LATERAL RESISTANCE OF POST-FRAME SHEAR WALLS WITH OPENINGS

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Over the past several years, the National Frame Building Association has sponsored several research and development projects to provide the technical data needed by engineers for the design of code-conforming post-frame buildings that will resist lateral loads. The outer shell of post-frame buildings can provide significant resistance to lateral loads, such as those from wind and seismic events. However, when openings are cut into the outer shell, the system can be weakened. The project reported on in this article focuses on the lateral resistance of steel-clad wood-framed shear walls with openings such as windows, doors and wainscoting. Wainscoting (steel and oriented strand board) and three different types of openings were investigated: a 4' x 4' window, a 6' x 6' window, and a 3' x 7' pedestrian door. The shear-wall capacities were first predicted using a computer-based finite element analysis to help guide the experimental design. Several shear walls with openings and wainscoting were then tested, along with some reinforcement methods. Finally, we examined design methods to account for shear walls with openings.

FINITE ELEMENT ANALYSIS

The finite element model developed by Mai (2016) was used prior to testing to investigate the lateral capacities of SCWF shear walls with openings. The model proved to be remarkably accurate, and it showed that steel and OSB wainscoting did not reduce the capacities of the shear walls, provided that the fastening schedule at the wainscot splice was the same as the one used in the perimeter of the shear wall. Testing was also performed on several walls with wainscoting, and the results agreed with the finite element modeling: no reduction in strength was observed. Details on the test results on wainscoting can be found in Bender and Gatchalian (2016). Given that no reduction in structural capacity was observed for the wainscoting options studied (steel panels and OSB), the remainder of this article focuses on shear walls with door and window openings.

Although finite element analysis can accurately predict the performance of SCWF shear walls with openings, it may not be practical for most design situations because of its complexity and computational requirements. Later in this article, we review a practical shear-wall design methodology for use with SCWF shear walls.

TESTING SCWF SHEAR WALLS WITH OPENINGS

Description of Wall Specimens

All test specimens used nominal 29-gauge, 80 ksi (thousand pounds per square inch) yield strength corrugated steel cladding (*Grandrib 3*). Steel panels were attached to the wood framing using #10 x 1-inch structural screws in the field, and #12 x 1.5-inch and #12 x 3/4-inch stitch screws at the steel lap joints. All wall specimens were 16 feet long by 12 feet high with 2 bays spaced at 8 feet. Three-ply nail-laminated posts were constructed using pressure-preservative-treated nominal 2-inch x 6-inch hem-fir No. 2 and Douglas fir–larch select structural lumber. Nominal 2-inch x 4-inch spruce-pine-fir 1650f-1.5E lumber was used for girts and blocking. The skirt board and truss members used nominal 2-inch x 8-inch PPT hem-fir No. 2 and nominal 2-inch x 6-inch Douglas fir–larch select structural lumber, respectively. Construction details of a subset of the walls can be seen **Figures 1–4**. **Figure 5** shows a shear wall with a window opening during a test, with major ribs spaced at 9 inches on center. Loads were applied along the tops of the shear walls from right to left. All openings were placed in the right bay of the SCWF shear wall so that the weakened segment of the shear wall was loaded first, i.e., the load was applied from right to left. Finite element analyses were used to compare the predicted strengths for simulated shear loads coming from the left or right, and the direction chosen was approximately 3% less; hence our loading configuration gave slightly conservative results. Additional details of the testing can be found in Bender and Gatchalian (2016).

The shear-wall tests were conducted in accordance with ANSI/ASAE EP558.1 (American Society of Agricultural and Biological Engineers, 2014). Fifteen wall types with a total of 21 specimens were tested. A majority of the wall types had 36-inch girt spacing, #12 x 1.5-inch structural screws along the steel overlap at the girt, and #12 x 3/4-inch stitch screws along the steel overlap between the girts. One wall type had 24-inch girt spacing and #12 x 1.5-inch structural screws along the steel overlap at the girt.

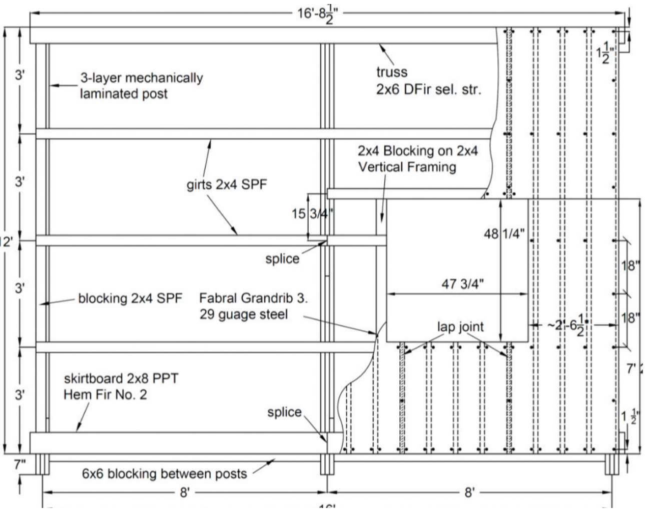

Figure 1. Case 1: 4′ x 4′ window opening

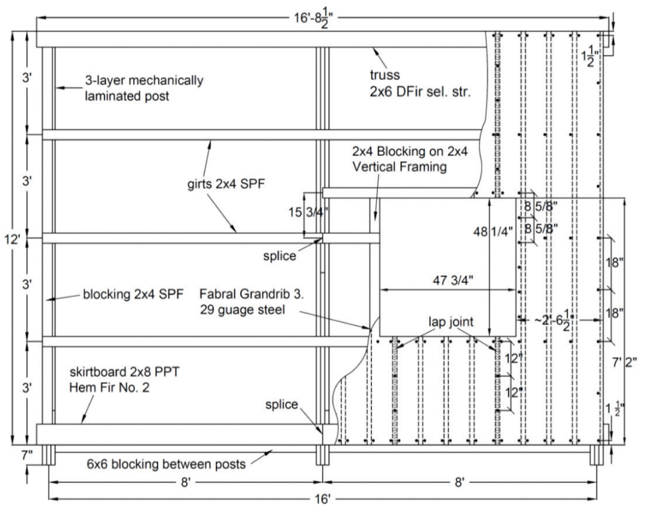

Figure 2. Case 2: 4′ x 4′ window opening with extra fasteners around the window

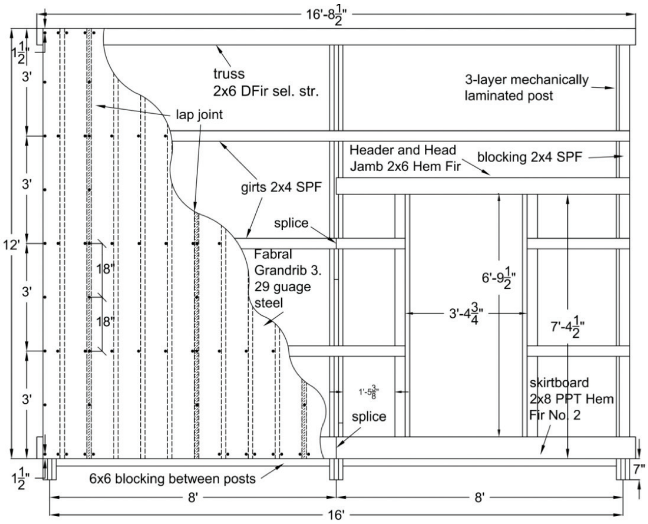

Figure 3. Case 3: Pedestrian door opening (3' x 7')

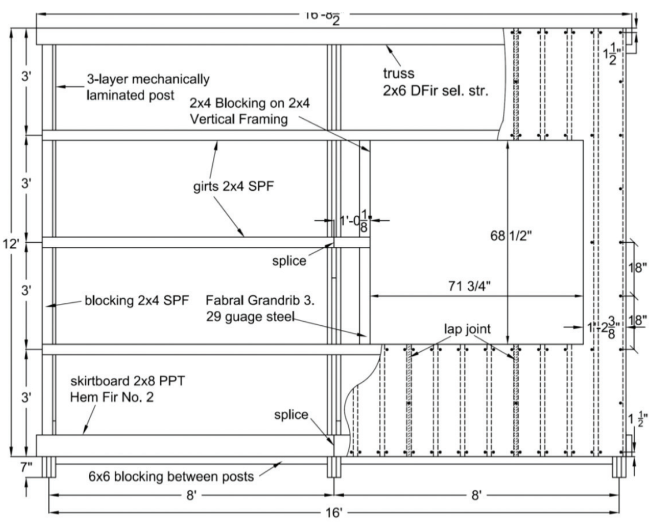

Figure 4. Case 9: 6' x 6' window opening

Testing Results

Various ways of reinforcing walls with openings were investigated, including extra fasteners around the opening perimeter, OSB, lumber bracing and steel straps. Although no reinforcement method completely restored the original capacity, all methods provided some benefit. Details can be found in Bender and Gatchalian (2016). For example, the 4' x 4' window opening was reinforced with extra screws around the window perimeter (Case 2 in Figure 2), and a slight improvement in strength can be seen in **Table 1**. If we simply subtracted the 4-foot window opening from the length of the shear wall, then we might expect the result of 75% residual strength: (16 ft. – 4 ft.)/16 ft. = 75%. However, the wall performed better, with residual strengths ranging from 88% to 92%. Similarly, for a 6-foot wall, we might expect a residual strength of 63%: (16 ft. – 6 ft.)/16 ft. = 63%; yet the wall actually retained 76% of its original capacity. Finally, the result for a 3-foot pedestrian door would be (16 ft. – 3 ft.)/16 ft. = 81%, which almost exactly matches the test data. Clearly, a door opening that extends to the bottom of the shear wall causes a greater strength reduction than a window with sheathing surrounding the opening.

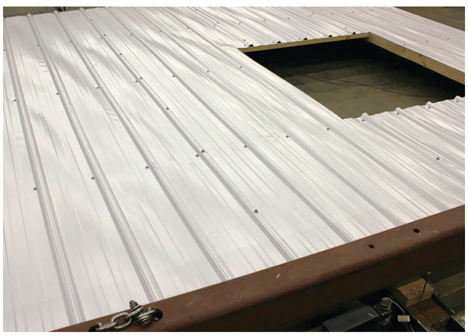

Figure 5. Buckling pattern for a shear wall with a 4′ x 4′ window. Note that the bottom fastening of the wall is obscured by the steel beam used to restrain out-of-plane movement during testing.

Table 1. Percentage of Original Capacity in Shear Wall with Opening

Shear Wall ID	Ultimate shear strength *with* opening (lb_f)	Ultimate shear strength *without* opening (lb_f)	Percent of original capacity
Wall with Window Opening			
4' x 4' opening–rep 1	5,677	6,443	88%
4' x 4' opening–rep 2	5,727	6,443	89%
4' x 4' opening with extra screws	5,895	6,443	92%
6' x 6' opening	4,911	6,443	76%
Wall with Door Opening			
Pedestrian door (3' x 7')	5,130	6,443	80%

Note. lb_f = pound-force.

DESIGN METHODS

The design of wood-sheathed wood-frame shear walls has been extensively studied, so we will seek clues from those studies of WSWF shear walls that might apply to SCWF post-frame shear walls. Three methods are commonly used for designing wood light-frame shear walls with openings: (1) the segmented shear-wall approach, (2) the perforated shear-wall approach, and (3) force transfer around openings. The segmented shear-wall approach ignores the contribution of wall segments with openings. The perforated shear-wall method uses an empirical reduction factor that was developed for wood shear walls. The force transfer around openings method requires a rational analysis to determine required reinforcements around the openings. The American Plywood Association (2011) performed tests and calculations to compare three rational methods, with the Diekmann (1997) method being the most accurate way to predict the reinforcing strap forces. Diekmann's method is a tool that post-frame designers can use to determine necessary reinforcement around openings for post-frame shear walls. A detailed explanation of Diekmann's method is beyond the scope of this article, but engineers will find it very useful and are encouraged to read his paper. In the next section, we discuss the simplest approach, called the segmented shear-wall method.

Segmented Shear-Wall Design Method

The segmented shear-wall approach is a common method for designing light-frame shear walls and is described in the *Post-Frame Building Design Manual*, second edition, published by NFBA (2016). This approach divides the wall into full-height sheathed segments, which can be seen in **Figure 6**. The contribution of a wall segment with an opening is assumed to add no resistance. The sum of the lengths of each full-height sheathed segment is the total length of the shear force resisting system. For this design, hold-down connectors are required at both corners of every full-height sheathed segment. It is important to note that for the shear walls studied, the only hold-downs were the three posts, located at each end and in the middle of the wall. Later we will see that even without having a hold-down at each wall segment, the segmented wall design method was conservative. Equation 1 is used to calculate the total allowable shear-wall capacity.

$$V = v \sum L_i \quad (1)$$

where

V = total allowable shear-wall capacity (lb_f)
v = allowable shear capacity per unit length (lb_f/ft)
$\sum L_i$ = sum of lengths of full-height sheathing segments

A summary comparison of two shear-wall design meth-

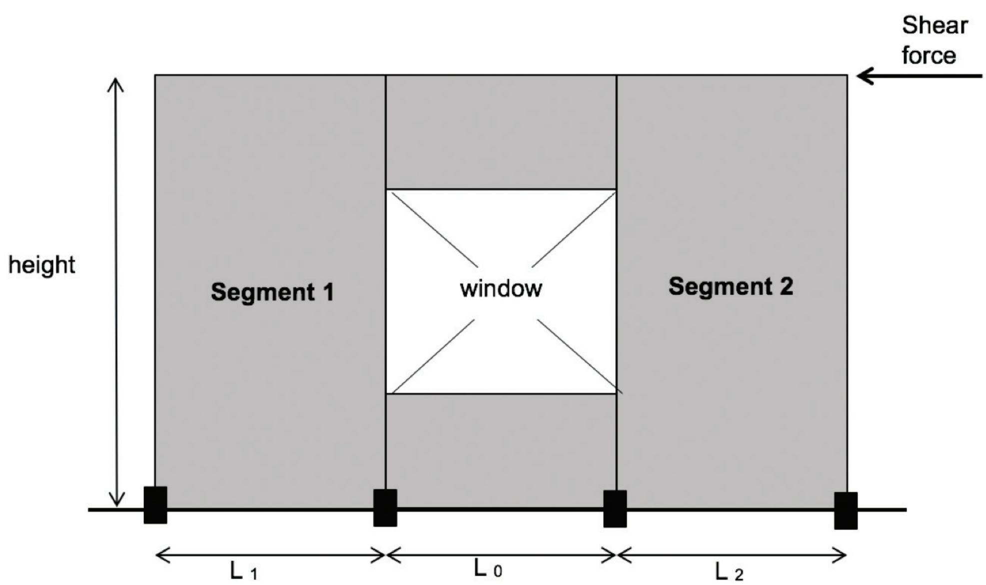

Figure 6. Sketch of the segmented shear-wall approach. Locations of hold-downs are marked.

Table 2. Comparison of Shear-Wall Design Methods

Shear-Wall Case	Description	Measured Allowable Design Shear, V (lb$_f$)	Ratio: Predicted/Tested	
			Segmented	Perforated
1	window 4' x 4'	2,271	85%	71%
3	door 3' x 7'	2,052	101%	89%
9	window 6' x 6'	1,964	81%	55%
		Average	**89%**	**72%**

ods can be seen in **Table 2**. The segmented shear-wall design approach was more accurate than the perforated shear-wall approach. As the window opening became larger, the perforated method provided less accurate (more conservative) calculated design values. This was expected because the perforated method relies on an empirical factor developed for wood shear walls.

Effect of Narrow Shear-Wall Segments

Tall, narrow shear-wall segments have relatively high aspect ratios (height/width). For high aspect ratios, the wall segments begin to act less like a shear wall and more like a beam. ANSI/AWC SDPWS-2015 provides strength reductions for WSWF shear walls with high aspect ratios. Little is known about the effect of aspect ratio on SCWF shear walls. To learn more, we used the finite element analysis model originally developed by Mai (2016) to analyze the effect of aspect ratio on the lateral capacities of SCWF shear-wall segments.

The SCWF shear walls analyzed had 24-inch girt spacing and three types of common constructions: unstitched, heavily stitched, and lightly stitched. The unstitched SCWF shear wall had no stitch screws at the lap joint of the steel panels; the heavily stitched and lightly stitched SCWF shear walls used #12 x 3/4-inch stitch screws at 8-inch-on-center and 24-inch-on-center spacing, respectively. Each simulated segment was set between two posts, and the segment height was kept constant at 12 feet. For all aspect ratios, an attempt was made to center the steel lap joints on the shear-wall segment without leaving excess material past a major rib. The shear-wall segment with an aspect ratio of 4:1 used two 18-inch corrugated steel sheets to allow the use of stitch screws at a lap joint.

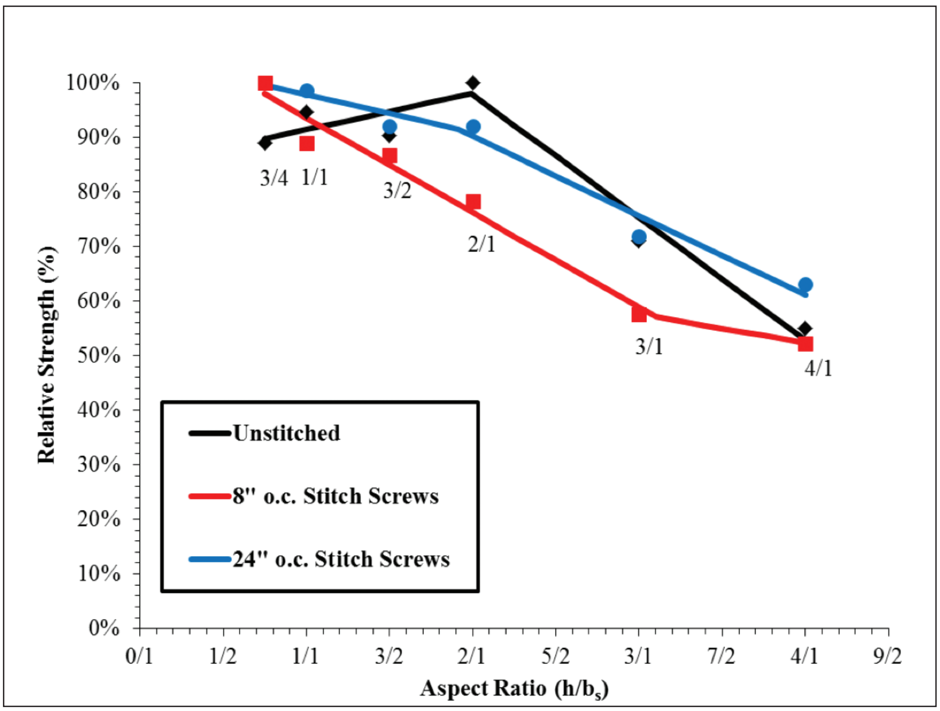

Figure 7. Relative design unit shear strength versus aspect ratio curve

The relative design unit shear strength versus the aspect ratio is shown in **Figure 7** for the unstitched, heavily stitched, and lightly stitched SCWF shear-wall constructions. The relative unit strength is not significantly affected until the aspect ratio reaches 2:1. Interestingly, the same is true for WSWF shear walls (American Wood Council, 2015). The maximum aspect ratio allowed for WSWF shear walls is 3.5:1. A linear strength reduction ranging from 1.0 to 0.81 must be applied for aspect ratios between 2:1 and 3.5:1 for WSWF shear walls, respectively. Figure 7 shows a larger reduction in strength for SCWF shear walls, with a reduction of approximately 0.64 at an aspect ratio of 3.5:1.

So how should a designer deal with narrow shear-wall segments that have high aspect ratios? We suggest that the technical community in NFBA examine this matter and develop design recommendations that can be incorporated into post-frame design standards and the *Post-Frame Building Design Manual*. In the interim, designers may want to follow the aspect ratio limits given in ANSI/AWC SDPWS-2015 (AWC, 2015), which indicates that for a wall segment with an aspect ratio greater than 3.5:1, the wall segment should not be considered in the sum of shear-wall segments in Equation 1. In addition, a reduction in wall strength appears warranted for aspect ratios greater than 2:1.

SUMMARY AND CONCLUSIONS

Post-frame buildings usually rely on diaphragm action and shear walls to resist lateral loads from wind and seismic events. Openings in shear walls, such as windows and doors, can reduce the lateral resistance capacity and should be considered in the design process. This article summarizes recent test results on shear walls with openings and examines design methods to account for the openings. Wainscoting (steel and OSB) were also evaluated and found not to reduce the shear-wall capacity when appropriate perimeter fastening was used.

The segmented shear-wall design method is perhaps the simplest and most intuitive approach, in which only those shear-wall segments with no openings are added together to provide the total lateral resistance. On the basis of on our study, the segmented shear-wall method will provide conservative results. One open question is how to deal with shear-wall segments that are narrow and that have high aspect ratios. We recommend that NFBA's technical community develop guidelines to account for aspect ratios in narrow shear-wall segments.

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