PERFORATED SHEARWALL DESIGN APPROACH

Bradford K. Douglas, P.E.[1]
Hideo Sugiyama, PhD.[2]

Introduction

Most wood-frame residential structures utilize a system of horizontal roof and floor diaphragms and vertical shearwalls to collect and transfer lateral loads to the foundation. Designers have used a traditional shearwall design methodology [1] for many years in the design of shearwall structures in areas exposed to high wind and seismic loads. However, conventional residential construction, primarily shearwall construction, has not been designed and constructed using this methodology due to increased engineering costs, the complexity of building layouts, and the requirements for additional shearwall anchorage. In addition, since only full-height sheathing is considered to resist lateral forces, and since a significant portion of the wall sheathing on residential structures is not full-height, the shear resistance of these structures is severely underestimated using traditional engineering methods.

Traditional shearwall design assumes that full-height shearwall segments, which are properly restrained against overturning, act as vertical cantilevers and that full resistance of the shearwall is provided by the segments of the wall sheathed with full-height sheathing (Figure 1). Contributions from wall segments above doors and above and below windows are ignored. Restraint against overturning of full-height shearwall segments is provided by dead load of the shearwall and the structure above, or from tension anchorage provided at the ends of the shearwall segments.

In 1981 Professor Hideo Sugiyama with the University of Tokyo proposed a simplified empirical equation for assigning shear strength and stiffness values for conventionally-constructed wall assemblies. Sugiyama's empirical equation has been incorporated into a new U. S. wood industry design methodology referred to as "Perforated Shearwall Design" (PSW). This method

[1] Director of Engineering, American Wood Council, American Forest and Paper Association

[2] Professor, Faculty of Engineering, Science University of Tokyo

allows, for the first time, the designer to account for the contributions from sheathing above and/or below doors and windows; the effects of unrestrained openings on wall shear capacity; and the effects of partial overturning resistance of individual shearwall segments.

Background

A series of studies to determine the influence of openings on shear strength and stiffness of conventionally-constructed shearwalls was conducted by Sugiyama in 1977. A procedure for calculating the shear strength and stiffness was proposed [2] and verified with experimental test results from racking tests of full-sized walls by Sugiyama and Suzuki [3] and Sugiyama and Nakata [4]. Further tests were conducted by Hayashi [5][6].

In 1981, Sugiyama [7] proposed a simplified empirical equation for assigning shear strength and stiffness to conventionally-constructed shearwall structures with openings (Figure 2). Yasumura and Sugiyama [8] verified the empirical equation from the results of one-third scale and full-scale tests of shearwall assemblies (Figure 3).

In 1992, Diekmann [9] proposed a new analytical procedure for designing openings in shearwalls. The procedure provided a calculation approach to account for the effects of horizontal restraint around openings. Horizontal restraint redistributes the panel shear stresses into the panels above and/or below the openings and thus reduces or eliminates the need for intermediate vertical restraint at the interior ends of shearwall segments (Figure 4).

In 1993, Sugiyama and Matsumoto proposed a more rigorous procedure to evaluate the effects of openings on shearwall strength and stiffness [10][11]. In 1994, Sugiyama and Matsumoto [12][13] evaluated the simplified empirical procedure against additional one-third scale racking tests conducted by Wakatsuki [14] and Uchida [15] in 1982 on walls with ratios of width to depth of the wall space above and/or below the opening of up to 8 and sheathing area ratios of 0.25. While the best-fit equations to Wakatsuki and Uchida's data were slightly higher than Sugiyama's original equation, Sugiyama's equation provided more conservative estimates of the shearwall performance (Figure 5).

In 1994, the American Plywood Association [16] conducted a series of four full-scale racking tests with a symmetrically placed opening to evaluate Sugiyama's empirical equation. The

results of these tests, with effective shear strength ratios ranging from 0.54 (72" x 71.25" door) to 0.67 (72" x 47.25" window), were within 10% of the estimates from Sugiyama's empirical equations (Figure 6).

Sugiyama Empirical Equation

Sugiyama's empirical equation estimates the effective shear strength and stiffness of the total wall. Overturning restraint is assumed to be provided at the ends of the wall. No additional overturning restraint is provided at intermediate locations at the ends of the individual shearwall segments.

There are two variables used in calculating the effective shear strength and stiffness of the total wall. These variables are:

1. Opening Area Ratio - ratio of the sum of the opening areas to the total wall area.

$$a = \frac{\sum A_{openings}}{A_{wall}} \tag{1}$$

2. Wall Length Ratio - ratio of the sum of the full-height segment lengths to the total wall length.

$$b = \frac{\sum L_{full-height}}{L_{wall}} \tag{2}$$

In Sugiyama's procedure, the opening area ratio and the wall length ratio are combined into a Sheathing Area Ratio (opening coefficient in Sugiyama's original work) of the form:

$$r = \frac{1}{1 + \dfrac{a}{b}} \tag{3}$$

The effective shear strength and stiffness ratio is computed using the following regression equation:

$$F = \frac{r}{3 - 2 \cdot r} \tag{4}$$

The final step in the Sugiyama empirical equation is to reduce the shear capacity or shear stiffness of the fully-sheathed wall by the effective shear strength and stiffness ratio.

$$V_{effective} = F \cdot V_{wall} \tag{5}$$

$$S_{effective} = F \cdot S_{wall} \tag{6}$$

Perforated Shearwall Design Approach

To incorporate the Sugiyama empirical equation into U.S. design procedures, several modifications were made. While the empirical equation matches very well with existing test data, it was felt that the procedure would be more widely accepted if it were tied to the traditional shearwall design methodology. Traditional shearwall design normally specifies a required length of full-height sheathing. To specify the required length of full-height sheathing, the effective shear strength ratio was assumed to equal the required shear capacity divided by the tabulated shear capacity of the full-height sheathing only ($F = V_{wall}/V_{full-height}$).

In addition, it was recognized that the opening area ratio and the wall length ratio are not independent variables, since the opening area ratio and the effective shear strength ratio contain the wall length ratio. For modeling of specific wall configurations, where these ratios have been set by design, this interdependency is not important. However, for this procedure to be used to determine the required length of full-height sheathing, an iterative solution would be required.

A solution to the interdependency issue was to combine the variable definitions and equations and factor out the common terms. To accomplish this objective, the maximum unrestrained opening height in the wall was conservatively selected as the height of all openings in the wall.

Solving for the required length of full-height sheathing yielded the equation:

$$L_{full-height} = L_{wall} \cdot \frac{1 - \dfrac{H_{wall}}{3 \cdot H_{opening}} \cdot \dfrac{V_{wall}}{V_{req}}}{1 - \dfrac{H_{wall}}{3 \cdot H_{opening}}} \tag{7}$$

Applications

The PSW design approach has been accepted as an alternative method for shearwall design in the American Forest and Paper Association's (AF&PA) new publication *Wood-Frame Construction Manual for One- and Two-Family Dwellings* (*WFCM*) [17]. In the performance section of the *WFCM*, effective shear strength ratios have been tabulated for various wall length ratios ($L_{full-height}/L_{wall}$) and unrestrained opening height ratios ($H_{opening}/H_{wall}$). These tabulated values (Figure 7) are used to adjust the shearwall capacities of materials used in the traditional shearwall design methodology. The effective shear ratios converge with traditional shearwall design when the maximum unrestrained opening height is less than or equal to one-third of the wall height ($H_{wall}/3$).

In the prescriptive section of the WFCM, the required length of full-height sheathing has been tabulated for designs based on both the traditional and perforated shearwall design methodologies (Figure 8). For simplification, the perforated shearwalls are designed assuming that all openings are unrestrained, vertical slits (no sheathing above or below the openings).

Three design limitations have been imposed to limit the use of the new procedure until more information is available. These limits are:

1. Shearwall segments are limited to a minimum length of one-half of the wall height ($H_{wall}/2$) to be considered part of the total full-height length.

2. Shear capacities of the sheathing materials have been limited to a maximum ultimate shear capacity of 1500 plf.

3. Holddowns with the capacity to resist the maximum overturning in a wall segment are required at each corner and at all discontinuities which occur in the wall line.

Future Research

Research is being considered to further the use of the PSW approach for determining the shear resistance of conventionally-framed walls. Since most of the full-scale verification research conducted in the U.S. has been on walls with symmetrically-placed openings, full-size testing of conventionally-framed walls with asymmetrically-placed openings is anticipated. Also, since

most of the full-scale testing has been conducted on walls of 12-24 feet in length, testing of longer walls with different opening ratios has been recommended to further the applicability of the PSW approach.

Dynamic performance of all shearwall systems and materials is currently being evaluated. Dynamic testing of conventionally-framed walls will be part of any major study program relating to the overall performance of wood-frame shearwalls. Based on the results of this research, more appropriate limitations and expanded applications of this new approach are expected.

Conclusion

Conventional residential construction has not been designed and constructed using traditional shearwall design methodology due to the increased engineering costs, the complexity of building layouts, and the requirements for additional shearwall anchorage. In addition, since only full-height sheathing is considered to resist lateral forces, and since a significant portion of the wall sheathing on residential structures is not full-height sheathing, the shear resistance of these structures is severely underestimated using traditional engineering methods.

In 1981 Professor Hideo Sugiyama proposed a simplified empirical equation for assigning shear strength and stiffness values for conventionally-constructed wall assemblies. After confirmatory tests, Sugiyama's empirical equation has been incorporated into a new U. S. wood industry design methodology referred to as "Perforated Shearwall Design" (PSW). This method allows, for the first time, the designer to account for the contributions from sheathing above and/or below doors and windows, the effects of unrestrained openings on wall shear capacity, and the effects of partial overturning resistance of individual shearwall segments.

Future research has been proposed to support the use and to increase the applicability of the proposed approach. The introduction of this design methodology and future research in this area will all assist in the engineering justification of conventional construction.

BIBLIOGRAPHY

1.   APA Design/Construction Guide - Diaphragms, American Plywood Association, 1991.

2.   Sugiyama, H., "The Proposal of the Method of Evaluation of Allowable Shear Load in the Wooden Wall Panel and on the Method of Prediction of Shear Strength and Stiffness for the Wooden Wall Panel with Openings", Transaction of the Architectural Institute of Japan, No. 186, August 1971.

3.   Sugiyama, H. and K. Suzuki, "Shear Strength and Stiffness of Wall Panel with Openings Constructed with Wooden Framing and Plywood Facing - Part 1", Transaction of the Architectural Institute of Japan, No. 187, September 1971.

4.   Sugiyama, H. and K. Nakata, "Shear Strength and Stiffness of Wall Panel with Openings Constructed with Wooden Framing and Plywood Facing - Part 2", Transaction of the Architectural Institute of Japan, No. 190, December 1971.

5.   Hayashi, K., "Studies on the Shear Strength of Wooden Wall Panels with Openings - Part 1", Transaction of the Architectural Institute of Japan, No. 233, July 1975.

6.   Hayashi, K., "Studies on the Shear Strength of Wooden Wall Panels with Openings - Part 2", Transaction of the Architectural Institute of Japan, No. 257, July 1977.

7.   Sugiyama, H. "The Evaluation of Shear Strength of Plywood-Sheathed Walls with Openings", Wood Industry, 36-7, July 1981.

8.   Yasumura, M. and H. Sugiyama, "Shear Properties of Plywood-sheathed wall panels with openings", Transaction of the Architectural Institute of Japan, No. 338, April 1984.

9.   Diekmann, E., "Designing for wind or seismic loads", Proceedings of the International Seminar on Wood Engineering, 1992.

10.   Sugiyama, H. and T. Matsumoto, "A Simplified Method of Calculating the Shear Strength of a Plywood-Sheathed Shear Wall with Openings I", Mokuzai Gakkaishi, Vol. 39, No.1, p. 75-79, 1993.

11.   Sugiyama, H. and T. Matsumoto, "A Simplified Method of Calculating the Shear Strength of a Plywood-Sheathed Shear Wall with Openings II", Mokuzai Gakkaishi, Vol. 39, No.8, p. 924-929, 1993.

12.   Sugiyama, H. and T. Matsumoto, "A Simplified Method of Calculating the Shear Strength of a Plywood-Sheathed Shear Wall with Openings III", Mokuzai Gakkaishi, Vol. 40, No.3, 1994.

13.   Sugiyama, H. and T. Matsumoto, "Empirical Equations for the Estimation of Racking Strength of a Plywood-Sheathed Shear Wall with Openings", Summaries of Technical Papers of Annual Meeting, Architectural Institute of Japan, September 1994.

14.   Wakatsuki, S. Bachelor Thesis at the University of Tokyo (under guidance of Professor Hideo Sugiyama), 1981.

15.   Uchida, J. Bachelor Thesis at the University of Tokyo (under guidance of Professor Hideo Sugiyama), 1982.

16.   Minutes of the AF&PA Subcommittee on Conventional Construction's Perforated Shearwall Task Group meeting, February, 1994.

17.   Wood-Framed Construction Manual for One- and Two-Family Dwellings, American Forest and Paper Association, January 1995 (expected).
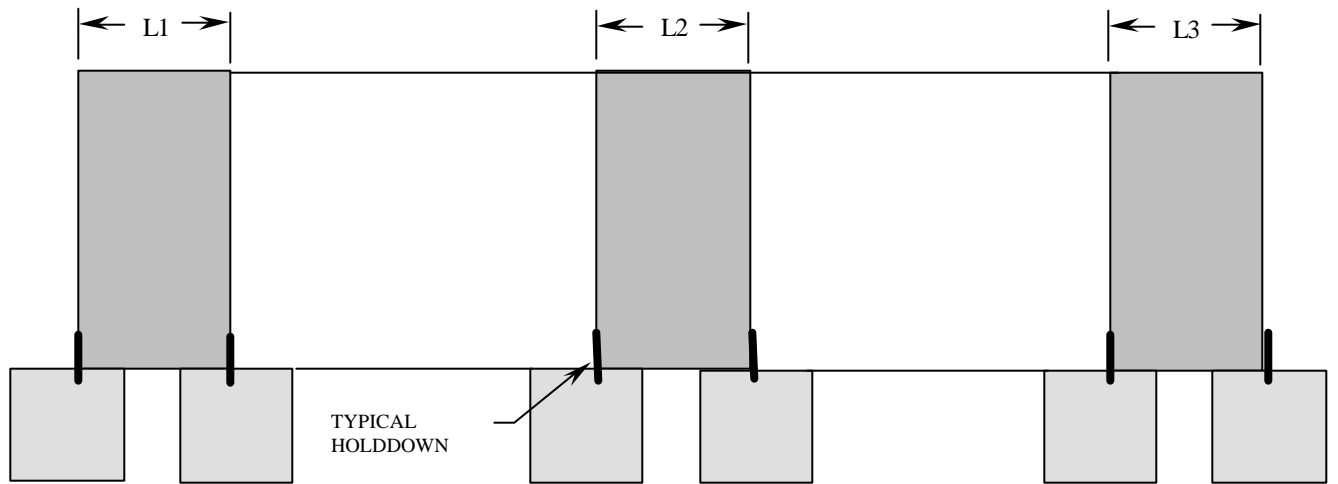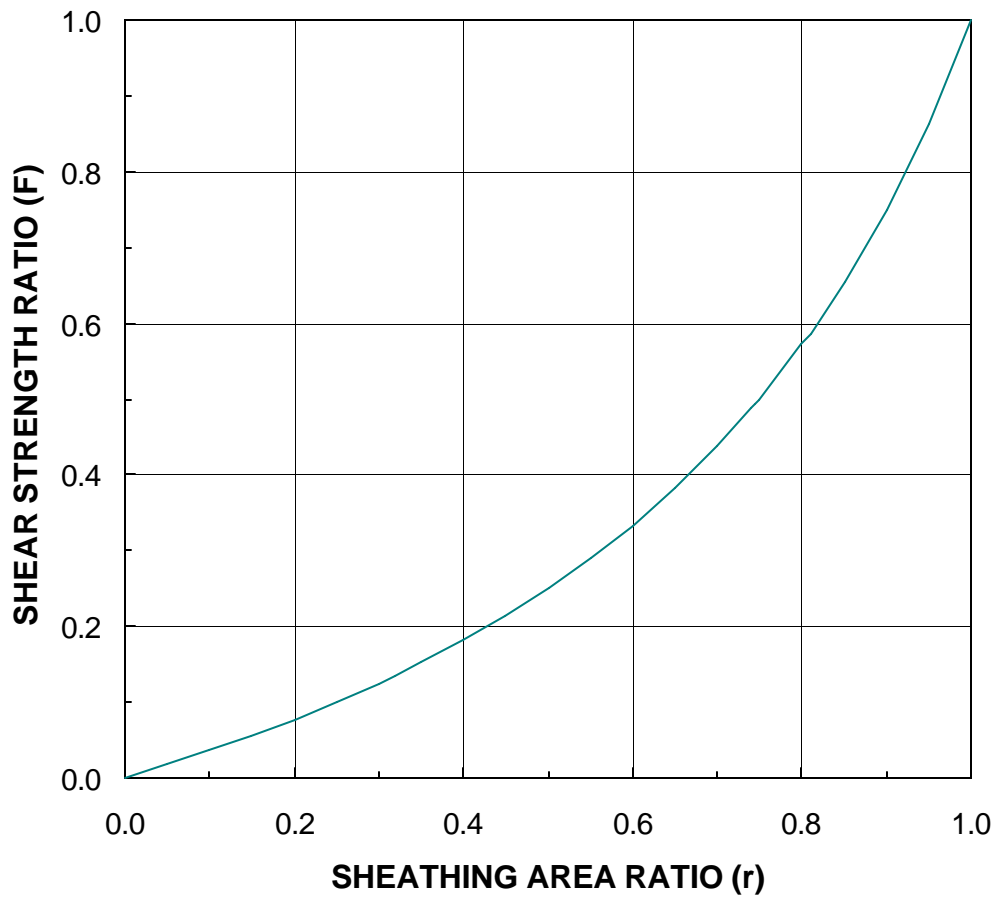
L1   L2   L3

TYPICAL
HOLDDOWN

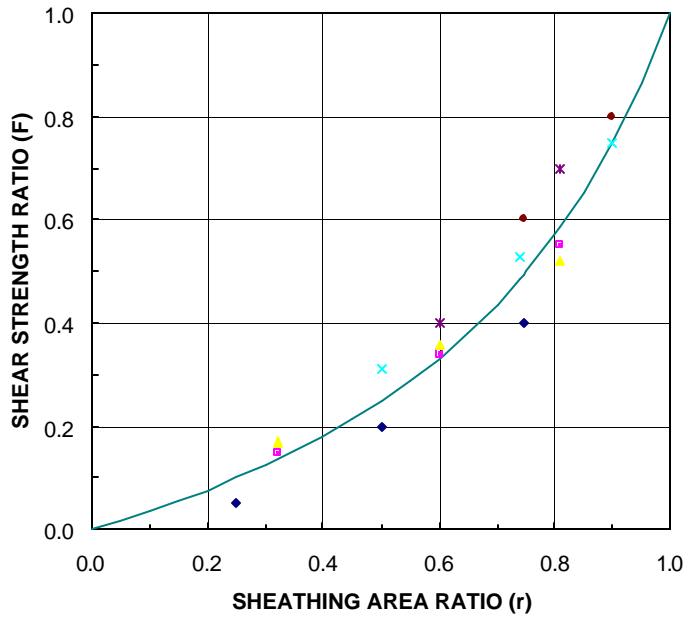**Figure 1 Traditional shearwall design**

Figure 2 Sugiyama shear strength and stiffness equation
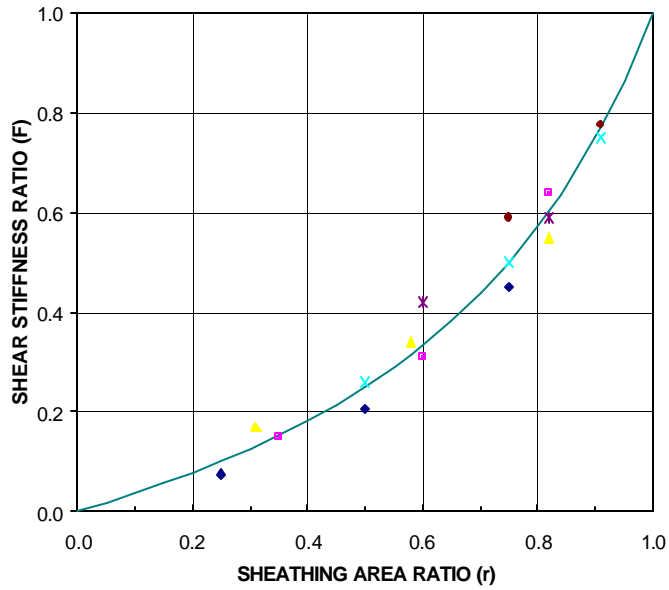
Figure 3 Results of Yasumura and Sugiyama tests of shearwall assemblies
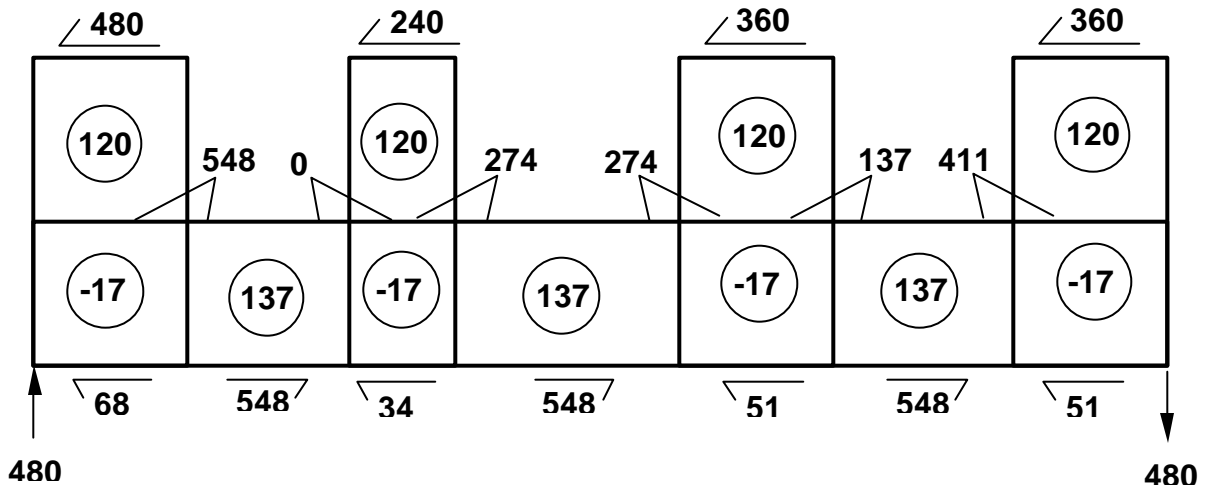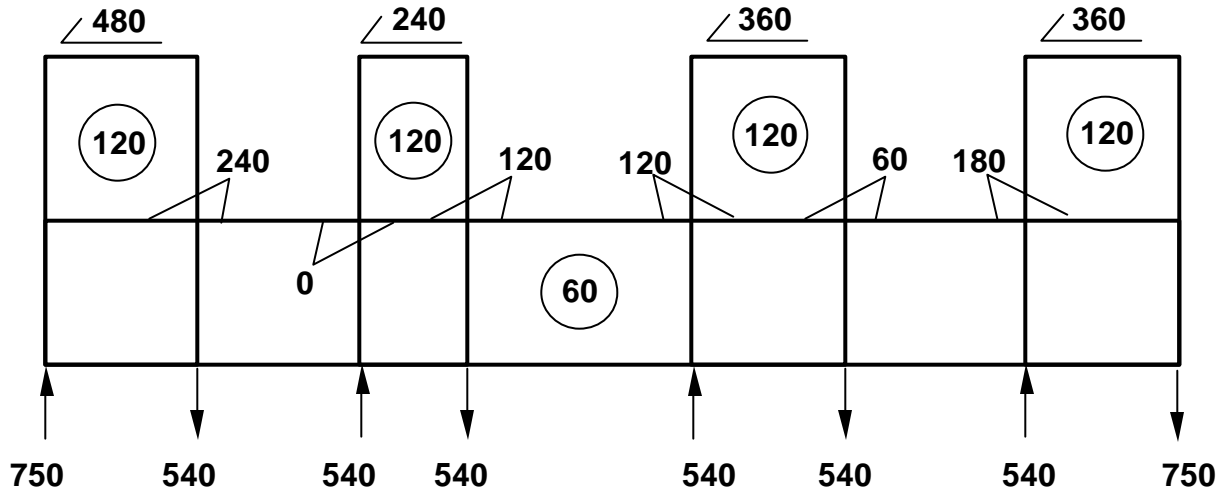
Figure 4 Diekmann's shearwall method
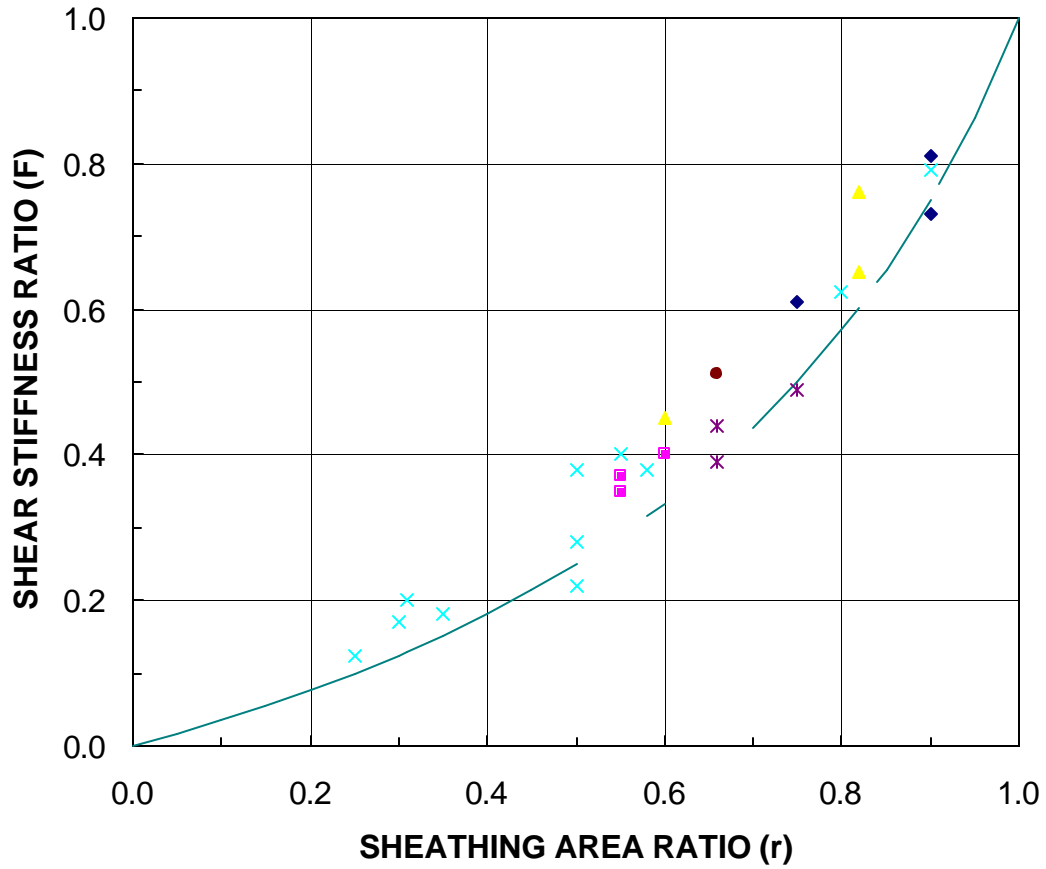
Figure 5 Results of Uchida's and Wakatsuki's tests of shearwall assemblies

| APA Wall		3	4	5	6	7
Opening		None	Door	Window	Window	Window
Opening Width, h (in.)		0	72	72	72	72
Wall Height, H (in.)		96	96	96	96	96
Top, a (in.)		0	12.75	12.75	12.75	12.75
Middle, b (in.)		0	83.25	42.25	59.25	71.25
Bottom, c (in.)		0	0	36	24	12
% Sheathed		100	50	50	50	50
Wall Length, L (in.)		96	144	144	144	144
Full Height Sheathing Length, L' (in.)		96	72	72	72	72
Opening Area (in^2)		0	5994	3402	4266	5130
Test Load (lbs)		16310	7240	9770	9110	8410
Test Capacity (plf)		2039	603	814	759	701
Test Shear Ratio (F-test)		1.00	0.30	0.40	0.37	0.34
Alpha		0.00	0.43	0.25	0.31	0.37
Beta		1.00	0.54	0.67	0.62	0.57
Sugiyama Shear Ratio (F-sugiyama)		1.00	0.28	0.40	0.35	0.31

APA Tests vs. Sugiyama Empirical Equation

Figure 6 Results of APA tests
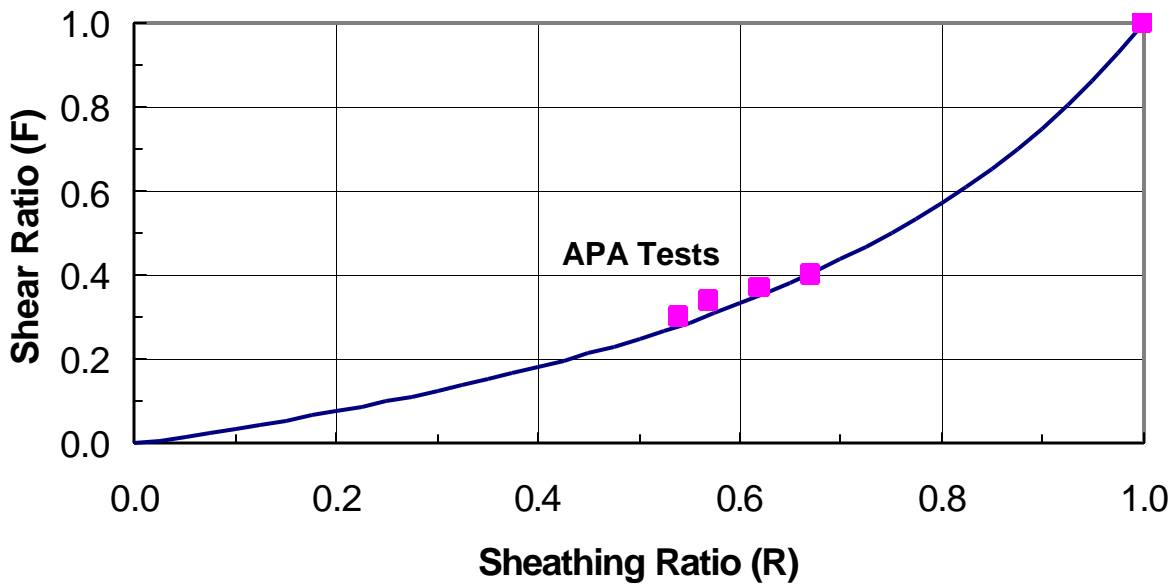
	Maximum Unrestrained Opening Height				
	Window Height			Door Height	
	H/3	H/2	2H/3	5H/6	H
8' Wall	2'-8"	4'-0"	5'-4"	6'-8"	8'-0"
10' Wall	3'-4"	5'-0"	6'-8"	8'-4"	10'-0"

Percent Full-Height Sheathing	Effective Shear Capacity Ratio				
0%	1.00	0.67	0.50	0.40	0.33
10%	1.00	0.69	0.53	0.43	0.36
20%	1.00	0.71	0.56	0.45	0.38
30%	1.00	0.74	0.59	0.49	0.42
40%	1.00	0.77	0.63	0.53	0.45
50%	1.00	0.80	0.67	0.57	0.50
60%	1.00	0.83	0.71	0.63	0.56
70%	1.00	0.87	0.77	0.69	0.63
80%	1.00	0.91	0.83	0.77	0.71
90%	1.00	0.95	0.91	0.87	0.83
100%	1.00	1.00	1.00	1.00	1.00

Figure 7 Adjustment factors to adjust for traditional shearwalls to perforated shearwalls

$$L_{required} = L_1 + L_2 + L_3$$

Bracing Wall Beneath:	Building Aspect Ratio (L/B)	Fastest Mile Wind Speed (mph)						Seismic Effective Peak Acceleration	
		70	80	90	100	110	120	0.30	0.40
		Minimum Length of Full-Height Sheathing Per 24 Lineal Feet of Wall Length [1,2,3] (ft.)							
Roof & Ceiling	1:1	3	4	5	7	8	10	7	10
	13:1	4	5	7	8	-	-	10	12
	12:1	5	6	8	-	-	-	11	14
	1::1	6	8	10	-	-	-	13	17
	2:1	7	9	-	-	-	-	14	19
Roof, Ceiling & 1 Floor	1:1	7	9	11	13	16	19	12	16
	13:1	8	11	14	17	-	-	15	20
	12:1	10	13	16	-	-	-	18	23[4]
	1::1	11	15	19	-	-	-	21	24[5]
	2:1	13	17	-	-	-	-	24	-
Roof, Ceiling & 2 Floors	1:1	10	13	16	20	-	-	17	22
	13:1	12	16	20	23[4]	-	-	21	24[5]
	12:1	15	19	23[4]	-	-	-	21[5]	-
	1::1	17	22	23[5]	-	-	-	-	-
	2:1	20	24[4]	-	-	-	-	-	-

Type I: Holddowns located at ends of each shearwall segment. Exterior sheathing in accordance with Table 3.3B
L: Maximum building dimension.
B: Minimum building dimension.

[1] For wind design, the total required sheathing length for walls in the maximum building dimension need not exceed the requirements for a building with an aspect ratio of 1:1.
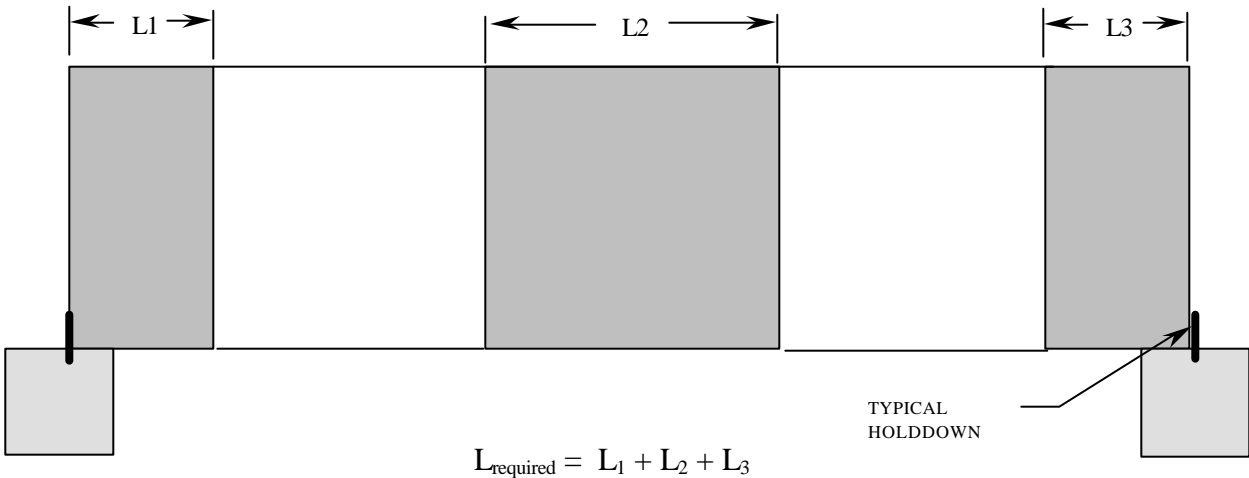[2] Required sheathing lengths are based on interior walls sheathed with 1/2 inch gypsum wallboard.
[3] The length of individual shearwall segments shall not be less than H/3.
[4] Maximum room size shall be limited to the minimum building dimension (B).
[5] Maximum spacing between fully-sheathed double-sided gypsum walls shall be limited to the minimum building dimension.

Figure 8a. Traditional shearwall sheathing length requirements

$$L_{required} = L_1 + L_2 + L_3$$

Bracing Wall Beneath:	Building Aspect Ratio (L/B)	Fastest Mile Wind Speed (mph)						Seismic Effective Peak Acceleration	
		70	80	90	100	110	120	0.30	0.40
		Minimum Length of Full-Height Sheathing Per 24 Lineal Feet of Wall Length [1,2,3,6] (ft.)							
Roof & Ceiling	1:1	8	10	11	13	15	16	13	16
	1¼:1	9	11	13	15	-	-	15	18
	1½:1	11	13	15	-	-	-	17	20
	1¾:1	12	14	16	-	-	-	18	21
	2:1	13	15	-	-	-	-	20	22
Roof, Ceiling & 1 Floor	1:1	13	15	17	19	21	22	18	21
	1¼:1	15	17	19	21	-	-	20	23
	1½:1	16	19	21	-	-	-	22	24[4]
	1¾:1	18	20	22	-	-	-	23	24[5]
	2:1	19	21	-	-	-	-	24	-
Roof Ceiling & 2 Floors	1:1	16	19	21	22	-	-	21	23
	1¼:1	18	21	23	24[4]	-	-	23	24[5]
	1½:1	20	22	24[4]	-	-	-	23[5]	-
	1¾:1	21	23	24[5]	-	-	-	-	-
	2:1	22	24[4]	-	-	-	-	-	-

Type II: Holddowns located at building corners only. Exterior sheathing in accordance with Table 3.3B
L: Maximum building dimension.
B: Minimum building dimension.

[1] For wind design, the total required sheathing length for walls in the maximum building dimension need not exceed the requirements for a building with an aspect ratio of 1:1.
[2] Required sheathing lengths are based on interior walls sheathed with 1/2 inch gypsum wallboard.
[3] The length of individual shearwall segments shall not be less than H/2.
[4] Maximum room size shall be limited to the minimum building dimension (B).
[5] Maximum spacing between fully-sheathed double-sided gypsum walls shall be limited to the minimum building dimension.
[6] When the height of a window does not exceed 32 inches and the areas above and below the window are sheathed in accordance with Table 3.3B, walls can be designed using the values tabulated for Type I walls.

Figure 8b. Perforated shearwall sheathing length requirements