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Experimental investigation on cyclic behavior of perforated steel plate shear walls

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ABSTRACT

In recent decades, steel plate shear walls have come to be considered as a convenient system for resisting lateral loads due to earthquakes and wind, especially in tall buildings, because of their ductile and energy absorption behaviors. The existence of openings affects the seismic behavior and performance of steel plate shear walls. In the present research, the effects of opening dimensions as well as slenderness factors of plates on the seismic behavior of steel plate shear walls are studied experimentally. Eight 1:6 scaled test specimens, with two plate thicknesses and four different circular opening ratios at the center of the panel, have been manufactured and were tested under the effects of cyclic hysteresis loading at the thin-walled structures research laboratory of Urmia University, Urmia, Iran. The hole was put in the center of the panel because this is the most detrimental location in view of the panel tension field action. The obtained results signify a stable and desired behavior of steel plate shear walls for large displacements of up to 6% drift. The creation of openings decreases the initial stiffness and strength of the system, and increasing the opening diameter will intensify this matter. The obtained ductility of specimens shows the stable functioning of a system in the nonlinear range. Although the stable cyclic behavior of specimens in the nonlinear range causes mostly a dissipation of energy during the loading of samples, but existence of an opening at the center of the panel causes a noticeable decrease in energy absorption of the system.

1. Introduction

Over the last decade, a widespread interest has been shown in the application of steel plate shear walls ($SPSW_s$)[1] as a desirable resistant system against the lateral load in buildings. A steel plate shear wall is similar to a plate girder that is placed vertically and is expanded in the total height of the building. High elastic stiffness, high ductility and stable hysteresis loops are some of the desirable characteristics of an SPW system. Because of the dissipation of a large amount of energy, steel plate shear walls can be beneficial in highly active seismic zones.

In comparison with reinforced concrete walls, an SPW system shows a high capacity for energy absorption with stable hysteresis behavior and diagonal tensile field action of the web. In addition, SPW systems are lighter than concrete walls. For these reasons, an SPW system will lead to a reduction in the earthquake force. By using shop-welded, field-bolted SPWs, field inspection is improved and a high level of quality control can be achieved. For architects, the increased versatility and space saving because of the smaller cross-section of SPWs, compared to reinforced concrete shear walls, is a distinct benefit, especially in high-rise buildings, where reinforced concrete shear walls in lower floors become very thick and occupy a large proportion of the floor plan [1].

In some cases, the existence of openings is inevitable because of architectural reasons, passing equipment, or structural reasons, such as ductility and rigidity control. Therefore, it is necessary to do research on the effects of openings on the seismic behavior of steel plate shear walls.

To study the load–displacement characteristics of SPWs, Sabouri-Ghomi and Roberts carried out a series of cyclic quasi-static tests in 1991 on 16 unreinforced thin panels, some of which had openings, at small scales [2,3]. The frame had hinge joints, and the plate was connected to boundary members by bolts. The loading and unloading operations were carried out along the diagonals for creating pure shear. All of the panels showed adequate ductility and a capability for dissipating a large amount of energy. They also presented a theoretical method for calculating the shear capacity of the steel plate shear walls, named the Plate and Frame Interaction (PFI) method. Studying the experimental perforated specimens, Sabouri and Roberts proposed an empirical factor $(1-D/d)$ for the decreasing strength and stiffness of steel plate shear walls due to the existence of openings, where D is the opening diameter and d is the panel height.

In 2000, Deylami and Daftari analyzed more than 50 models with a rectangular opening in the center of the panel using a NISA Π nonlinear finite element program. They investigated the effects of some important geometric parameters, such as sheet thickness, the ratio of opening height to width, and the areal percentage of the opening [4]. In cases of small opening percentages, the decrease in shear capacity was more dependent on the plate thickness. The ratio of

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[1] Or steel plate walls (SPW_s).

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height to optimized width of the opening has been a function of the plate thickness, and it has not been dependent on the opening percentage. In thinner steel plate shear walls, the maximum shear capacity has been achieved by a smaller ratio of height to width of the opening. Also, the decrease in shear capacity after reaching a maximum amount has been slower in thick plates than in thin plates. In all cases, the optimized shear capacity is achieved when the ratio of height to width of the openings is greater than 1.

In 2004, Vian and Bruneau from the University at Buffalo began a joint experimental study on SPWs with National Taiwan University [5]. Three single-story steel panel shear wall specimens were tested. The specimens utilized low yield strength steel infill panels and reduced beam sections at the beam ends. The first specimen had a solid panel, the second one had 20 openings with diameters of 200 mm and the third specimen had quarter-circle cutouts in the panel corner, which were reinforced to transfer the panel forces to the adjacent framing. In this research all specimens were tested under cyclic quasi-static loading according to the ATC-24 protocol [6]. The results of these experiments indicate that steel plate shear walls with low yield strengths can be considered as a practical choice for resistance against lateral loads during earthquakes. Utilizing a thin panel with small yield strength will cause a decrease in the strength and quick start of energy dissipation by the panel. The panels with openings show a decrease in strength and stiffness, so they may be used when steel plates with small yield strength are not readily available.

Kharrazi et al. [7] have proposed a theoretical model named Modified Plate and Frame Interaction (M-PFI) for the shear and bending analysis of ductile steel plate shear walls. In this model, the behavior of steel plate shear walls was divided into three different parts: elastic buckling, post buckling, and yielding. Considering the interaction between shear and flexural behavior of steel shear walls, the M-PFI model describes the behavior of SPW systems, and a good compatibility with different experimental results is accessible.

By studying the previous work on steel plates shear walls, it seems that, despite the inevitable reasons for existing openings in SPW systems, few researchers have studied the effects of openings on the seismic behavior of SPWs. In this research, to study the effect of slenderness factor, opening ratio and the failure modes of steel plate shear walls, eight specimens were designed to 1:6 scale and subjected to cyclic loading. The hole is put in the center of panel because this is the most detrimental location in view of the panel tension field action. The primary parameters of initial stiffness, shear strength, ductility and energy dissipation rate were determined.

2. Analytical formulas for shear force-displacement

The results obtained from experimental specimens can be investigated by M-PFI formulas proposed for calculating the critical buckling and yielding capacity [7]. Because of the hinged beam column joints of the laboratory frame, the frame system does not provide any considerable resistance against lateral forces. Thus, the panel strength against lateral forces only includes the strength of the infill plate. A diagram of shear force-displacement related to a steel plate with dimensions of b, d and a thickness of t is given in Fig. 1. Points C and D in Fig. 1 indicate the buckling and yielding points of the steel plate, respectively.

2.1. Buckling stage

The critical buckling shear stress, τ_{cr}, for a steel plate is calculated as follows [8]:

$$\tau_{\mathrm{cr}} = \frac{k\pi^2 E}{12(1-\mu^2)}\left(\frac{t}{b}\right)^2 \leq \tau_{\mathrm{y}} = \frac{\sigma_0}{\sqrt{3}} \tag{1}$$

where t, b, E, μ, τ_{Y} and σ_0 are the thickness of the steel plate, width of the steel plate, elasticity modulus, Poisson's ratio, shear yielding stress and uniaxial yielding stress of the plate, respectively. The shear buckling factor k depends on the steel plate aspect ratio and boundary conditions, it is equal to 9.35 for a simple supported square plate.

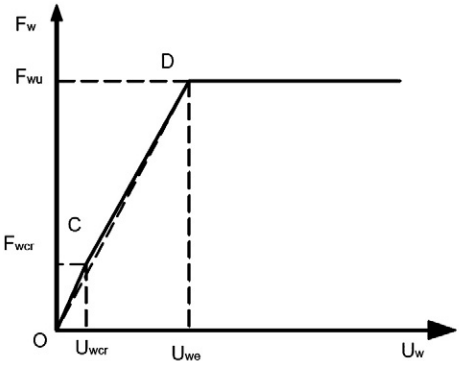

Fig. 1. Shear force-displacement diagram of a steel plate with sufficient supports only [1].

Thus, the critical shear force, F_{cr}, and critical shear displacement, U_{cr}, of a plate can be calculated by:

$$F_{\mathrm{cr}} = \tau_{\mathrm{cr}}\, b\, t \tag{2}$$

$$U_{\mathrm{cr}} = \frac{\tau_{\mathrm{cr}}}{G}\, d \tag{3}$$

where G and d are the shear modulus of the steel plate's materials and height of the steel plate, respectively. By calculating F_{cr} and U_{cr} using Eqs. (2) and (3), the position of point C will be specified in the shear force-displacement diagram of Fig. 1.

2.2. Post-buckling stage

It is assumed that in the post-buckling stage, the diagonal tension field will expand with an angle θ from the horizon throughout the entire web plate. By calculating the total stress of the plate at the time of yielding according to the Von Mises yield criterion for thin plates, the shear strength of the web plate, F_{u}, can be specified as follows [7]:

$$F_{\mathrm{u}} = \left(\tau_{\mathrm{cr}} + \frac{1}{2}\sigma_{\mathrm{ty}} \sin 2\theta\right) b\, t \tag{4}$$

where σ_{ty} is the stress of the tension field in yielding time.

The limiting elastic shear displacement, U_{e}, is given as [7]:

$$U_{\mathrm{e}} = \left(\frac{\tau_{\mathrm{cr}}}{G} + \frac{2\sigma_{\mathrm{ty}}}{E \sin 2\theta}\right) d \tag{5}$$

To further simplify the calculations of the shear load displacement diagram, lines OC and CD in Fig. 1 can be substituted by a straight line *OD*.

Roberts and Sabouri concluded that the strength and stiffness linearly decreases with the increases in $(1-D/d)$, where D is the opening diameter and d is the panel height [3]. The reduction factors proposed by Roberts and Sabouri were used in the aforementioned formulas for considering the strength and stiffness decrease in perforated specimens in the present study.

3. Test program

For studying the effect of the slenderness factor and opening dimension on the seismic parameters of steel plate shear walls, eight 1:6 scale specimens were prepared and tested under cyclic loading in the thin-walled structure research laboratory of Urmia University. The details of the testing hinge frame, preparation of specimens and loading process are given below.