Perforated Shearwall Design Method[1]

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Abstract

Wood frame shearwalls are traditionally designed using full-height shearwall segments restrained against overturning by structure weight and/or tension anchorage. Traditional methods require shearwalls that contain openings to be considered as multiple shearwall segments, increasing the requirements for tension anchorage within the wall. The perforated shearwall design method, described in the *Wood Frame Construction Manual for One- and Two-Family Dwellings*, allows openings in shearwalls and reduces the need for additional intermediate tension anchorage. This paper reviews the development and technical elements for this new procedure and provides an example of the application of the perforated shearwall design method.

Keywords: Shearwall, Wall, Wood.

Introduction

Wood frame shearwalls are traditionally designed using shearwall segments that extend the full-height of the wall. They are considered to act as single cantilever beams. The transfer of shear forces is accomplished with fasteners attaching the wall bottom plate to the elements below. Restraint against overturning forces is provided by the weight of the structure and/or from tension anchorage provided at each end of the shearwall segment. Figure 1 shows a typical shearwall consisting of one shearwall segment, with overturning restraint provided by a hold-down at each end of the wall.

Following the traditional method, shearwalls containing openings are treated as multiple shearwall segments, as shown in Figure 2. Each segment requires fasteners to transfer shear and provide overturning restraint resulting in additional hold-downs per wall. The design capacity of the shearwall is assumed to equal the sum of the capacities of each shearwall segment. Sheathing above and below openings typically is not considered to contribute to the overall performance of the wall.

Another approach considers a shearwall segment with openings, which is illustrated in Figure 3. Here, the wall is identical to the shearwall in Figure 2, but without intermediate overturning restraints next to the openings. This condition is considered a shearwall segment with unrestrained openings (perforated shearwall). The capacity is clearly less than would be expected from the same shearwall containing multiple shearwall segments, each fully restrained against overturning. However, the capacity of the wall shown in Figure 3 may be sufficient for a particular application while reducing the total number of overturning connections.

Background

In 1981, Professor Hideo Sugiyama, University of Tokyo, proposed an empirical equation allowing designers to calculate the shear capacity and stiffness of perforated shearwall segments without intermediate overturning restraint (Sugiyama, 1981). Sugiyama's empirical equation forms the basis of the perforated shearwall design method. Sugiyama's equation, the perforated shearwall design methodology, and several studies evaluating the effects of unrestrained openings in shearwalls have been summarized (Douglas et al., 1994). Additionally, full scale tests provide further verification of Sugiyama's empirical equation (Dolan et al., 1996). Test results are shown in Figure 4.

Other methods for the design of shearwalls with openings have been suggested but are not part of the perforated shearwall design method. One promising method is a mechanics-based approach that accounts for the effects of horizontal restraint around openings (Diekmann, 1992). Horizontal restraint is used to redistribute panel shear forces into the panels above and/or below openings to reduce or eliminate the need for intermediate vertical restraint next to openings.

Sugiyama's Empirical Equation

Using Sugiyama's equation, the total shear capacity of a

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shearwall segment with unrestrained openings equals the shear capacity of a traditional shearwall segment of equal length times the shear load ratio, F. The shear load ratio is calculated from the following equation:

$$F = \frac{r}{(3 - 2r)} \qquad (1)$$

where r = sheathing area ratio.

Sheathing area ratio, r, is calculated by the following expression:

$$r = \frac{1}{\left(1 + \dfrac{a}{b}\right)} \qquad (2)$$

$$\alpha = \frac{\text{Area of Openings}}{H \cdot L} \qquad (3)$$

$$\beta = \frac{\sum L_i}{L} \qquad (4)$$

where
α = opening area ratio,
β = wall length ratio,
$\sum L_i$ = sum of the length of full-height sheathing,
L = shearwall length, and
H = wall height.

Equation 1 provides a conservative estimate of the shear load ratio at ultimate capacity. Empirical equations for shear load ratios at various deformation levels have also been developed and verified by testing.

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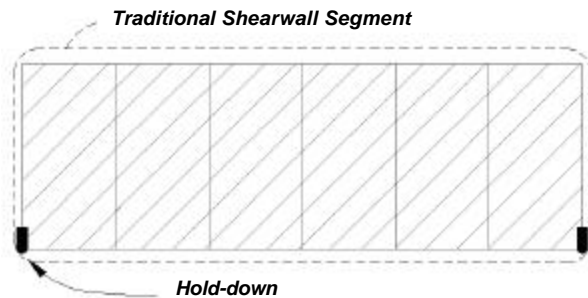
The *Standard Building Code* (SBC, 1994 revised) and the
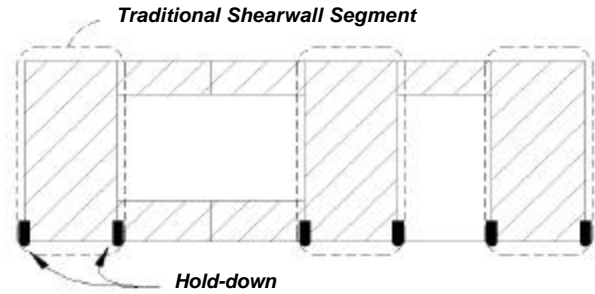

Figure 1. Traditional Shearwall

Figure 2. Typical Shearwall Composed of Three Traditional Shearwall Segments

Wood Frame Construction Manual for One- and Two-Family Dwellings - 1995 SBC High Wind (WFCM, 1996) recognize the perforated shearwall design method as an accepted method for wind design of wood frame shearwalls with unrestrained openings. Provisions in the SBC and WFCM allow the design of perforated shearwalls without intermediate overturning restraint. This results in shearwalls with fewer hold-downs and more efficient use of construction materials.

Following is a review of the process by which a perforated shearwall can be designed. The application of this procedure is currently limited to wood frame panel shearwalls meeting conditions based on testing. With additional research, modification of limitations and expanded applications of this approach are expected.

Applicability

The perforated shearwall design method is applicable to the design and analysis of new and existing conventionally-framed shearwalls that have all of the following characteristics. The shearwall:

1) is mechanically restrained against overturning and shear;
2) has hold-downs to provide overturning restraint and maintain a continuous load path to the foundation where any plan discontinuities occur in the wall line;
3) has a minimum length of full-height sheathing at each end of the shearwall (prescribed by the applicable building code); and,
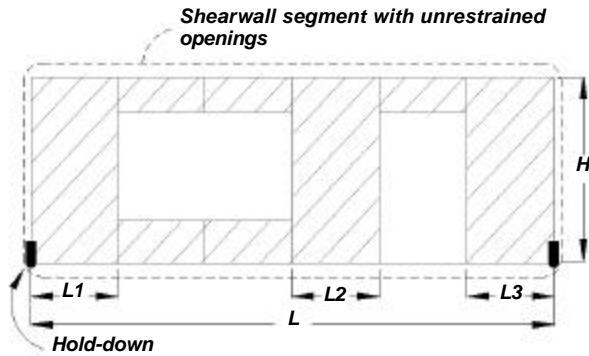4) has sheathing materials that do not exceed a maximum ultimate shear capacity of 1500 plf.

Figure 3. Typical Perforated Shearwall with Unrestrained Openings

Procedure

Finding the design shear capacity involves relating the strength of a shearwall with unrestrained openings to a similar shearwall consisting of traditional shearwall segments. Both wall types are assumed to have identical construction (i.e., same sheathing thickness, fasteners and fastener schedules, and framing member species and spacing) and attachment to elements above and below. The shear capacity of a traditionally designed shearwall is the assumed upper limit on perforated shearwall strength.

Empirically derived adjustment factors that relate the strength of shearwalls with unrestrained openings to similar shearwalls containing multiple traditional shearwall segments are presented in Table 1. The perforated shearwall procedure calls the adjustment factor the "opening adjustment factor." It accounts for the presence of unrestrained openings and their strength reducing effect on shearwall capacity. For a shearwall of fixed length, shear capacity decreases as wall opening sizes increase. The shear capacity of shearwalls with unrestrained openings is always less than similar, traditional shearwalls without openings.

If shearwall and opening dimensions are known, the calculation of the percent of full-height sheathing (based on total length of the shearwall segment) and determination of the maximum unrestrained opening height allows the use of Table 1. Once a factor is obtained, it can be used to find the allowable shear capacity of a shearwall segment with unrestrained openings. The allowable shear capacity, $V_{perforated}$, is calculated by the following expression:

$$V_{perforated} = C_o \cdot v \cdot \sum L_i \qquad (5)$$

where $V_{perforated}$ =   allowable shear capacity in units of force,

      C_o =   opening adjustment factor,

      $\sum L_i$ =   sum of the lengths of full-height sheathing, and

      v =   allowable unit shear for traditional

shearwall segments in units of force per unit length.

Allowable unit shears (plf) for traditional shearwall segments are readily available in the U.S. model building codes for various combinations and thicknesses of sheathing materials, framing spacing, fasteners and fastening schedules.

Unrestrained Opening Height

The unrestrained opening height is found by measuring the vertical dimension of an opening. Such openings can be contained between:

- two sheathing elements at the top and bottom of the wall (as for most window installations),
- one sheathing element and the top or bottom of the wall (which would include most doors and some windows),
- or the top and bottom of the wall (as for extremely tall windows or doors; or where structural sheathing is not present above or below openings).

Additionally, areas sheathed with a non structural sheathing or with full-height sheathing that do not meet building code prescribed height-to-length ratios are considered openings.

To find the opening adjustment factor from Table 1, the maximum unrestrained opening height within the shearwall segment must be known. The factors conservatively assume that the heights of all openings in the shearwall segment are equal to the maximum unrestrained opening height. Linear interpolation may be used to find opening adjustment factors for maximum opening sizes that are between tabulated sizes.

Opening adjustment factors for a range of typical opening heights are provided in Table 1 for eight and ten-foot high walls. Factors for other wall heights can be determined from the ratio of opening height to wall height. Column headings for the window and door height identify typical values for windows and/or doors but are not limited to these values. For example if structural sheathing is not placed above and below openings the wall height becomes the maximum unrestrained opening height.

Table 1 - Opening Adjustment Factor for Perforated Shearwalls

	Maximum Unrestrained Opening Height (Window or 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

Percent Full-Height Sheathing

The percentage of full-height sheathing is based on the ratio of full-height sheathing length to shearwall segment length. To be considered full-height sheathing, the length of each full-height sheathed section must equal or exceed the prescribed height-to-length ratios for shearwall segments in the applicable building code. Linear interpolation may be used to find opening adjustment factors between the percent full-height sheathing shown.

Table 1 presents the percent full-height sheathing in 10% increments from 0% to 100%. Values for 0% full-height sheathing are provided for interpolation purposes only. The 100% full-height sheathed case represents a traditional shearwall segment with a corresponding opening adjustment factor of one.

Connection Requirements

Hold-downs are required at each end of the shearwall and at all plan discontinuities that occur in the wall line, to provide restraint against overturning and to maintain a continuous load path to the foundation. The hold-down capacity at each end of the shearwall must equal or exceed the overturning restraint required for a traditional shearwall segment.

Shear connections capable of resisting the allowable unit shear of a traditional shearwall segment are required throughout the segment. While the actual shear connection requirements may be less when using the perforated shearwall method, using traditional shearwall segment shear connector requirements account for the non-uniform distribution of shear loads in the perforated wall.

Design Example

Problem Description - The perforated shearwall illustrated in Figure 3 is composed of Southern Pine framing members and is fully sheathed on the exterior with 15/32" Structural I plywood. Sheathing is attached to the framing members with 8d common nails spaced 6" o.c. at panel edges and 12" o.c. in the panel field. All full-height sheathed sections (sheathed area between the end of the shearwall segment and an opening or between two openings) have height-to-length ratios which meet building code requirements. The window opening is 4'-0" high by 8'-0" wide. The door opening is 6'- 8" high by 4'-0" wide. Sheathing is provided above and below the window and above the door. The wall length and height are 24'-0" and 8'-0" respectively. Hold-down connectors are at the ends of the shearwall to provide overturning restraint and anchor bolts are used to restrain the wall against shear. Determine the allowable shear capacity of the shearwall and requirements for the hold-down and shear connections.

Solution - The wall defined in the problem description meets the application criteria outlined for the perforated shearwall design method. The length of sheathing at each end of the shearwall meets building code prescribed height-to-length requirements (3-1/2:1) and the ultimate shear capacity of the plywood sheathing does not exceed 1500 plf. Additionally, the wall will be mechanically restrained against overturning and shear.

The process of calculating the design shear capacity involves multiplying the allowable unit shear capacity of a traditional shearwall segment (based on the framing, sheathing, and sheathing attachment) by the length of full-height sheathing and the opening adjustment factor. The resulting design shear capacity will always be less than expected from a similar traditional shearwall without openings.

The calculation process includes finding the length of full-height sheathing, percent full-height sheathing, maximum unrestrained opening height, and the allowable unit shear capacity of a traditional shearwall segment. The length of the full-height sheathing is 12'-0" (24'-0" - (4'-0" + 8'-0")) and percent full-height sheathing is 50 percent (12'/24').
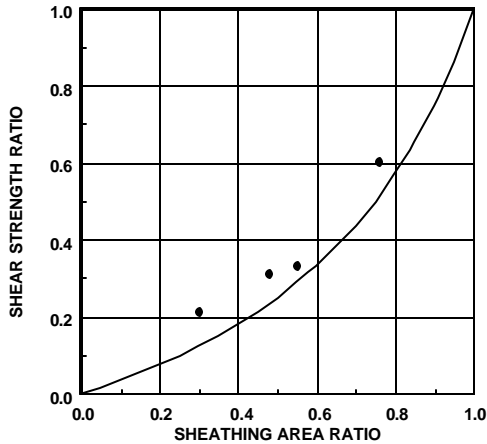
SHEATHING AREA RATIO	WALL CONFIGURATIONS
0.76	
0.55	
0.48	
0.30	

Figure 4. Results of Perforated Shearwall Tests

The opening adjustment factor ($C_O = 0.57$) can be obtained from Table 1 for a maximum unrestrained height of 6'-8" (door height) and percent full-height sheathing equal to 50 percent. An allowable unit shear for the combination of framing, sheathing and nailing schedule equal to 280 plf can be obtained from the *Standard Building Code* (Chapter 23).

Using equation 5, the net allowable shear capacity of the perforated shearwall can be determined as:

$$V_{perforated} = C_o \cdot v \cdot \sum L_i$$

where $C_O = 0.57$, $\text{S}L_i = 12'$, and $v = 280$ plf. The net allowable shear capacity is 280 plf x 12 feet x 0.57 or 1915 pounds. The shear capacity of the identical wall with intermediate overturning restraint next to all openings (traditional shearwall design with multiple traditional shearwall segments) equals 280 plf x 12 ft or 3,360 pounds.

Hold-down capacities at each end of the shearwall must equal or exceed the overturning restraint required for a traditional shearwall segment. Here, the hold-down must provide overturning restraint equal to the allowable unit shear capacity (280 plf) multiplied by the height of the

wall (8 feet) or 2,240 pounds. Assuming the dead load provides minimal or no overturning restraint, a similar shearwall consisting of multiple traditional shearwall segments would also require hold-down capacities equal to 280 plf x 8 feet or 2,240 lbs at each end of the shearwall and next to all openings.

Shear connector spacing can be conservatively determined based on the allowable unit shear of a traditional shearwall segment. Assuming an anchor bolt with a shear capacity of 1000 pounds is used to transfer shear forces, the maximum spacing between connectors equals 3.6 feet (1000 lbs/280 plf).

Conclusion

A perforated shearwall technique for design and analysis of shearwalls with openings has been presented. This method is published in both the *Standard Building Code* and the *Wood Frame Construction Manual for One- and Two-Family Dwellings*. While giving designers an additional design method and analytical tool, it also provides verification of conventional construction techniques, allows for fewer uplift restraints, and more efficient use of construction materials.

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