

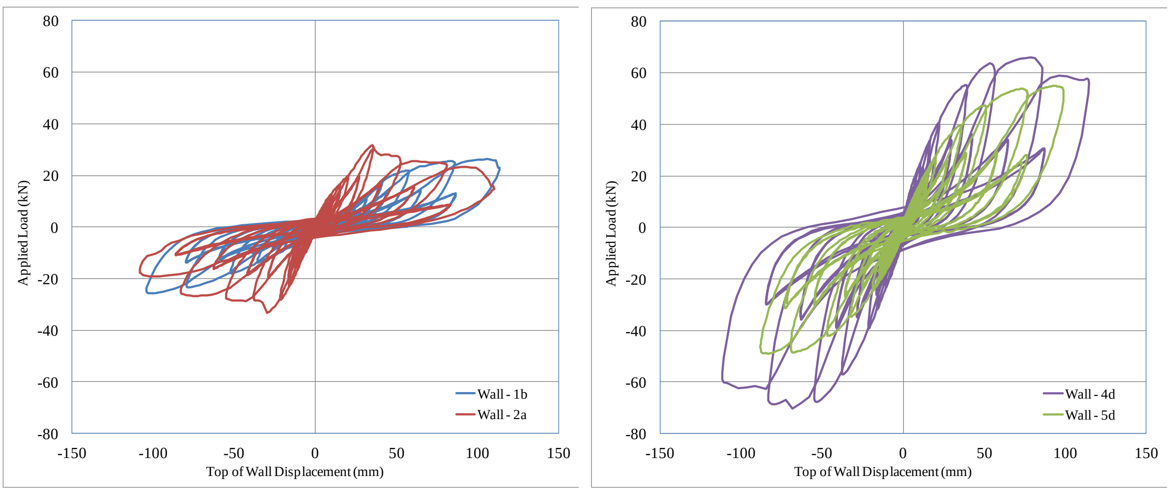

Figure 4. Hysteretic behaviour of various walls, typical of the cyclic tests

Table 1 represents the maximum loads resisted by the various walls and calculated load factors. The expected wall capacity is based on the code listed allowable stress unit shear multiplied by the length of the wall. For the perforated shear walls, a further factor of C_o was included.

Table 1. Global response of tested walls

Wall ID	ASD Unit Shear [1], v (kN/m)	Effective Wall Length [2] (m)	Wall Capacity [3] (kN)	Maximum Applied Load to Wall			ASD Load Factor[4]
				negative (kN)	positive (kN)	average (kN)	
Wall 1a	12.7	1.37	17.4	-23.9	24.4	24.1	1.4
Wall 1b	12.7	1.37	17.4	-25.7	26.3	26.0	1.5
Wall 2a	12.7	1.37	16.2	-33.3	31.6	32.5	2.0
Wall 3a	12.7	1.37	16.2	-43.2	49.1	46.1	2.9
Wall 4a	12.7	1.37	17.4	-62.7	70.2	66.4	3.8
Wall 4d	12.7	1.37	17.4	-70.4	66.0	68.2	3.9
Wall 5d	12.7	1.37	17.4	-49.1	54.9	52.0	3.0
Wall 6a	12.7	1.37	17.4	-47.1	59.2	53.1	3.1
Wall 7a	12.7	2.44	31.0	-54.7	56.8	55.8	1.8
Wall 8a	12.7	2.44	31.0	-66.3	70.6	68.5	2.2
Wall 8b [5]	12.7	2.44	31.0	-66.0	72.1	69.0	2.2
Wall 9a	12.7	2.44	31.0	-66.2	69.4	67.8	2.2
Wall 10a	12.7	1.22	15.5	-31.2	35.3	33.2	2.1
Wall 11a	12.7	1.22	15.5	-29.5	28.1	28.8	1.9
Wall 12a	12.7	1.83	23.2	-76.0	66.7	71.3	3.1

(1) Typical U.S. tabulated values are based on allowable stress design (ASD) unit shear.
(2) Based on sum of the lengths of the full height segments of the wall.
(3) The shear capacity of the wall, V, is the sum of the full height segments times the unit shear capacity. For "perforated shear walls" (Walls 2 & 3), this capacity was multiplied by C_o = 0.93.
(4) Wall capacity divided by the average load applied to the wall.
(5) Loading time increased by 10x.

In general, the segmented walls (Wall 1 and Wall 7) resulted in the lowest load factors of the walls tested. The perforated shear wall (Wall 2) also performed at a lower level than the walls specifically detailed with force transfer around openings. Surprisingly, the compression blocking with no straps (Wall 3a) resulted in a significantly improved performance over Wall 2. Another general observation is that the larger the wall opening, the lower the load factors. The wall global behaviour seemed to be insensitive to the different loading rate (Walls 8a and 8b). Finally, for walls with typical window openings with sheathing both above and below openings, the walls with the narrowest piers (height-to-width ratios of 3-1/2:1) based on minimum pier width in North American codes, resulted in higher load factors than walls with full width piers (height-to-width ratio of 2:1).

3.2 Local Response

The internal forces around openings were measured with calibrated tension bolts, as discussed in the test plan above. Although data is not presented in this paper, the tension forces in the hold-downs were also collected. Figure 5 illustrates the notation of the force gages as well as a typical response curve of wall load versus internal force around opening. The response curves show hysteretic behaviour, which is likely due to cumulative damage of the wall as well as the orientation of the bolt recording tension forces, which may be influenced by the differential displacement of the hold-down seats in the vertical direction. Deflection measurements were taken which could potentially be used to correct the load to "pure horizontal tension". However, in the range of the ASD capacity, the internal load response was relatively linear elastic. Table 2 provides a summary of measured internal forces at the allowable stress capacity of the walls. Test results on Wall 12 are not included in this paper due to the need for additional analysis and will be reported in a future paper.

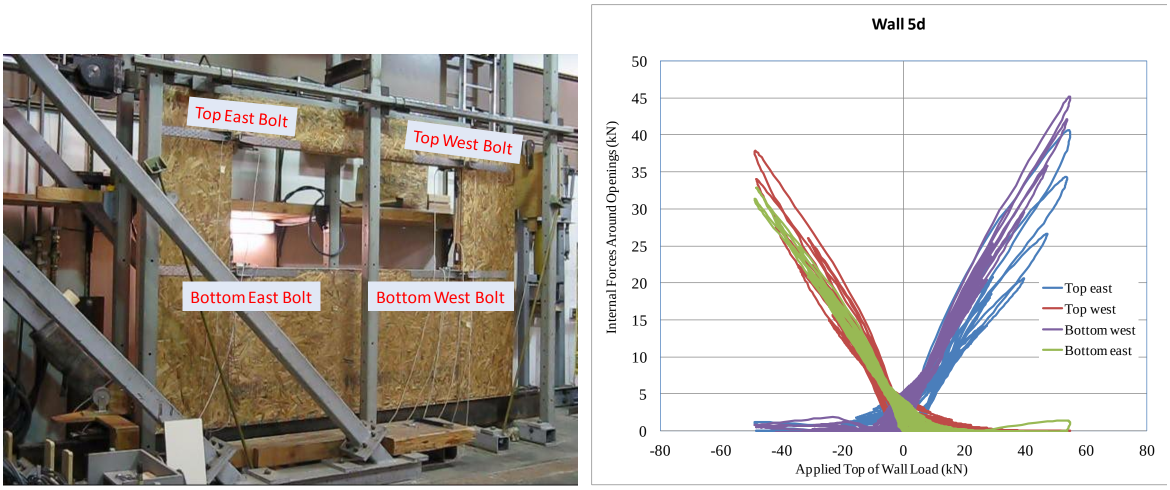

Figure 5. Notation of internal force gages (left), and typical response curve (right)

Table 2. Internal forces of tested walls at the design capacity (ASD) of the walls as compared to various predictions of strap forces

Wall ID	Measured Strap Forces (kN) [(1)]		Predicted Strap Forced at ASD Capacity (kN)				
			Drag Strut Technique		Cantilever Beam Technique		Diekmann Technique
	Top	Bottom	Top	Bottom	Top	Bottom	Top/Bottom
Wall 4a	3.3	6.6	5.4	5.4	19.9	12.1	8.7
	Error (%) [(2)]		165%	83%	603%	184%	132%
Wall 4d	4.2	6.8	5.4	5.4	19.9	12.1	8.7
	Error (%) [(2)]		131%	80%	478%	177%	128%
Wall 5d	7.7	10.5	5.4	5.4	27.4	20.6	14.5
	Error (%) [(2)]		71%	52%	355%	197%	139%
Wall 6a	2.1	2.0	5.4	5.4	19.9	12.1	8.7
	Error (%) [(2)]		262%	268%	957%	597%	419%
Wall 8a	4.4	6.3	5.2	5.2	35.4	21.5	8.3
	Error (%) [(2)]		117%	82%	802%	344%	132%
Wall 8b [(3)]	3.1	4.4	5.2	5.2	35.4	21.5	8.3
	Error (%) [(2)]		167%	116%	1145%	486%	186%
Wall 9a	7.9	8.3	5.2	5.2	35.4	28.1	13.8
	Error (%) [(2)]		65%	62%	449%	340%	166%
Wall 10a	8.2		5.2		34.8	--	41.3
	Error (%) [(2)]		63%		423%		502%
Wall 11a	9.6		5.2		34.8	--	41.3
	Error (%) [(2)]		54%		362%		429%
Wall 12a	Further analysis required						

(1) Reported strap forces were based on the mean of the "East" and "West" recorded forces at the capacity of the walls as tabulated in Table 1.

(2) Error based on ratio of predicted forces to mean measured strap forces. For Diekmann method, the larger of the top and bottom strap forces was used for calculation. Highlighted errors represent under-conservative predictions and significant ultra-conservative prediction (arbitrarily assigned as 300%).

(3) Loading time increased by 10x.

As shown in Table 2, the measured strap forces were based in the mean east and west strap forces for the top of the opening and the bottom of the opening. As demonstrated in Figure 5, the strap forces were symmetric about the y-axis, thus averaging strap forces was justifiable. Also shown in Table 2 are the predicted strap forces at wall capacity for the three techniques discussed above. The calculation of these forces is beyond the scope of this paper. However, Martin (2005) covers the drag strut and cantilever beam calculations, and Breyer (2007) covers the Diekmann calculations.

The Diekmann technique assumes symmetric forces at the top and the bottom of the wall; hence the maximum of the two measured strap forces was used for the error calculation. Also included in Table 2 is the error, in percent, of the calculated strap forces. There is shading for predictions that fall below 100% of the observed strap forces, which would be considered under-conservative. The errors are also shaded when the predictions exceed the measured forces by three times (300%), which are considered excessively conservative.

Several items may be observed from the test results reported in Table 2. First, in general, the forces at the bottom of the window openings were higher than the forces at the top of the window opening in all cases except for Wall 6. The measured strap forces for Wall 6 were the smallest strap forces of any of the walls tested. This is due to the fact that the forces were transferred through the wrap-around OSB sheathing, thus little demand was placed on the straps at this low load level. Also, as one would expect, as the openings in the walls increased, the strap forces increased. In addition, as the width of the full height pier decreased, the relative magnitude of the strap forces increased. The largest strap forces, relative to the applied load, were observed for the large garage type openings, Wall 10 and Wall 11. Other observations are that the strap forces are reasonably repeatable (Walls 4a and 4b, Walls 8a and 8b), and that the strap forces are relatively insensitive to loading rate (Walls 8a and 8b).

Several observations can also be made about the three methods for predicting strap forces. First, the drag strut technique, arguably the simplest method for estimating strap forces, resulted in predicted strap forces that were less than the observed strap forces for nearly every wall. The cantilever beam technique was, by far, the most conservative method. For every wall tested, the cantilever beam technique over predicted at least one of the strap forces by more than 300 percent. It should also be noted that although the cantilever beam technique decouples the strap forces at the top and the bottom of the window, it always predicted the strap forces at the top of the wall as higher than the bottom of the wall, which is based on the underlying assumption of the moment couples, since the height of the sheathed area above the wall was consistently less than the height of the sheathing below the opening.

Finally the Diekmann technique provided reasonable predicted results (within 190 percent) for all walls with the exception of Walls 6, 10, and 11. As discussed above, Wall 6 was an atypical wall since the sheathing wrapped around the opening, thus the forces were transferred through the sheathing as opposed to the strap forces. For the large openings, it is believed that the Diekmann technique was very conservative due to the assumption that the walls behave as a homogeneous monolith. However, much wood crushing, separation between ends of header and pier studs and compression between adjacent pieces of OSB resulted in the observed forces as being significantly less than the predicted strap forces for all three techniques.

4. Summary and Conclusion

Twelve different wall assemblies were tested to study the effects of openings on both the global and local response of walls. Several of these assemblies were tested with multiple replications. The replications showed good agreement between each other, even when test duration was extended to ten times greater the original duration. In terms of global response, the segmented wall approach resulted in walls with the lowest load factors (based on observed global load divided by allowable capacity of the walls), followed by walls built as perforated shear walls (i.e. no special detailing for forces around openings), and finally the walls specifically detailed for force transfer around openings. In general, as opening sizes increased, the wall strength and stiffness values were negatively impacted. An observation that was not expected is that for walls with typical window openings, the walls with the narrowest piers based on minimum pier width in North American codes, resulted in higher load factors than walls with full width piers (height-to-width ratio of 2:1).

Of the twelve walls tested, internal forces were collected on eight of the assemblies. For the walls tested, the measured forces at the bottom of the windows were greater than the measured forces at the top of the window. Also, as expected, as the window opening increased and as the pier width decreased, the strap forces increased relative to the global applied force to the wall. Of these eight assemblies, one can conclude that the drag strut technique consistently underestimated the strap forces, and the cantilever beam technique consistently overestimated the strap forces. The Diekmann technique, the most computationally intensive, provided reasonable strap force predictions for the walls with window type openings. The Diekmann technique significantly over predicted the strap forces for large garage type openings.

5. Acknowledgements

This work is a joint research project of APA – The Engineered Wood Association, the University of British Columbia, and the USDA Forest Products Laboratory. This research was supported in part by funds provided by the Forest Products Laboratory, Forest Service, USDA.

6. References

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