

Advancements in Force Transfer Around Openings for Wood Framed Shear Walls

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Abstract

A joint research project of *APA – The Engineered Wood Association*, University of British Columbia (UBC), and USDA Forest Products Laboratory 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 analysis techniques, including the segmented method, the perforated shear wall method, and the force transfer around openings method. Full-scale wall tests as well as analytical modeling were performed. The research results obtained from this study have been used to support design methodologies in estimating the forces around the openings. Test results from the (8 feet x 12 feet) full-scale wall configurations, in conjunction with the analytical results from a computer model developed by UBC, were used to develop and refine rational design methodologies for adoption in the U.S. design codes and standards.

Asymmetric piers, multiple openings, and C-shaped sheathing were investigated and rational design methodologies in accordance with the International Building Code (and California Building Code) have been created. A new *APA System Report, SR-105: Design for Force Transfer Around Openings*, is under development and will guide users on the application of this new methodology to provide a structurally sound and efficient shear wall system. This paper provides insight to the creation of the System Report, examples of its application, and how to best utilize this method in wood framed construction. This research was supported in part by funds provided by the USDA Forest Products Laboratory, which is acknowledged and greatly appreciated by the project team.

Introduction

Force transfer around openings (FTAO) is a popular method of shear wall analysis for wood-framed shear walls. However, the analysis method varies from engineer to engineer, published design examples typically assume the wall is symmetric around a single opening, and until recently, this design method has not been tested.

This paper discusses the shear wall design challenges structural engineers currently face, the shear wall testing that APA – The Engineered Wood Association has recently conducted, and its results. Outcomes from our testing include a rational analysis for applying FTAO to walls with asymmetric piers and walls with multiple openings, and calculating the deflection for walls detailed for FTAO. For clarity, design examples are provided in addition to the test results.

Shear Wall Design Challenges

Proper design of wood shear walls is a critical component of the lateral force resisting system. The California Building Code (based on the 2012 International Building Code) refers the engineer to the Special Design Provisions for Wind and Seismic (SDPWS-08 Section 4.3.5) for three design methods: individual full-height wall segments (segmented), force-transfer shear walls (FTAO), and perforated shear walls (perforated). Each method has benefits and challenges. Most structural engineers use the first approach, segmented, where feasible. Segmented design utilizes wood structural panels (WSP, being either plywood or Oriented Strand Board [OSB]) in full-height segments without any penetrations included (Figure 1). The WSPs transfer the shear, anchor

bolts resist the sliding, and hold-downs resist the overturning of the wall. The main benefit of the segmented approach is simplified design (no need to detail for openings), which lends itself to a faster design. The main limitation is the aspect ratio as discussed below.

FTAO utilizes wood structural panels with openings. As with the segmented approach, the WSPs transfer the shear force; generally, flat steel straps are used on top of the WSPs, above and below the opening, to transfer tension forces, with flat blocking on the inside of the wall to transfer compression forces around the opening (Figure 2). This design method requires a more comprehensive analysis and detailing, depending on the wall's geometry. However, it has significant benefits when considering aspect ratio, anchorage requirements, and the nonstructural benefits of a consistent wall plane created through the use of continuous sheathing.

Finally, perforated also uses WSPs with openings, but it is an empirically based method where the engineer applies a penalty to the shear, hold-downs, and anchorage capacities based on the percentage of full height sheathing and the size of the largest opening in the wall. The main benefit to this method is its ease of design, but its limitations include the aspect ratio and additional anchorage required at the bottom of the wall.

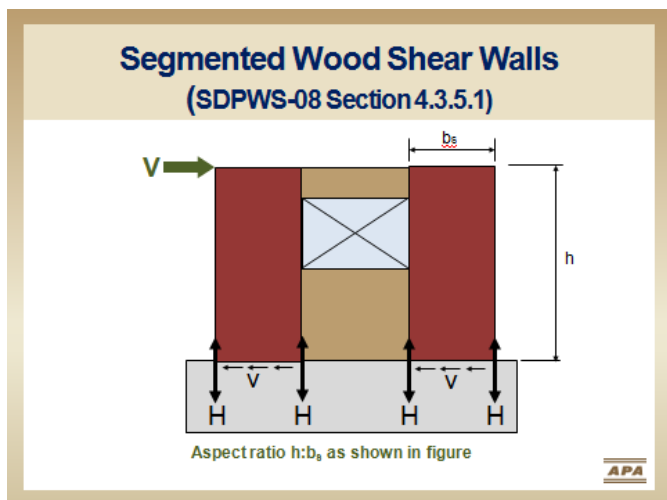


Figure 1—Representation of segmented design methodology.

Maximum aspect ratios are defined in SDPWS-08 Section 4.3.4 for all three design methods. For walls designed to resist seismic forces, the maximum aspect ratio is limited to 2:1 unless the designer chooses to apply a penalty of multiplying the nominal shear capacity by $2b_s/h$ (twice the shear wall width divided by the wall height) which allows an aspect ratio of 3.5:1 for blocked wood structural panel shear walls. Differentiating the three design methods with regard to aspect ratios, the segmented and perforated methods define h

as the height of the wall segment from bottom plate to top plate. On the other hand, FTAO's h is the height of the opening the segment is adjacent to. This is a major advantage to FTAO, as most structural engineers use FTAO when they cannot meet the aspect ratio limitations for segmented design.

In APA's experience, engineers typically use the segmented approach first, and FTAO when the aspect ratio will not work for segmented. As previously stated, FTAO requires designing the forces to transfer around the opening using a rational analysis. Yet, there is a wide array of analysis methods used that result in very different solutions. This was a key motivating factor for APA's first phase of research into FTAO. At the same time, the research investigated the impacts of different wall geometries and detailing as discussed below. In APA's research of published FTAO design examples, it was observed that all methods assumed equal pier widths and only one opening. Results from our testing include walls with multiple openings and asymmetric piers.

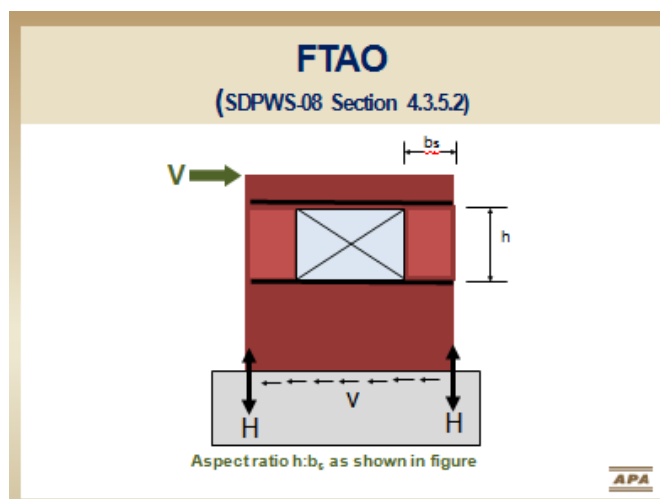


Figure 2—Representation of force transfer around openings (FTAO) methodology.

Using this new rational analysis, engineers will be better equipped to quickly design shear walls with openings. Another structural advantage is the elimination of hold-downs. Using FTAO, the engineer designs the hold-downs for the boundaries, eliminating two or more hold-downs that would otherwise be sized for the segmented approach.

Aside from the structural benefits of WSPs, there are additional benefits to continuous sheathing, including: creating an uninterrupted drainage plane; enabling the WSPs to act as an air barrier; providing a continuous nail base for stucco (cladding materials); and creating a stiffer wall, mitigating stucco cracking, as well.

Drainage planes are typically covered by architectural details and can be accommodated in many fashions. One general rule is to direct water away from the building. Using continuous WSPs assists in the drainage process. Even when homes are sheathed only at the full-height piers, often sheathing will be added around the perimeter of the windows and the base of the wall to assist in the attachment of flashing and cladding.

There is widespread agreement that air infiltration is one of the most significant sources of energy loss in buildings. An air barrier inhibits air leakage through the building envelope. An efficient and cost-effective way to achieve an effective air barrier on walls is to incorporate a continuous, solid layer on the exterior of a building. The continuous solid material should be stiff enough to minimize the amount of deflection when pressure is applied to tape or sealants, which are applied to panel joints and around penetrations. Using continuous structural sheathing as part of the air barrier system provides a stiff support base for stucco, permits the option to incorporate box beam headers, and results in more earthquake resistant buildings.

Finally, the cladding needs to be attached to the structure to resist wind pressures and mitigate cracking in brittle materials such as stucco. Without continuous WSPs, the framer needs to connect the cladding to studs located 16 to 24 inches on center. With continuous sheathing, you have a constant nail base for attaching your finishes to. Beebe (2014) provides more detailed recommendations for addressing energy concerns and cladding detailing.

History of FTAO Research at APA

The APA research on FTAO was initiated by Zeno Martin (2005). Martin provided a detailed review of the three common design methods of a wood shear wall with openings: traditional segmented shear wall approach, drag strut method, and cantilevered beam analogy. Diekmann (2005) provided a discussion on Martin's article and presented a method he proposed (1997) based on Vierendeel truss analogy. One of the interesting findings of the Martin/Diekmann dialogue was that, depending on the geometry of wall and openings, the three design methodologies significantly differed. For the example wall with opening, the cantilever beam analogy yielded strap forces approximately five times higher than estimated following the drag strut analogy. The Diekmann method provided strap force estimates that were approximately two times higher than the drag strut method. This discussion raised a question of which design analogy was more correct. Kolba (2000) performed a detailed experimental study on perforated wood shear walls focusing on the applicability of Diekmann's method. Although the results were inconclusive, detailed explanations of the

assumptions of Diekmann's method were provided. Although not rigorously discussed by Yeh et al. (2011) the technique developed by Doug Thompson (SEAOC, 2007) is also included in the data analysis in this paper.

The FTAO method is codified and accepted as following rational analysis. The 2008 SDPWS specifies minimum pier length (2 feet) and provides limitations on out-of-plane offsets. Significant engineering consideration has been given to the topic of rational analysis (SEAOC Seismology Committee, 2007) and excellent examples targeted to practitioners have been developed by a number of sources (SEAOC, 2007; Breyer et al., 2015; Diekmann, 1997). The lack of available test data and the number of rational analyses were the main motivators of the 2009 joint research project. Yeh (2011) provides a comprehensive discussion on various rational analyses, as well as test data that will be highlighted below.

Test Data

In an effort to collect internal forces around openings of loaded walls, a series of twelve wall configurations were tested, as shown in Figure 3. The left-hand side of Figure 3 illustrates a framing plan, which also includes anchor bolt and hold-down location and additional details. On the right-hand side of Figure 3, the sheathing and strapping plan is illustrated. This test series is based on the North American code-permitted walls nailed with 10d common nails (0.148 inches by 3 inches) at a nail spacing of 2 inches. The sheathing used in all cases was nominal 15/32-inch oriented strand board (OSB) APA STR I Rated Sheathing. All walls were 12 feet long and 8 feet tall. The lumber used for all of these tests was kiln-dried Douglas-fir, purchased from the open market, and tested after conditioning to indoor laboratory environments (i.e., dry conditions). Each individual 2x4 stud was nailed to the respective end plates with two 16d common (0.162 inch by 3-1/2 inches) end nails. The headers were built-up double 2x12s with a 1/2-inch wood structural panel spacer between the two pieces of lumber. In general, built-up 2x members were face-nailed to each other, with 10d common nails face-nailed at 8 inches on center.

The walls were attached to the steel test jig with 5/8-inch diameter anchor bolts, spaced as shown in Figure 3, with 3x3 x0.229-inch square plate washers. In some cases, 5/8-inch Strainert calibrated bolts were substituted for the anchor bolts such that uplift forces at the anchor bolts could be directly measured. Figure 3 illustrates anchor bolt location, including location of the calibrated bolts. Simpson Strong-Tie HDQ8 hold-downs, attached to the double 2x4 end studs with twenty 1/4-x3-inch SDS screws, were used to resist the overturning restraint for the twelve wall configurations.

These hold-downs were attached to the steel test jig with 7/8-inch diameter bolts. In some cases, 7/8-inch calibrated bolts were substituted for the hold-down bolts such that hold-down forces could be directly measured.

Wall 1 is 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 (segmented approach). The height of the window opening for Wall 1 is common to many walls tested in this plan, at 3 feet. 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 with no special detailing other than the compression blocking on Wall 3. Wall 4 is a force transfer around openings (FTAO) wall, which has identical geometry to Walls 1, 2 and 3, and is used 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 height was increased to 5 feet. Wall 6 was identical to Wall 4, with the exception that the typical 4 feet x 8 feet sheathing was wrapped around the wall opening in 'C' shaped pieces. This framing technique is commonly used in North America. It can be more time efficient to first sheath over openings, and remove the sheathing in the openings with a hand power saw or router later.

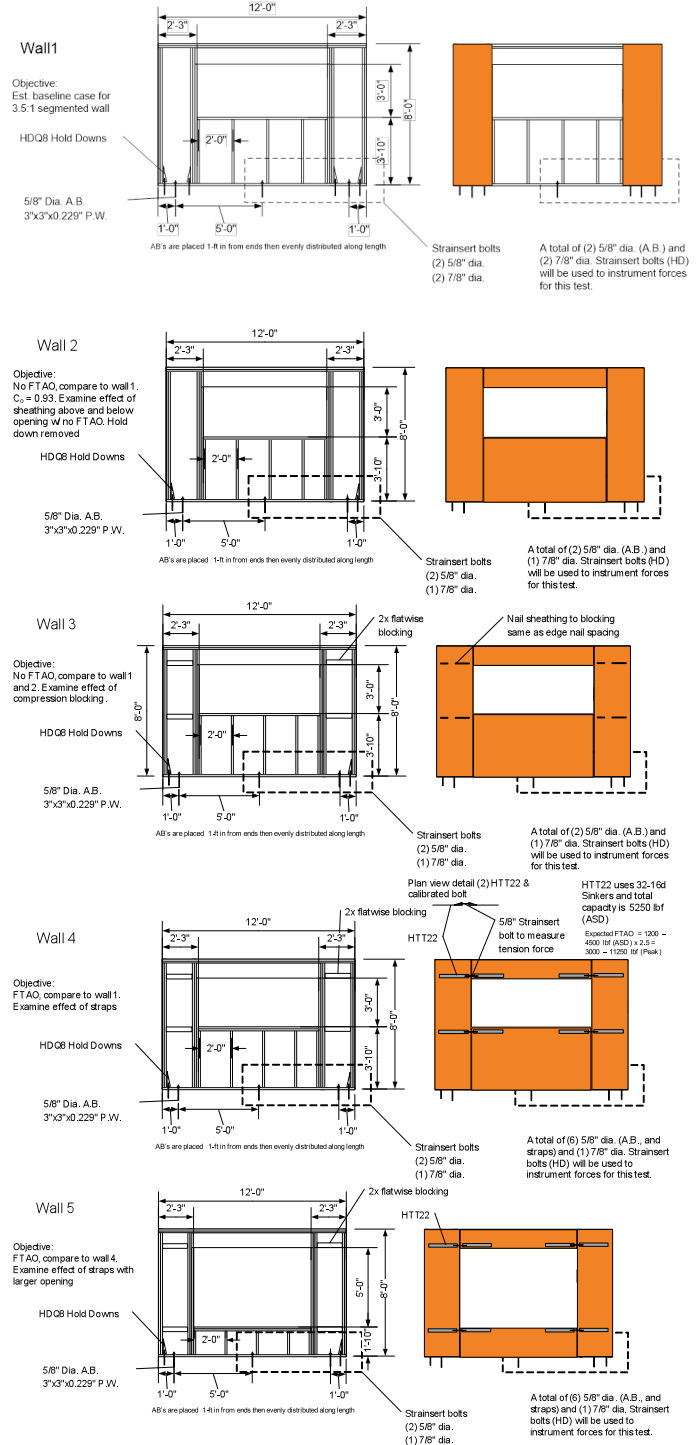
Wall 7 is a segmented wall with height-to-width ratio of the full-height segments equal to 2:1. Wall 8 is a match to Wall 7, but designed as a FTAO wall. The window height in Wall 9 is increased from 3 feet to 5 feet tall. Walls 10 and 11 contain very narrow wall segments for use in large openings such as garage fronts. The two walls are designed with openings on either side of a pier and only one wall boundary, respectively. Wall 12 contains a wall with two asymmetric openings.

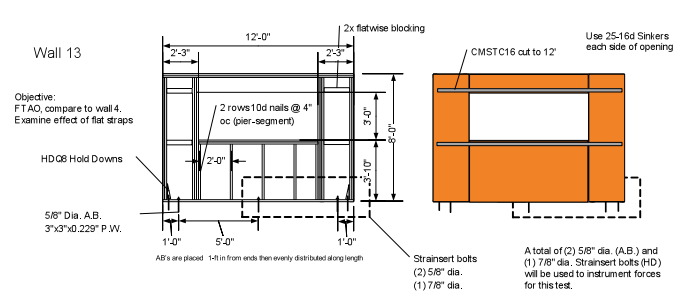
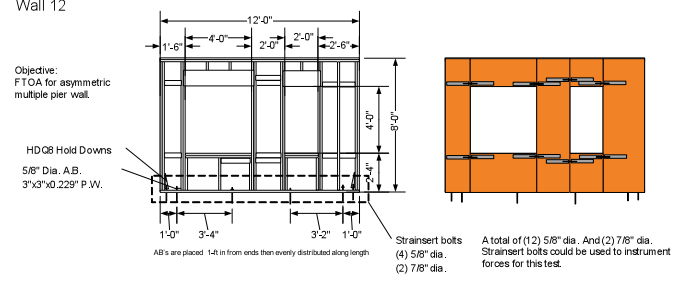
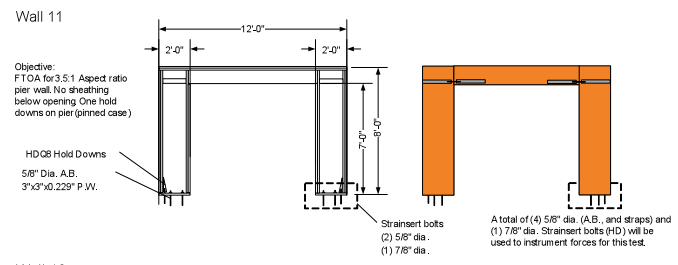
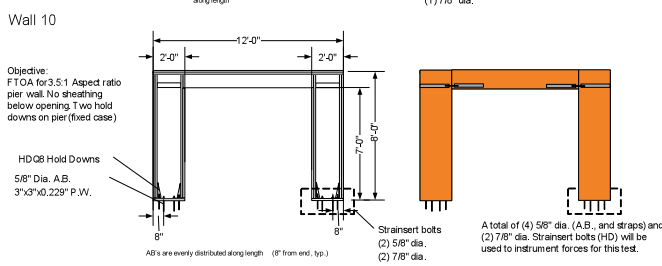
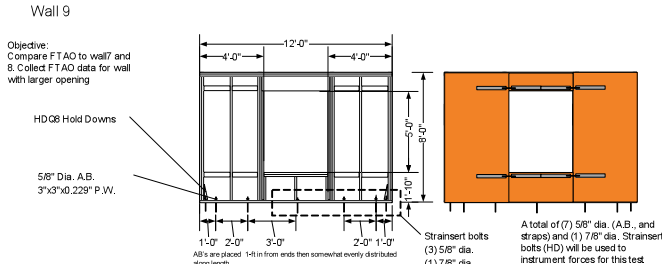
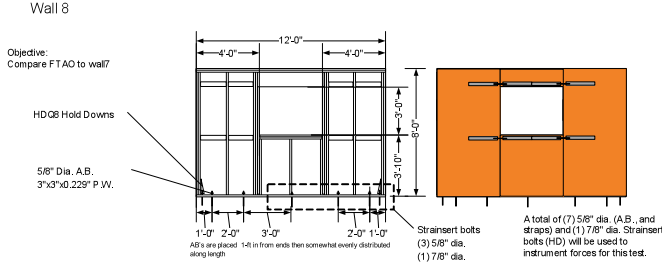
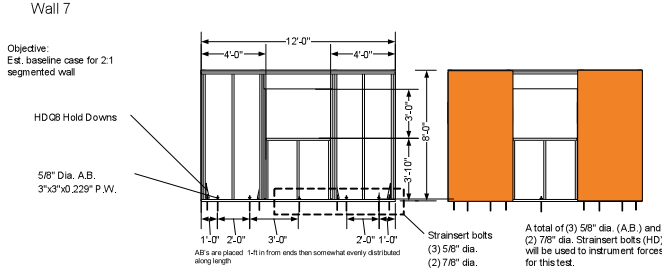
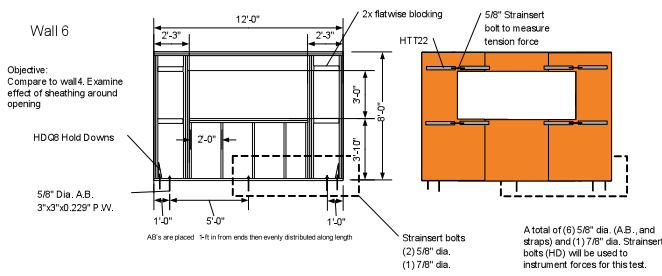
Wall 13 was an additional wall test that was not documented by Yeh et al. (2011). This test matched the geometry of Wall 4; however, the more typical continuous straps (Simpson Strong-Tie CMSTC16) were used in lieu of the back-to-back hold-downs for resisting the forces around the openings. Although the strap forces were not measured for this test, the global response was recorded.

Most walls were tested with a cyclic loading protocol following ASTM E2126, Method C, CUREE Basic Loading Protocol. The reference deformation, Δ , was set as 2.4 inches. The term α was 0.5, resulting in maximum displacements applied to the wall of ± 4.8 inches. This displacement level was based on APA's past experience with cyclic testing of WSP shear walls. 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. Two walls (Wall

4c and 5c) were tested following a monotonic test in accordance with ASTM E564.

Figure 3—Framing plans (left) and sheathing plans (right) for various force transfer around openings assemblies.





Several different top plate boundary conditions were used for this series of tests, including a short load head, an intermediate load head, and a long load head. The implications of these three boundary conditions are further discussed in Yeh et al. (2011).

In addition to the cyclic tests, monotonic racking tests were conducted with the load being transferred directly into the top plate; thus, no load head was utilized. The wall remained planar via structural tubes and low friction rub blocks directly bearing on the face and back side of the wall.

For walls detailed with FTAO (with the exception of Wall 13), two Simpson Strong-Tie HTT22 hold-downs in line (facing seat-to-seat) were fastened through the sheathing and into the flat blocking as shown in Figure 4. The hold-downs were intended to provide similar force transfer as the typically detailed flat strapping around openings. The hold-downs were connected via a 5/8-inch diameter calibrated tension bolt for measuring tension forces.



Figure 4—Wall 5, with intermediate length load head; note the instrumented hold-downs which were used in lieu of flat straps.

Global Response

Cyclic hysteretic plots and various cyclic parameters of the individual walls are provided in Yeh et al. (2011). Since this paper is primarily focusing on the forces around the openings, very limited discussion will be provided on the global response of the walls. Figure 5 provides hysteretic plots of the applied load versus the displacement of the walls for several different variables. These 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, the relatively brittle nature of the perforated walls should be noted, as the perforated shear wall testing resulted in sheathing tearing. As one might expect, the walls detailed with FTAO (Wall 4d and 5d) demonstrated increased stiffness as well as 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. Finally, the behavior of Wall 4 and Wall 13, which was intended to show that the seat-to-seat hold-downs did not significantly affect the results, was quite similar in terms of wall stiffness, and reasonably similar in terms of wall strength. Wall 13 provided confidence that the strap force measurements, which will be discussed below, were reasonably representative of typical walls detailed with FTAO.

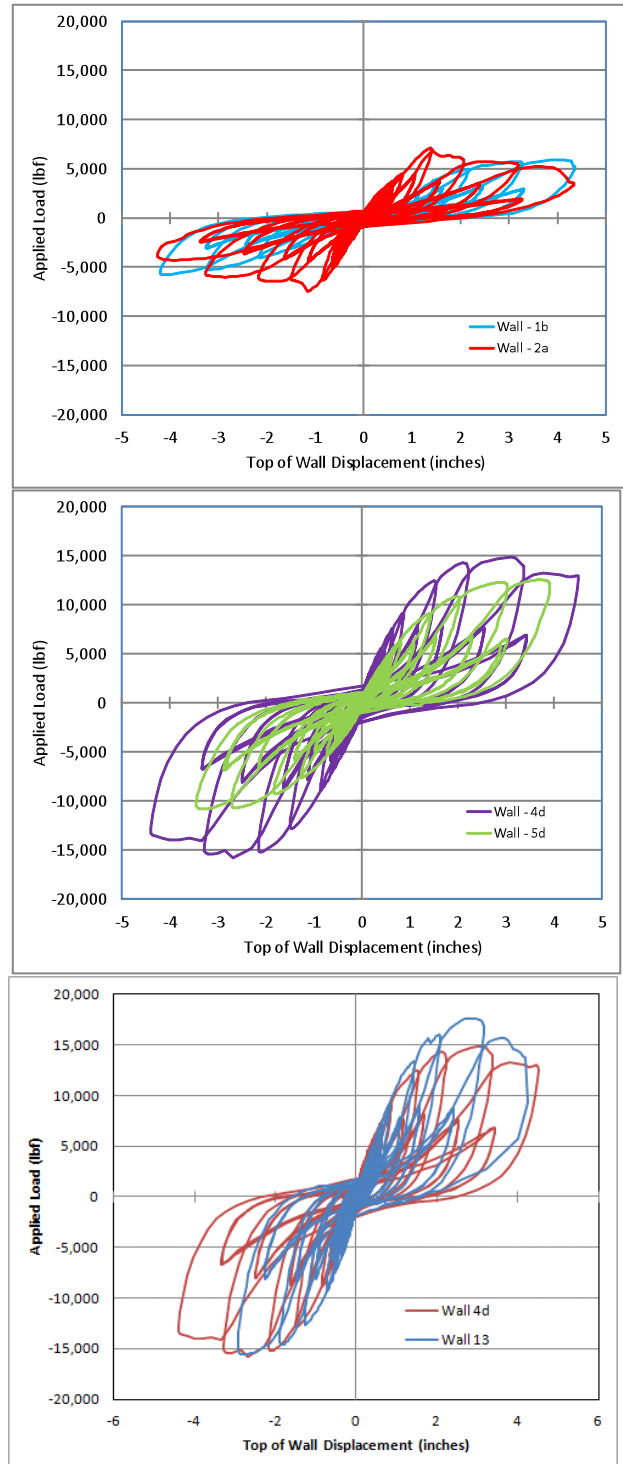


Figure 5—Hysteretic behavior of various walls, typical of the cyclic tests.

Local Response and Model Prediction

The internal forces around openings were measured with calibrated tension bolts, as discussed above. Figure 6 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 behavior, which is likely due to cumulative damage of the wall, as well as the orientation of the bolt recording tension forces, as influenced by the differential displacement of the hold-down seats in the vertical direction. Although deflection measurements were collected that could potentially be used to correct the load to “pure horizontal tension,” for range of the reported strap forces, as well as the wall ASD design value, the internal load response was relatively linear elastic.

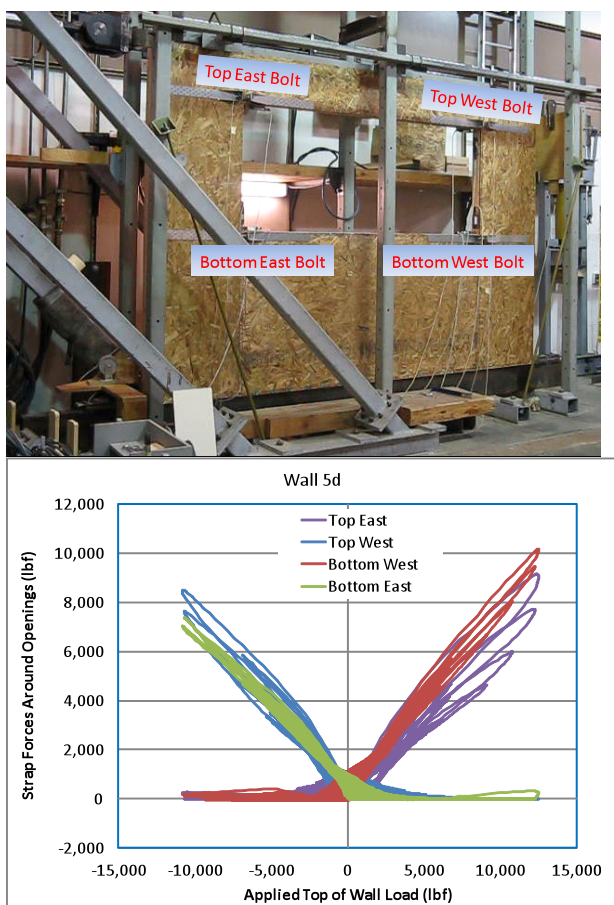


Figure 6—Notation of internal force gages (top figure), and typical cyclic response.

Table 1 provides a summary of the predicted forces based on the various techniques. Table 2 provides a comparison of the measured internal forces at the wall at the allowable value to the predicted strap forces. The measured internal forces were

taken at the cycle in which the walls were loaded to the allowable design value.

As shown in Table 2, the measured strap forces were based on the mean east and west strap forces for the top and bottom of the opening. As demonstrated in Figure 6, the strap forces were symmetric about the y-axis; thus, averaging strap forces was justifiable.

Table 2 provides the predicted strap forces at the wall ASD value for the four 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, Breyer (2015) covers the Diekmann calculations, and SEAOC (2007) covers the Thompson/SEAOC approach.

The Diekmann technique assumes symmetric forces at the top and bottom of the window opening-to-wall interface; hence the maximum of the two measured strap forces was used for the error calculation in Table 2. 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 non-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. The measured strap forces for Wall 6 were smaller than those measured for the matching wall opening, Wall 4. This is due to the fact that the forces were transferred through the wrap-around OSB sheathing in Wall 6; thus, less demand was placed on the straps. 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, Walls 10 and 11. Other observations are that the strap forces are reasonably repeatable and that the strap forces are relatively insensitive to loading rate (Walls 8a and 8b) and cyclic versus monotonic loading (Walls 4c and 5c).

Several observations can also be made about the four 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

Table 1—Predicted strap forces at the ASD design capacity of the walls

Wall ID	Predicted Strap Forces at ASD Capacity (lbf)						
	Drag Strut Technique		Cantilever Beam Technique		Diekmann Technique	SEAOC/Thompson Technique	
	Top	Bottom	Top	Bottom	Top/Bottom	Top	Bottom
Wall 4	1,223	1,223	4,474	2,724	1,958	2,792	1,703
Wall 5	1,223	1,223	6,151	4,627	3,263	3,838	2,895
Wall 6	1,223	1,223	4,474	2,724	1,958	2,792	1,703
Wall 8	1,160	1,160	7,953	4,842	1,856	2,647	1,614
Wall 9	1,160	1,160	7,953	6,328	3,093	3,639	2,745
Wall 10	1,160	n.a. ⁽¹⁾	7,830	n.a. ⁽¹⁾	n.a. ⁽¹⁾	n.a. ⁽¹⁾	n.a. ⁽¹⁾
Wall 11	1,160	n.a. ⁽¹⁾	7,830	n.a. ⁽¹⁾	n.a. ⁽¹⁾	n.a. ⁽¹⁾	n.a. ⁽¹⁾
Wall 12	653	1,088	4,784	4,040	1,491	n.a. ⁽¹⁾	n.a. ⁽¹⁾

⁽¹⁾ Not applicable.

Table 2—Internal forces of tested walls at the ASD design capacity as compared to various predicted strap forces

Wall ID	Measured Strap Forces (lbf) ⁽¹⁾		Error ⁽²⁾ for Predicted Strap Forces at the ASD Design Value						
			Drag Strut Technique		Cantilever Beam Technique		Diekmann Technique	SEAOC/Thompson Technique	
			Top	Bottom	Top	Bottom	Top	Bottom	Top/Bottom
Wall 4a	687	1,485	178%	82%	652%	183%	132%	406%	115%
Wall 4b	560	1,477	219%	83%	800%	184%	133%	499%	115%
Wall 4c ⁽³⁾	668	1,316	183%	93%	670%	207%	149%	418%	129%
Wall 4d	1,006	1,665	122%	73%	445%	164%	118%	278%	102%
Wall 5b	1,883	1,809	65%	68%	327%	256%	173%	204%	160%
Wall 5c ⁽³⁾	1,611	1,744	76%	70%	382%	265%	187%	238%	166%
Wall 5d	1,633	2,307	75%	53%	377%	201%	141%	235%	125%
Wall 6a	421	477	291%	256%	1,063%	571%	410%	663%	357%
Wall 6b	609	614	201%	199%	735%	444%	319%	458%	277%
Wall 8a	985	1,347	118%	86%	808%	359%	138%	269%	120%
Wall 8b ⁽⁴⁾	1,493	1,079	78%	108%	533%	449%	124%	177%	150%
Wall 9a	1,675	1,653	69%	70%	475%	383%	185%	217%	166%
Wall 9b	1,671	1,594	69%	73%	476%	397%	185%	218%	172%
Wall 10a	1,580	n.a. ⁽⁵⁾	73%	n.a. ⁽⁵⁾	496%	n.a. ⁽⁵⁾	n.a. ⁽⁵⁾	n.a. ⁽⁵⁾	n.a. ⁽⁵⁾
Wall 10b	2,002	n.a. ⁽⁵⁾	58%	n.a. ⁽⁵⁾	391%	n.a. ⁽⁵⁾	n.a. ⁽⁵⁾	n.a. ⁽⁵⁾	n.a. ⁽⁵⁾
Wall 11a	2,466	n.a. ⁽⁵⁾	47%	n.a. ⁽⁵⁾	318%	n.a. ⁽⁵⁾	n.a. ⁽⁵⁾	n.a. ⁽⁵⁾	n.a. ⁽⁵⁾
Wall 11b	3,062	n.a. ⁽⁵⁾	38%	n.a. ⁽⁵⁾	256%	n.a. ⁽⁵⁾	n.a. ⁽⁵⁾	n.a. ⁽⁵⁾	n.a. ⁽⁵⁾
Wall 12a	807	1,163	81%	94%	593%	348%	128%	n.a. ⁽⁵⁾	n.a. ⁽⁵⁾
Wall 12b	1,083	1,002	60%	109%	442%	403%	138%	n.a. ⁽⁵⁾	n.a. ⁽⁵⁾

⁽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 **non-conservative** predictions and significant **ultra-conservative** prediction (arbitrarily assigned as 300%).

⁽³⁾ Monotonic test.

⁽⁴⁾ Loading time increased by 10x.

⁽⁵⁾ Not applicable.

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 for the walls tested.

The Thompson technique and the Diekmann technique provided similar results, with good agreement between predicted and measured strap forces. The Diekmann technique provided reasonable predicted results (within 190 percent) for all walls, with the exception of Wall 6. 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. It is important to note that even though the Diekmann technique provides reasonable prediction, it is still quite crude and extremely conservative in some cases. Improved force transfer around openings design procedures could result in more efficient sizing of straps, blocking, and nailing to transfer forces around openings.

Advancements—Asymmetric Pier Widths

Most design examples for FTAO show symmetric pier widths. The testing phase of this project also was mostly conducted on symmetric pier widths. Nonetheless, Martin (2005) and Diekmann (2005) provided design examples using the drag strut analogy, the cantilever beam analogy and the Diekmann technique utilizing asymmetric piers. These design examples will not be repeated for this paper.

Advancements—Multiple Openings

The authors of this paper are not aware of design examples that show how one would use FTAO methods for multiple openings. During the joint research project discussed above, one of the wall geometries, Wall 12, contained multiple openings. Ed Diekmann was kind enough to review some of the earlier versions of this information, and provided us with a detailed solution of the force transfer around openings for Wall 12. From Table 2, the calculated forces for wall 12, using the Diekmann technique, reasonably matched the measured forces, within 25%. It may be possible for the Thompson/SEAOC methodology to be extended to multiple openings; however, the authors have not seen these calculation examples.

For the benefit of the reader, an example calculation is shown below for a wall with multiple openings, as shown in Figures 7 and 8. Given a 26-foot-long wall that is 8 feet tall with a 3,750 pound shear force, the shear wall is designed using FTAO around two windows with different pier widths.

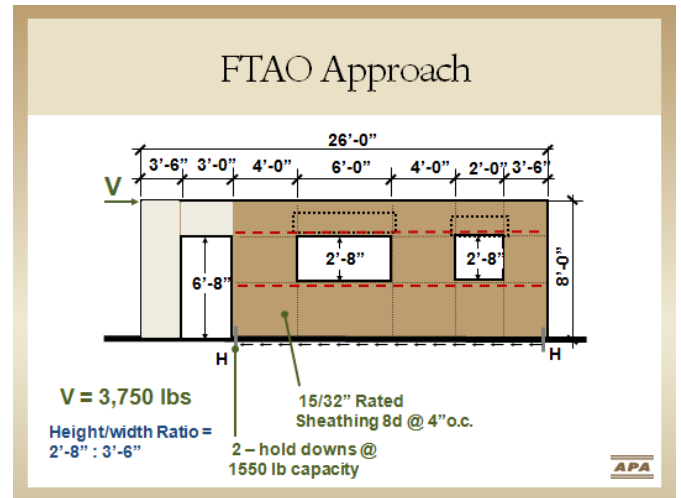


Figure 7—Calculation example for using FTAO for multiple openings.

This design has been processed using an Excel spreadsheet (Figure 8) using the following steps:

1. Calculate the hold-down forces: $H = Vh/L = 1538\#$
2. Solve for the unit shear above and below the openings: $v_a = v_b = H/(h_a + h_b) = 288 \text{ plf}$
3. Find the total boundary force above and below the openings
 - a. First opening: $O1 = v_a \times (L_{o1}) = 1731\#$
 - b. Second opening: $O2 = v_a \times (L_{o2}) = 577\#$
4. Calculate the corner forces:
 - a. $F1 = O1(L1)/(L1+L2) = 865\#$
 - b. $F2 = O1(L2)/(L1+L2) = 865\#$
 - c. $F3 = O2(L2)/(L2+L3) = 308\#$
 - d. $F4 = O2(L3)/(L2+L3) = 269\#$
5. Tributary length of openings (ft)
 - a. $T1 = L1(L_{o1})/(L1+L2) = 3'$
 - b. $T2 = L2(L_{o1})/(L1+L2) = 3'$
 - c. $T3 = L2(L_{o2})/(L2+L3) = 1.1'$
 - d. $T4 = L3(L_{o2})/(L2+L3) = 0.9'$
6. Unit shear beside the opening
 - a. $V1 = (V/L)(L1+T1)/L1 = 337 \text{ plf}$
 - b. $V2 = (V/L)(T2+L2+T3)/L2 = 388 \text{ plf}$
 - c. $V3 = (V/L)(T4+L3)/L3 = 244 \text{ plf}$
 - d. Check $V1 * L1 + V2 * L2 + V3 * L3 = V$? YES
7. Resistance to corner forces
 - a. $R1 = V1L1 = 1346\#$
 - b. $R2 = V2L2 = 1551\#$
 - c. $R3 = V3L3 = 853\#$
8. Difference of the corner force and resistance
 - a. $R1 - F1 = 481\#$
 - b. $R2 - F2 - F3 = 378\#$
 - c. $R3 - F4 = 583\#$

9. Unit shear in the corner zones
 - a. $va1 = (R1-F1)/L1 = 120 \text{ plf}$
 - b. $va2 = (R2-F2-F3)/L2 = 95 \text{ plf}$
 - c. $va3 = (R3-F4)/L3 = 167 \text{ plf}$
10. Check your solution – YES to all
 - a. Line 1: $va1(ha+hb)+v1(ho)=H?$
 - b. Line 2: $va(ha+hb)-va1(ha+hb)-V1(ho)=0?$
 - c. Line 3: $va2(ha+hb)+V2(ho)-va(ha+hb)=0?$
 - d. Line 4 = Line 3
 - e. Line 5: $va(ha+hb)-va3(ha+hb)-V3(ho)=0?$
 - f. Line 6: $va3(ha+hb)+V3(ho)=H?$

strapping. This rational analysis should take into consideration that the ultimate failure of the wall sheathing was due to tearing. Although APA has not further developed this concept, obvious items to consider are panel shear, panel tension, in-plane bending and geometry of the remaining portion of the panel. Regardless, many framers hang full four foot width panels and later cut the opening out of it, yielding added structural redundancy.

Variables				CHECK			
V (pounds)	3750	L wall (ft)	19.5	V/L (plf)	192.3077		
h wall (ft)	8.00	L1 (ft)	4				
ha (ft)	1.33	Lo1 (ft)	6				
ho (ft)	2.67	L2 (ft)	4				
hb (ft)	4.00	Lo2 (ft)	2				
		L3 (ft)	3.5				
1. Hold down forces: $H = Vh/L$				6. Unit shear beside opening			
	H (lb)		1538	$V1 = (V/L)(L1+T1)/L1$		337	
2. Unit shear above + below opening				$V2 = (V/L)(T2+L2+T3)/L2$			
	$va = vb = H/(ha+hb)$	$va = vb$ (plf)	288	$V3 = (V/L)(T4+L3)/L3$		244	
3. Total boundary force above + below openings				7. Resistance to corner forces			
	First opening: $O1 = va \times (Lo1)$		1731	$R1 = v1L1 =$	1346		
	Second opening: $O2 = va \times (Lo2)$		577	$R2 = v2L2 =$	1551		
4. Corner Forces (pounds)				$R3 = v3L3 =$	853		
	$F1 = O1(L1)/(L1+L2)$		865	8. Difference Corner Force + Resistance			
	$F2 = O1(L2)/(L1+L2)$		865	$R1 - F1$		481	
	$F3 = O2(L2)/(L2+L3)$		308	$R2 - F2 - F3$		378	
	$F4 = O2(L3)/(L2+L3)$		269	$R3 - F4$		583	
5. Tributary Length of Openings (ft)				9. Unit shear in corner zones			
	$T1 = (L1 \times Lo1)/(L1+L2)$		3.0	$va1 = (R1 - F1)/L1$		120	
	$T2 = (L2 \times Lo1)/(L1+L2)$		3.0	$va2 = (R2 - F2 - F3)/L2$		95	
	$T3 = (L2 \times Lo2)/(L2+L3)$		1.1	$va3 = (R3 - F4)/L3$		167	
	$T4 = (L3 \times Lo2)/(L2+L3)$		0.9				

Figure 8—Design Calculations for Multiple Openings

As shown by step 10, the solution checks. Refer to step 6 for the shear force in the piers ranging from 244 to 388 plf. 15/32 Category Rated Sheathing with 8d nails at four inches on center is good for 380 plf. The shear force on pier 2 (V2) is overstressed by 2%, but within an acceptable range. The strap force varies from 269 to 865 pounds, well within the common CS16 strap capacity of 1705 pounds.

Advancements—C-Shaped Panels

Another result from the first phase of testing was the contribution of the sheathing to the corner forces measured on wall 6. This was the only wall where the estimated forces using the drag strut method were accurate and the rest were ultraconservative. This finding shows the wood structural panels are transferring a significant portion of the force around the openings. A rational analysis may be considered particularly for low tension forces to eliminate tension

Advancements—Deflection Calculations for FTAO

The authors have presented a portion of this information in various forms, including seminars and webinars. One of the common questions is, “How does one estimate wall drift when one details the wall for FTAO?” Based on observations during the original shear wall tests and an extensive review of the global wall data collected during the joint research project, the following methodology is presented.

The methodology begins with the historical four term deflection equation (APA, 2007). The concept is that the FTAO wall is controlled by the deflection of the full-height piers. For calculation purposes, the height of the pier that is deflecting away from the sheathed area under the window opening is the full height of the wall. For the pier that is being loaded toward the sheathed area under the window, the wall height is calculated as the distance from the top of sheathed area below the window opening to the top of the

wall. The deflection of the wall is then calculated as the average of the four term deflection equations. The remainder of the terms in the four term deflection equation are identical to the traditional use of the equation.

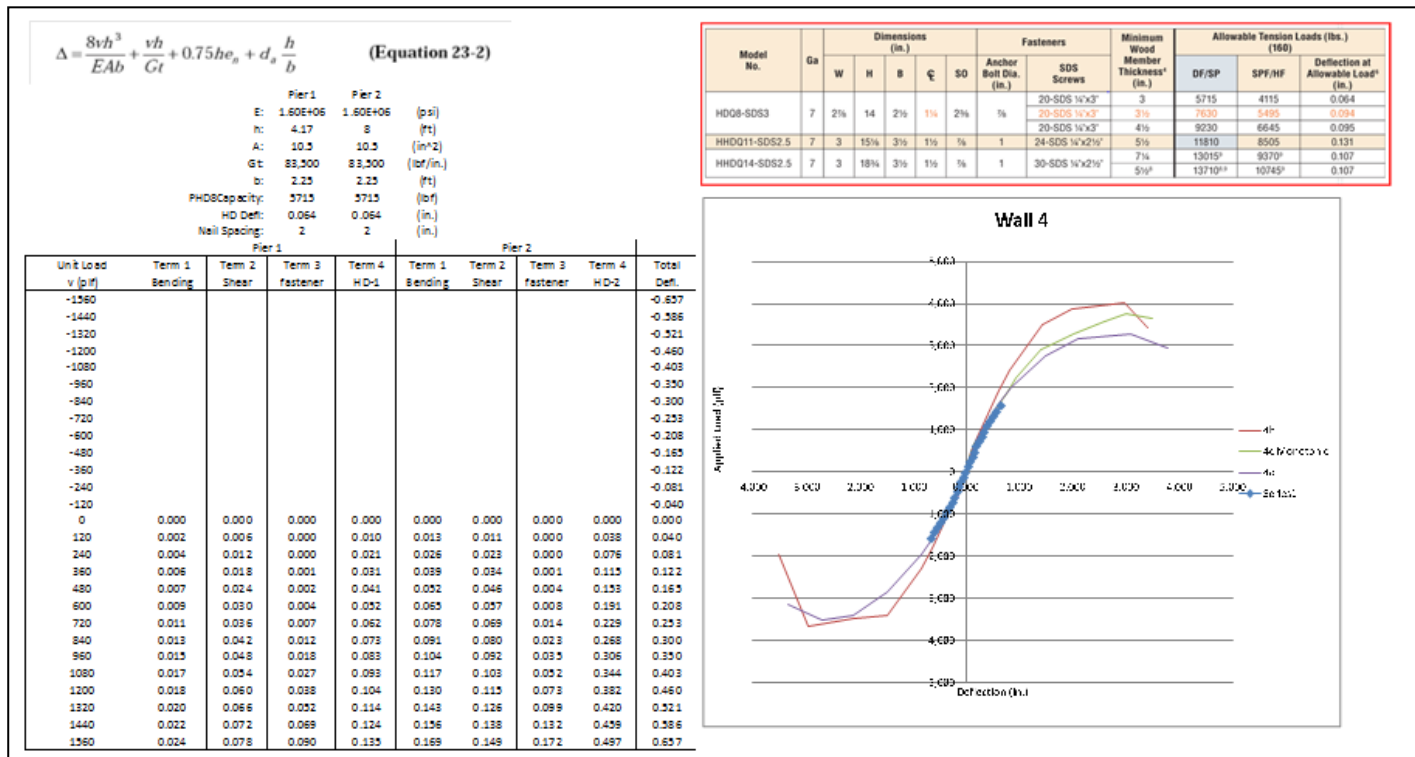


Figure 9—Estimating wall deflection of Wall 4 with backbone curves overlaid

Figure 9 is a snapshot of a worksheet showing the calculation example for Wall 4. The plot, on the right hand side of Figure 9, shows the backbone curves of the cyclic response, as well as the predicted deflection following the above methodology. Since the two pier widths are equal, one treats the left pier (Pier 1) as the pier that was pushed toward the sheathed area below the window opening (i.e. $h_{\text{pier 1}} = 4$ feet, 2 inches). The right pier (Pier 2) has a height of 8 feet.

A similar methodology can also be used for multiple openings. Wall 12 is a more complicated calculation, since each pier has different widths. However, Figure 10 shows the predicted response to the backbone curves for Wall 12.

Conceptual Keys

This rational analysis is fairly straightforward and easy to program into Excel, a web based application or other preferred software. The check at the end gives the structural engineer confidence that the calculations are done correctly.

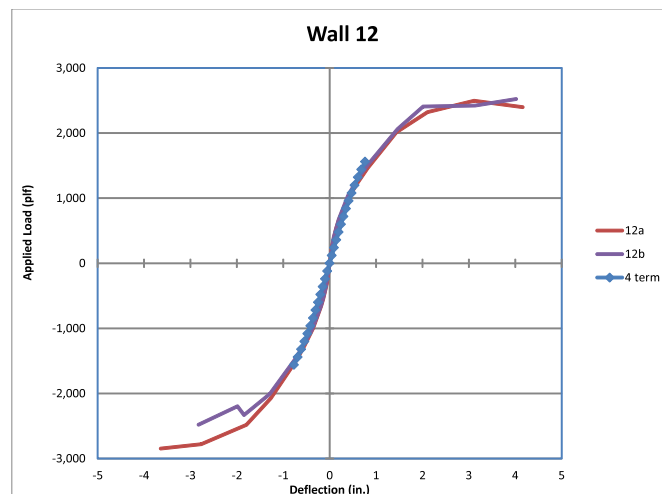


Figure 10—Calculated deflection methodology for asymmetric piers and multiple openings (Wall 12).

The method assumes the following:

1. The unit shear above and below the openings is equivalent.
2. The corner forces are based on the shear above and below the openings and only the piers adjacent to that unique opening.
3. The tributary length of the opening is the basis for calculating the shear to each pier. This tributary length is the ratio of the length of the pier multiplied by the length of the opening it is adjacent to, then divided by the sum of the length of the pier and the length of the pier on the other side of the opening.
 - a. For example, $T1 = (L1 * L_{o1}) / (L1 + L2)$
4. The shear of each pier is the total shear divided by the L of the wall, multiplied by the sum of the length of the pier and its tributary length, divided by the length of the pier:
 - a. $(V/L)(L1 + T1) / L1$
5. The unit shear of the corner zones is equal to subtracting the corner forces from the panel resistance, R. R is equal to the shear of the pier multiplied by the pier length:
 - a. $V_{a1} = (v1L1 - F1) / L1$
6. Once the entire segment shears have been calculated, then the design is checked by summing the shears vertically along each line. The first and last line equal the hold-down force, and the rest should sum to zero.

Conclusion

Based on the recent force transfer around openings (FTAO) research and forthcoming APA System Report, structural engineers can utilize a new rational analysis to design shear walls with multiple, asymmetric openings. FTAO continues to be a popular solution where walls have narrow piers, and it provides structural and nonstructural benefits, including reduced anchorage and added redundancy. Also, FTAO's incorporation of continuous wall sheathing aids with cladding attachment and improves drainage and energy efficiency of the building.

Acknowledgements

The authors wish to express appreciation to those who contributed to the successful completion of the research and/or this technical paper. They are numerous and all of the individuals listed below had a helpful hand in the project. Any omissions are entirely unintentional. Again, this research was supported in part by funds provided by the USDA Forest Products Laboratory, which is acknowledged and greatly appreciated by the project team.

- *Frank Lam*, Ph.D., P.Eng, University of British Columbia, Vancouver, BC
- *Minghao Li*, Ph.D., University of British Columbia, Vancouver, BC
- *Dana Ohler*, Writer and Web Content Developer, APA
- *Doug Rammer*, Ph.D., P.E., USDA Forest Products Laboratory, Madison, WI
- *Tom VanDorpe*, S.E., VCA Structural, Orange, CA
- *James Wacker*, P.E., USDA Forest Products Laboratory, Madison, WI
- *Borjen Yeh*, Ph.D., P.E., Technical Services Division Director, APA, Tacoma, WA

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