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Experimental study on diagonally stiffened steel plate shear walls with central perforation

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ABSTRACT

One of the advantages of Steel Plate Shear Walls (SPSWs) is the easiness of openings application in infill plate. The openings are sometimes required for passing utilities, architectural purposes, and/or structural reasons. However, the recent researches on perforated steel plate shear walls have shown that the shear strength and stiffness of an un-stiffened steel shear wall decrease due to perforation of the infill plate. Hence, this paper presents a special combination of diagonal stiffeners with a central perforation. The seismic behavior of the new system is experimentally investigated and compared to the solid infill plate models. Experimental testing is performed on three ½ scaled single-story SPSW specimens under cyclic quasi-static loading. One of the specimens is un-stiffened and the two others are diagonally stiffened, which in one of them, a circular opening with the diameter of ⅓ depth of the panel is cutout from the wall center. It is observed that by means of the proposed stiffening method the shear strength of the perforated shear walls is achieved close to the un-stiffened wall with the solid panel, and the seismic behavior of the system is considerably improved. Test results show that the ductility ratio of the specially perforated specimen is about 14% greater than the un-stiffened specimen. A formula is developed and verified for the estimation of the shear strength of a perforated and diagonally stiffened SPSW. There are good agreements between the experimental outcomes and the theoretical predictions.

1. Introduction

Upon the recent researches, Steel Plate Shear Wall (SPSW) is known as a reliable lateral load resisting system in the high seismic risk zones [1–4]. In addition, one of the advantages of steel shear walls is the easiness of application of openings in the infill plate, which sometimes are required for passing utilities, architectural purposes, and/or structural reasons. Nonetheless, the current building codes and structural designers are mostly conservative against using perforations in the shear walls, where they prescribe special details and restrictions whenever openings are required. Since, if a perforated shear wall is not designed properly, the seismic performance of the structure might be diminished. Besides, application of openings in the shear walls usually complicates the structural analysis. Moreover, the recent researches on perforated steel plate shear walls have verified that the shear strength and stiffness of an un-stiffened steel shear wall diminish due to perforation of the infill plate which may not be often desirable in the design. These contradictory requirements have provided research fields toward the goal of finding solutions for reducing the undesirable effects of openings on the structural and seismic properties of steel shear walls. A history of the main researches on the perforated SPSWs is briefly presented in the following:

The idea of using special openings in shear walls returns to Omori et al. [5] and Mutoh et al. [6] who proposed using slits in reinforced concrete shear walls in order to improve the seismic behavior of the RC shear walls. Hitaka and Matsui [7] studied the performances of slits in steel shear walls. They tested 42 steel plate walls of one-third scaled specimens under monotonic and cyclic lateral loading. All specimens behaved very ductile, although some degradation in the shear strengths of the walls happened after initiation of the out-of-plane buckling in the plates. They applied vertical edge stiffeners to restrain out-of-plane deformation of the plate, and found them effective.

Roberts and Sabouri-Ghomi [8] carried out a series of cyclic quasi-static testing on 16 specimens which numbers of them had central circular openings. The panel depth (d) was taken 300 mm in the all of specimens and the values of the circular opening diameter (D) were selected as 0, 1/5, 1/3, and 1/2 of d. The connections of the peripheral frames were of hinge type. The loading on the specimens was applied diagonally. On the basis of the experimental results, they concluded an approximate strength and stiffness reduction factor as $(1 - D/d)$ for a perforated panel with a circular single hole at its center in comparison to the solid panel. The pinching was observed in the cyclic loops of the tested specimens, especially, this phenomenon became increased in the envelope curves of the perforated specimens.

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The effects of holes in the infill plate of un-stiffened SPSWs were also investigated by Vian and Bruneau [9]. They used low yield steel material for the infill plates and performed experimental testing on three ½ scaled single-story with single-bay specimens. One of the specimens was specially perforated with multiple holes laid out in the steel panel. In the second specimen, quarter-circles were cutout from the panel corners, and the corners were reinforced to transfer the panel forces to the adjacent frame. The third specimen was designed as a SPSW with the solid panel; it was tested as a reference sample. They reported that all the specimens resisted against imposed input history of increasing displacements to a minimum drift of 3%. The elastic stiffness and overall strength of the perforated panel were found decreased by 15% in comparison to the solid panel sample.

The recent investigations on diagonally stiffened steel shear walls have shown that the diagonal stiffeners increase shear strength and improve cyclic behavior of a thin SPSW, authors [10,11]. On that account, it is deemed that a combination of special perforation with diagonal stiffeners might behave effectively. Hence, this study has focused on the rehabilitation of the shear strength and stiffness of perforated panels and even improvement of the non-linear behavior of perforated steel walls by means of the diagonally stiffening method. This paper presents the research results from experimental and numerical investigations on three ½ scaled single-story SPSWs. A set of comparative studies are also included to evaluate the seismic performance of a diagonally stiffened steel shear wall with a central opening in competition with the un-stiffened and diagonally stiffened solid-plate shear walls. Furthermore, a formula is derived and proposed for the estimation of shear strength of the new system.

2. SPSW specimens and test set-up

Laboratory study was conducted on ½ scaled single-story single-bay specimens of diagonally stiffened and un-stiffened steel shear walls at IIEES (Tehran-Iran). The laboratory is equipped with two reaction steel frames and a strong base, significantly stiffer than the specimens. One of the reaction frames was employed for installation of the specimens and applying the loads and the second frame for the lateral supporting of the specimens. Each test was performed under fully reversed cyclic quasi-static loading in compliance with ATC-24 [12] test protocol. The horizontal loads were applied on the specimens by means of a hydraulic jack with 1000 kN capacity. The gravity load of a magnitude for a typical building and corresponding to the dimensions of the specimens was applied to the specimens by a vertical jack. Total gravity load was taken as 160 kN; in which, 80 kN for each column of the specimen.

2.1. Steel shear wall specimens

Three ½ scaled one-story specimens with around 2 m width and 1.5 m height of SPSWs were designed and fabricated for the test program. The width-to-height aspect ratio of the specimens was selected as 1.33 to represent the moderate dimensions of a shear wall in the buildings. This aspect ratio was considered corresponding to the actual sizes of a shear wall with 4 m width and 3 m typical story height. The boundary elements were made of the standard profile HEB160, and the infill steel plate thickness taken 0.8 mm for SPSW(s1, 2) and 1.0 mm for SPSW(s4). The boundary elements were such designed to meet the preliminary requirements of steel shear walls and AISC 341-05 [13] provisions. Full moment connections were provided at all beam-to-column joints by complete penetration groove welds and using the electrode type of E7018. At the top of each specimen, an additional HEB160 was placed on the frame beam and they were welded along with their flanges to each other to better anchor the internal panel forces and to contribute transferring loads of the horizontal jack to the specimen. This method was previously examined by Lubell [14] and resulted in good performance of the un-stiffened specimen.

In the specimen SPSW(s1), two-sided diagonal stiffeners plate of 40 mm × 4 mm were utilized in combination with the edge stiffeners (40 mm × 4 mm). The specimen SPSW(s4) was stiffened with two-sided diagonal and edge stiffeners plates (40 mm × 5 mm), and it was perforated in the centre with a circular opening. The diameter of hole was selected 400 mm corresponding to 1/3 of the wall depth. Observations on SPSW(s1) test regarding tears zone led to this size of the opening, besides, a hole with this relative dimension to the wall height could also satisfy the needs of the accessibility. The special hole was stiffened by means of a ring-shape stiffener plate of 90 mm × 5 mm. The diagonal stiffeners were placed between the edge and the ring-shape stiffeners and connected to them and to the infill plate by the fillet welds. Fig. 1 shows a framing view and geometrical details of this specimen. The third specimen SPSW2 was designed un-stiffened as a reference sample. Steel materials were chosen from the structural steel type. The mechanical properties of the steel materials are indicated in Table 1 were measured from the tension coupon tests in accordance with ASTM A370-05 [16].

The following steps were taken in the design of the diagonal stiffeners:

a) The stiffeners contribution in the seismic behavior of the shear walls was first evaluated through the pushover analysis of the stiffened systems, and the preliminary dimensions of the stiffeners were obtained accordingly.
b) Concerning the local buckling prevention, the width-to-thickness ratio (b/t) of the stiffeners was designed in compliance with the requirements of the compacted section requirements. In the specimen SPSW(s4), this ratio was taken under the plastic limit ($b/t \sim 8.5$) to improve performance of the stiffeners in the high inelastic zones.
c) The section and dimensions of the edge stiffeners were designed similar to the diagonal stiffeners, not less than them. The edge stiffeners were placed near to the midpoint of the connection of the fish-plates to each other in the corners, parallel to the diagonal stiffener in the same direction. They were also welded to the fish-plates.
d) An argon gas shield was used in the welding process of the stiffeners to the infill plate, because the infill plates were of the thin plates. This method of welding is known as MIG (metal inert gas) in the case of argon.

Fish plates with dimensions of 70 mm × 5 mm were used all around the panel for connection of the infill plates to the boundary members. A similar connection to the modified detail type B of the work of Schumakher et al. [15] was utilized. Accordingly, four holes with the dimensions of 25 mm × 25 mm were cut out in the corners of the fish plates to relieve the corners from the stress concentration. Fillet welds was used in connecting the fish plates to the boundary elements. The infill plate was connected to the fish plates by means of Argon welding since the thin plates were used for the infill plate.

2.2. Test Set-up

A test set-up was designed and arranged to meet the experimental requirements. For that mean, in addition to the analytical and numerical studies on the models, the existing experiences on the experimental works of the steel plate shear walls were taken into the design of the test set-up. A view of the test set-up is shown in Fig. 2. More details of the test set-up are described in following:

A strong plate girder was placed between the base plates of the specimens and the strong floor in order to provide appropriate connection between the two bases and to move the specimens up to a required elevation. The lateral supports were designed and installed at the top level of the specimens; two numbers of them were placed near to the two ends of the specimens and the third one adjacent to