Thin-Walled Structures 75 (2014) 30–42

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

Seismic behavior of steel plate shear walls with centrally placed circular perforations

Anjan K. Bhowmick*

Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, Quebec, Canada

ARTICLE INFO

Article history:
Received 14 December 2012
Received in revised form
24 June 2013
Accepted 10 September 2013
Available online 15 November 2013

Keywords:
Steel plate shear wall
Seismic analysis
Circular perforations
Unstiffened thin plate

ABSTRACT

The behavior of unstiffened thin steel plate shear walls with circular perforations placed at the center of the infill plates is examined. A shear strength equation is developed for perforated steel plate shear wall with circular perforation at the center. A series of single storey perforated steel plate shear walls with different aspect ratios and different perforation diameters were analyzed to assess the proposed shear strength equation. A comparison between the nonlinear pushover analysis and the proposed equation shows excellent agreement. The proposed shear strength equation is applied for design of boundary columns of one 4-storey and one 6-storey perforated steel plate shear walls. The predicted design forces in the boundary columns for the selected perforated shear walls are compared to the forces obtained from nonlinear seismic analysis. The proposed equation gives very good predictions for the design forces in the boundary columns.

1. Introduction

Steel plate shear walls (SPSWs) are a very effective system for resisting lateral loads due to wind and earthquakes. A properly designed SPSW has high ductility, high initial stiffness, high redundancy, and excellent energy absorption capacity in comparison to many conventional lateral load resisting systems. Steel plate shear walls are also lighter and more ductile than reinforced concrete shear walls and they are relatively easy to install. In North America, the current practice is to use thin unstiffened steel plates for the infill plates, relying on post-buckling strength of the infill plates to calculate the capacity of SPSWs. The surrounding framing members are generally “capacity designed”, i.e., designed to develop the infill plate tension field capacity, while themselves remaining essentially elastic.

Because of the efficiency of the infill plate in carrying storey shears, it has been observed [1] that plate thickness requirements in SPSWs are generally very low, especially for mid to low-rise buildings, even under relatively severe seismic loading. Very often, in some SPSW applications, the minimum panel thicknesses available from steel producers are much thicker than that required by the design. Use of larger than required infill plate thickness introduces a problem in capacity design, as this will introduce excessive forces to the surrounding frame members, thus increasing their required size as per capacity design. Recently, attempts have been made to address this problem by (a) using light-gauge cold-formed steel infill plates instead of regular hot-rolled infill plates [2,3], (b) using low yield strength (LYS) steel for infill plates [3], (c) introducing vertical slits in the infill plate [4,5], (d) connecting the infill plate only with the beams in a moment frame of SPSW system [6], or (e) introducing a regular pattern of circular perforations in the infill plate [3]. Among all the proposed options, the perforated SPSW recommended by Vian [3], shown in Fig. 1, represents an attractive system since it can also accommodate the need of utility systems to pass through the infill plates.

Research on circular perforations in shear panels similar to SPSWs started with Roberts and Sabouri-Ghomi [7]. They conducted a series of quasi-static tests under cyclic diagonal loading on unstiffened steel plate shear panels with centrally-placed circular perforations. Based on the results, the researchers proposed the following approximate equation for 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. The equation proposed by Roberts and Sabouri-Ghomi [7] was only tested for relatively small rectangular and square shear panel specimens (maximum size: 450 mm × 300 mm) loaded in shear.

Purba [8] analyzed a 4000 mm by 2000 mm single storey SPSW with multiple regularly-spaced circular perforations of equal diameter. It was observed that for multiple regularly-spaced perforations, Eq. (1)

---

* Tel.: +1 514 848 2424; fax: +1 514 848 7965.
E-mail address: anjan.bhowmick@concordia.ca

0263-8231/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.tws.2013.09.027

Nomenclature

A_{bi}	$i$thbeam cross-sectional area.
D	Perforation diameter.
d_p	Panel height.
F_y	Yield strength.
F_{yb}	$i$thbeam yield strength.
I_c	Moment of inertia of each column.
P_b	Axial forces in beams.
R_y	Ratio of the expected steel yield stress to the nominal yield stress.
S_{diag}	Diagonal distance between each perforation line.
V_{op}	Shear strength of perforated plate.
V_p	Shear strength of solid plate.
w	Infill plate thickness.
α	Angle of tension field.
ω_h	Column flexibility parameter.
ω_{xci}	Distributed loads (x-component) from plate yielding applied to the $i$thcolumn
ω_{yci}	Distributed loads (y-component) from plate yielding applied to the $i$thcolumn.
ω_{bi}	Distributed loads from plate yielding applied to the $i$thbeam.
ω_{xbi}	Distributed loads (x-component) from plate yielding applied to the $i$thbeam.
ω_{xbi+1}	Distributed loads (x-component) from $(i+1)$thplate yielding applied to the $i$thbeam.
ω_{xbi-1}	Distributed loads (x-component) from $(i-1)$thplate yielding applied to the $i$thbeam.
ω_{ybi}	Distributed loads (y-component) from plate yielding applied to the $i$thbeam.
ω_{ybi-1}	Distributed loads (y-component) from $(i-1)$thplate yielding applied to the $i$thbeam.
ω_{ybi+1}	Distributed loads (y-component) from $(i+1)$thplate yielding applied to the $i$thbeam.
$L_{p,eff}$	Effective width of the perforated infill plate.
L_p	Width of perforated infill plate.
$M_{col,i}$	Moment at $i$thcolumn.
M_{pri}	Reduced plastic moment capacity at the ends of beam i.
$P_{b(col)}$	Beam axial force, contribution from column with inward infill plate forces applied to it.
$P_{b(plate)}$	Beam axial force, contribution from difference in infill plate's forces above and below the beam.
V_{bi}	Shear forces at the ends of beam i.
Z_{xi}	Beam plastic section modulus.

provides a conservative estimate of the strength of the perforated infill plate 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 [3]:

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

Although Eq. (2) was found to provide good strength predictions of SPSWs for the regular perforation pattern proposed by Vian [3], very often engineers want to place only a single larger opening at the center of the infill plate. This is mainly for ease of fabrication. A single perforation at the center of the infill plate would significantly reduce the cost of fabrication in compare to the existing regularly spaced perforation layout. Currently there are no guidelines available to design SPSWs with a single circular opening at the center of the shear walls.

This paper presents a simple equation for determining the strength of perforated SPSWs with centrally located circular perforations. The proposed equation is based on a strip model concept, and is derived by discounting the strip that is intercepted by the perforation. Finite element models of three single storey SPSWs (with aspect ratios of 2.0, 1.5, and 1.0) with nine different types of perforation diameters are analyzed to investigate the effectiveness of the proposed equation.

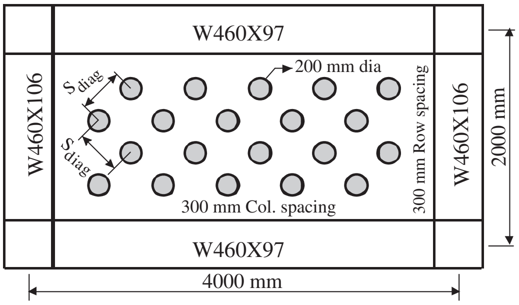

Fig. 1. Perforation layout of test specimen from Vian [3].

AISC Steel Design Guide 20 [9] presents a capacity design method for the design of SPSW columns with solid infill plates. The method in AISC Steel Design Guide 20 [9] assumes that all the infill plates over the building height reach their full yield capacity, and plastic hinges are assumed at the ends of all the horizontal members of the frame. Forces from the infill plate tension fields and the force effects from the beams are then applied to free body diagrams of the boundary columns to determine their design axial forces and moments. The presence of perforations in the infill plates affects the axial forces and moments in the boundary columns, thus requiring modifications to the current design method. This paper presents modifications to the capacity design method of AISC Steel Design Guide 20 [9] to accommodate SPSWs with centrally located circular perforations. With the modifications in the current capacity design method, columns of one 4-storey and one 6-storey perforated SPSWs with centrally placed circular perforations are designed. The resulting design forces for the boundary columns are compared with the design forces obtained from seismic analysis of the selected SPSWs under site specific earthquake ground motions for Vancouver, Canada.

2. Strength equation for infill plate with centrally located perforation

To develop a general strength model, it is assumed that the shear strength of the SPSW is provided strictly by tension field action in the infill plate. The angle of the tension field, α, is obtained from the equation specified both in Canadian standard, CAN/CSA-S16-09 [10] and AISC seismic Specification [11]. It is assumed that in the presence of a circular hole of diameter D, as shown in Fig. 2, one can discount the steel within a diagonal strip of width D. This assumption will be investigated by conducting series of finite element analysis. If the diagonal strip containing the circular hole is at an angle α, angle of tension field, the horizontal projection of the portion of the strip to be discounted is $D/\cos\alpha$. After discounting the strip with the circular perforation, the effective width of the perforated infill plate,