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Nonlinear seismic analysis of perforated steel plate shear walls

Anjan K. Bhowmick [a,*], Gilbert Y. Grondin [b], Robert G. Driver [c]

[a] Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, QC, Canada
[b] AECOM, Edmonton, AB, Canada
[c] Department of Civil and Environmental Engineering, University of Alberta, Edmonton, AB, Canada

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ABSTRACT

The behaviour of unstiffened steel plate shear walls with circular perforations in the infill plates is examined. A shear strength model of the infill plate with multiple circular openings is proposed based on a strip model. Eight perforation patterns in a single storey steel plate shear wall of two different aspect ratios were analyzed using a geometric and material non-linear finite element model to assess the proposed shear strength model. A comparison between the nonlinear pushover analysis and the proposed shear strength equation shows excellent agreement. The proposed model is used to design the boundary columns of three sample four-storey perforated shear walls. A comparison between the predicted design forces in the boundary columns for the selected shear walls with the forces obtained from nonlinear seismic analyses demonstrates the accuracy of the proposed simple model to predict the design forces in the columns.

1. Introduction

Unstiffened steel plate shear walls have been in use for a long time. Properly designed steel plate shear walls (SPSW) have high ductility, high initial stiffness, high redundancy, and excellent energy absorption capacity. Most recent practice for SPSW is to use thin unstiffened plates for the infill panels, relying on tension field action to provide lateral load resistance. For seismic design, the surrounding framing members are generally "capacity designed", i.e., they are designed to develop the full capacity of the infill plate tension field, while they remain essentially elastic.

The thickness of the infill plate used in a SPSW is often governed by factors other than strength (e.g. handling and welding), which often results in much stronger shear walls than required for lateral load resistance. This creates a problem in capacity design, as it introduces excessive design forces to the surrounding frame members, thus increasing their required size. Recent attempts to address this problem have included the use of light-gauge, cold-formed, steel infill plates or low yield strength (LYS) steel for infill plates [1,2], introducing vertical slits in the infill plate [3,4], or introducing a regular pattern of circular perforations in the infill plate [2]. Among all these methods of weakening the infill plate, the perforated SPSW proposed by Vian [2], illustrated in Fig. 1, represents an attractive system since it also provides a route for the utility systems to pass through the infill plates.

Research on circular perforations in shear panels started with Roberts and Sabouri-Ghomi [5]. They conducted a series of quasi-static tests under cyclic diagonal loading on unstiffened steel plate shear panels with centred circular openings. The following approximate equation was proposed for the calculation of the strength of an unstiffened infill panel with a central circular opening:

$$V_{op} = V_p\left(1-\frac{D}{d_p}\right) \tag{1}$$

where V_{op} and V_p are the strength of a perforated and a solid shear panel, respectively, D is the perforation diameter, and d_p is the panel height.

Purba [6] analyzed a 4000 mm by 2000 mm single storey SPSW with multiple regularly-spaced circular perforations of equal diameter. An investigation of the effect of infill plate thickness and perforation diameter on the shear strength indicated that Eq. (1) provides a conservative estimate of the strength of perforated infill plates with multiple perforations when d_p in Eq. (1) is replaced by S_{diag}, the diagonal distance between each perforation line (see Fig. 1). Through a calibration study, the following modified equation was proposed to calculate the shear strength of perforated SPSWs with the regular perforation pattern used by Vian [2]:

$$V_{op} = V_p\left(1-0.7\frac{D}{S_{diag}}\right). \tag{2}$$

Purba [6] also found that results from an individual perforated strip analysis can accurately predict the behavior of a complete SPSW with perforations provided that the hole diameter is less than 60% of the strip width, namely, $\left(\frac{D}{S_{diag}}\leq 0.6\right)$. Although Eq. (2) was found to provide good strength predictions of SPSWs for the regular perforation

* Corresponding author. Tel.: +1 514 848 2424; fax: +1 514 848 7965.
E-mail address: anjan.bhowmick@concordia.ca (A.K. Bhowmick).

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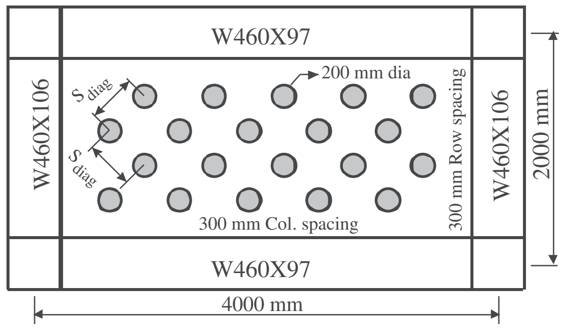

Fig. 1. Test specimen from Vian [2].

pattern proposed by Vian [2], a more general expression, applicable to any pattern of perforations, is clearly desirable.

This paper presents a general equation for determining the strength of perforated SPSWs. The proposed equation is based on a strip model, and is derived by discounting the strips that are intercepted by perforations. Finite element models of two single storey SPSWs (with aspect ratios of 2.0 and 1.5) and with eight different types of perforation patterns are analyzed to investigate the effectiveness of the proposed equation.

AISC Steel Design Guide 20 [7] presents a capacity design method for the design of SPSW with solid infill plates. The method assumes that all the infill plates over the building height reach their full yield capacity and plastic hinges develop at the ends of all the horizontal members of the frame. The columns axial forces are a function of the tension field in the infill plates and the bending moments and shear forces in the beams. The presence of perforations in the infill plates affects the forces and moments in the boundary columns, thus requiring modifications to the current design method. This paper proposes modifications to the capacity design method to accommodate SPSWs with circular perforations. The use of the modified capacity design method is illustrated on three SPSWs with circular perforations. The design force effects in the boundary columns are compared with the design forces obtained from a seismic analysis of the 4-storey SPSWs under four spectrum-compatible earthquake ground motions for Vancouver, Canada.

2. Strength prediction of perforated infill plate

To develop a general strength model, it is assumed that the infill plate has negligible buckling capacity and that the shear strength of the SPSW is provided strictly by tension field action. The angle of the tension field, α, is obtained from the equation specified both in Canadian standard CAN/CSA-S16-09 [8] and in the AISC seismic Specification [9]. In the presence of a circular hole of diameter D, as shown in Fig. 2, one can discount part of the contribution, β, of the steel within a

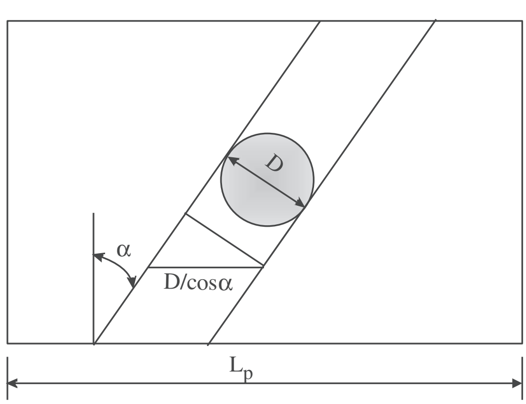

Fig. 2. Strip model for perforated infill plate.

diagonal strip of width D [2]. Taking the diagonal strip containing the circular hole to be at the angle of the tension field, α, the horizontal projection of the portion of the strip to be discounted is $\beta\frac{D}{\cos\alpha}$. The effective width of a perforated infill plate, $L_{p,eff}$, accounting for the presence of a single circular perforation or multiple perforations affecting only one strip, is:

$$L_{p,eff} = L_p - \beta\frac{D}{\cos\alpha} \tag{3}$$

where L_p is the width of infill plate.

When more than one strip is affected by perforations, the effective width of the perforated infill plate, $L_{p,eff}$, is

$$L_{p,eff} = \left(L_p - N_r\beta\frac{D}{\cos\alpha}\right) \tag{4}$$

where N_r is the maximum number of diagonal strips (counted at any section cut parallel to length L_p) with circular perforations to be discounted.

It is assumed that all the strips with perforations are inclined by the same angle. Also, Eq. (4) assumes that all the perforations have same diameter. In case of different perforation diameters, Eq. (4) can be modified as:

$$L_{p,eff} = \left(L_p - \sum_{i=1}^{N_r}\beta\frac{D_i}{\cos\alpha}\right). \tag{5}$$

For this study, perforations with same diameters will be considered and thus Eq. (4) will be used for the development of shear strength equation for perforated infill plate.

The shear strength of a solid infill plate, V_p, is given by [10]:

$$V_p = 0.5\,\sigma\,wL_p\sin 2\alpha. \tag{6}$$

Thus, the shear strength of a perforated infill plate, V_{op} is

$$V_{op} = 0.5\,\sigma\,w\;L_{p,eff}\sin 2\alpha \tag{7}$$

where w is the infill plate thickness and σ is the stress in the infill plate tension strips, taken as the material yield strength for design.

From Eqs. (6) and (7)

$$\frac{V_{op}}{V_p} = \left(1 - \beta\,N_r\frac{D}{L_p\cos\alpha}\right). \tag{8}$$

The designer can estimate graphically the value of $N_r\frac{D}{L_p\cos\alpha}$ from the geometry of the SPSW. As discussed in the next section, the value of the perforated strip contribution, β, is derived from the analysis of a series of single storey SPSWs with a variety of circular perforation patterns.

3. Analysis of perforated steel plate shear walls

Nonlinear finite element analyses of a series of single-storey SPSWs were carried out using ABAQUS [11] to determine the magnitude of the constant β. Both material and geometric nonlinearities were considered. In total, eight different types of perforation patterns were considered in this study. Variation in perforation diameters was also considered for each type of perforation pattern.

3.1. Selection of shear wall system

The single-storey SPSW considered here is part of a hypothetical symmetrical office building located in Vancouver, Canada. The 3.8 m tall building has a floor area of 2014 m^2. As shown in Fig. 3, the building