Numerical investigation on cyclic behavior of steel shear panels endowed with innovative perforation patterns

H.M. Ahmadi & G. De Matteis

Department of Architecture and Industrial Design, University of Campania Luigi Vanvitelli, Aversa, Italy

ABSTRACT: Steel Plate Shear walls (SPSWs) due to their high seismic performance such as ductility and valuable energy dissipation capacity, have been deemed as an effective seismic device in buildings for protecting constructions from fatal fractures. The present study investigates the structural behavior of SPSWs with an innovative elliptical perforation pattern. The elliptical perforation pattern is consisted of ellipse-shaped holes which are located in the perimeter of the web plate same as a peripheral perforation layout. Therefore, the effectiveness of geometric properties of links between both ellipse-shaped holes and opening array on hysteretic behavior are studied numerically. To this aim, two experimental laboratory cyclic tests were initially verified through finite element models and the corresponding deformation shapes according to the Von-Mises stresses were perfectly captured. Subsequently, sixteen perforated specimens with various geometric properties of links which are different in the length and the slenderness ratios are investigated. The results show that the specimens with narrow links improve the pinching force significantly allowing for large energy dissipation capacity.

1 INTRODUCTION

Since 1970, Steel Plate Shear Walls (SPSWs) are deemed as one of the most effective dissipating seismic energy system, which are commonly used in high rise buildings against lateral loads (Formisano et al., 2018a). Shear panels, boundary elements, plate-frame interactions and beam-to-column connections are the main components of the SPSWs. To eliminate the fatal fracture phenomenon of the main members of SPSWs, shear panels should be designed to satisfy the inelasticity demands of structures (Formisano, et al., 2018b). Therefore, the weak shear panels and strong frame is a design approach of SPSWs to provide the inelasticity capacity of shear panels (De Matteis et al., 2009). Based on this design approach, the boundary elements of SPSWs should remain in the elastic range up to the shear panel is completely yielded before destabilizing of frame members (Monsef Ahmadi and De Matteis, 2020).

Recently, several types of shear panels have been proposed i.e., with and without perforation, with and without stiffeners, slender and compact (De Matteis et al., 2007). The perforated SPSWs, based on the opening area that are the main subject of this study, intend to decrease the shear strength and initial stiffness of shear panels to reach in earlier the plastic capacity. For this reason, these types of shear panels are an alternative of shear panels with low yield stress material which are difficult to be found in the market (De Matteis et al., 2003). However, the hysteresis response of perforated shear panels suffers pinching effect owing to the buckling phenomenon at early stage of drift (De Matteis et al., 2008). Decreasing the web plate slenderness ratio, which is the ratio of length of sheet over the thickness of web plate, is an effective option to improve the pinching behavior in the hysteresis curves of perforated shear panels (Monsef Ahmadi et al., 2020).

Formisano et al. (2016) investigated several geometries of perforated shear panels under cyclic shear load. The numerical results illustrated that increasing the opening area greatly reduces the structural behavior such as shear strength, initial stiffness and energy-dissipation capacity, and also increases the ductility ratio. Similarly, a study by De Matteis et al. (2016) evaluated the effect of hourglass-shaped links that gap between circular holes, experimentally and numerically. The shear strength and initial stiffness of perforated shear panel with narrow links were decreased and reduction of the shear yielding of links by bending mode was found. Subsequently, the structural behavior of perforated shear panels in terms of pinching load was improved when the web plate slenderness decreased. For this reason, the hysteretic response of these types of perforated shear panels was plumper and the energy-dissipating capacity was increased.

Monsef Ahmadi et al. (2020) tested two perforated shear panels under cyclic shear load according to the SAC loading protocol. The perforated shear panels were constant in the opening area and web plate slenderness. The perforated specimens were cut-outed according to the code requirements and author's suggestion. The perforation pattern of author's suggestion was consisted of hourglass-shaped links that were located in the perimeter of shear panel. The experimental results proved that the second type of perforated shear panel had good structural behavior in terms of energy-dissipation capacity up to 3% of drift. Subsequently, the shear strength and initial stiffness of this type of shear panels were able to control by geometry properties of hourglass-shaped links. Likewise, the web plate slenderness had significantly influence on the hysteresis behavior according to the numerical analyses.

In this paper, the structural behavior of sixteen perforated shear panels including elliptical holes are numerically investigated. To reach the main objectives of this study, two experimented perforated shear panels are simulated and validated by finite element (FE) models through ABAQUS software. Likewise, the considered specimens which are various in length of links and area of perforation are numerically evaluated. The obtained results shown that the specimens with narrow links are able to achieve dissipative mechanisms based on bending deformation of links.

2 CALIBRATION OF THE FEM MODEL

2.1 Reference tested specimens

Two different, approximately $1 \times 1 \text{ m}^2$, perforated shear panels with web plate thickness equal to 0.7 mm , as shown in Figure 1 have been investigated. They were tested under cyclic shear load according to the SAC loading protocol by Monsef Ahmadi et al. (2020). The diameter of circular holes was constant and equal to 92 mm . To obtain the pure shear behavior of perforated shear panels the beam-to-column connections were designed as a hinged connection. The hinged frame was connected to the reaction frame from right side, and also, to the hydraulic

Figure 1. Tested specimens details: a) SP1 and b) SP2.

Figure 2. Failure modes: a) SP1 and b) SP2.

jack from left side. The beam element was used to transfer the cyclic load from actuator to the hinged frame. More details can be found in the reference study.

The failure modes of both tested specimens are shown in Figure 2. As experimental results, the fracture phenomenon of the SP1 and SP2 occurred around the corner holes and plate-frame interactions, respectively. Different failure modes of specimens were found. The SP1, owing to the perforation pattern, did not allow the tension field mechanism transfers into the center of the web plate. Therefore, the stress was concentrated between the holes and fracture was developed. For this reason, the shear strength of this type of perforated shear panel and ductility ratio was lower than the SP2. On the other hand, due to the shear behavior of links between circular holes in the SP1 specimen the energy dissipation capacity was larger than the SP2 up to 3% of drift.

2.2 Finite element (FE) models and comparison of results

To validate the experimental results, a FE model has been developed by ABAQUS software. The boundary elements and web plate were modeled by beam and shell elements, respectively. The TIE and HING connector types were considered in the plate-to-frame interaction and beam-to-column connections. The yield stress, modulus of elasticity and the Poisson ratio of the web plate were calibrated 180 MPa, 176 GPa and 0.3, respectively. As the boundary elements essentially remained in the elastic range during the cyclic load condition, only the elastic properties of steel were considered. The cyclic load was attached to the beam element. The hysteretic curves are compared in Figure 3, where it is evidenced that there is a good agreement between experimental and numerical analyses.

3 INVESTIGATED SPECIMENS

According to the features of the SP1 type perforated shear panel, sixteen of perforated numerical models $1 \times 1 \text{ m}^2$ including elliptical holes (SP-E), as shown in Figure 4, have been considered and analyzed. Except of length of links (L) and web plate thickness (t), the SP-E specimens are constant in the middle-length ($a=30 \text{ mm}$) and end-length ($b=90 \text{ mm}$) of links. It is worth noticing that the material properties and the load condition are like as the one considered in the reference study. Additional details of the investigated specimens are shown in Table 1.

4 THE OBTAINED RESULTS

The structural behavior of numerical specimens is examined in terms of maximum shear strength, initial stiffness and cumulative energy dissipation capacity up to 6% of drift. The maximum shear strength and initial stiffness are evaluated according to ECCS bilinear method.

Figure 3. Comparison between experimental and numerical results: a) SP1 and b) SP2.

Figure 4. Schematic shapes of SP-E models.

The cumulative energy dissipation capacity was obtained by summing of the area of cyclic loops. The results of hysteresis responses of SP-E-:100-3, 150-3, 200-3, 250-3 and SP-E-:100-12, 150-12, 200-12,250-12, as an example among the tested specimens, are shown in Figure 5. As shown in Figure 5, the hysteretic responses are stable and affected by pinching phenomenon. According to the results, the shear strength, initial stiffness and energy dissipation capacity of specimens increase when the web plate slenderness decreases. On the other hand, this process repeats by increasing the slenderness of links. However, the pinching effect of specimens has been significantly improved by decreasing the web plate slenderness, and also increasing slenderness ratio of links. This is a worth achievement of this study. This is because narrow links allow concentrating the stress along the links instead of the plate-frame interaction, thus dissipating the seismic energy through a bending deformation of links. Therefore, the links under shear deformation activate a tension field mechanism over the panel surface. Likewise, the boundary elements and plate-frame interactions are prone to fracture phenomenon. The shear strength, initial stiffness, cumulative energy dissipation capacity and ratio of maximum shear strength over yield strength are compared in Figure 6. It is apparent that the structural behavior of the considered specimens improves as the web plate slenderness decreases.

Table 1. Main parameters of the considered specimens.

Specimens	Dimensions		Slenderness	
	t (mm)	L (mm)	Plate	Link
SP-E-100-3	3	100	322	33
SP-E-100-6	6	100	161	17
SP-E-100-9	9	100	107	11
SP-E-100-12	12	100	80	8
SP-E-150-3	3	150	322	50
SP-E-150-6	6	150	161	25
SP-E-150-9	9	150	107	17
SP-E-150-12	12	150	80	12.5
SP-E-200-3	3	200	322	67
SP-E-200-6	6	200	161	33
SP-E-200-9	9	200	107	22
SP-E-200-12	12	200	80	17
SP-E-250-3	3	250	322	83
SP-E-250-6	6	250	161	42
SP-E-250-9	9	250	107	28
SP-E-250-12	12	250	80	21

Figure 5. Hysteretic curves for considered specimens: a) SP-E-100-3, b) SP-E-150-3, c) SP-E-200-3, d) SP-E-250-12, e) SP-E-100-12, f) SP-E-150-12, g) SP-E-200-12, and h) SP-E-250-12.

5 CONCLUSION

In this paper, sixteen specimens of perforated shear panels have been modeled and analyzed through finite element (FE) method by ABAQUS software. The computational models considered elliptical holes which were constant in the middle-length and end-length of the links between two elliptical-shaped holes. The effectiveness of slenderness ratios of the web plate and links on structural behavior of FE models have been deeply evaluated.

Figure 6. Structural behavior of elliptical perforated shear panels.

The results indicated that the structural behavior of elliptical perforated shear panels could be controlled by geometric properties of the links. As a result, the shear panels with higher slenderness ratios of the links and lower ratios of the web plate slenderness significantly improve the pinching effects on the cyclic response due to the high ratios of the maximum shear strength over the yield strength.

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