Research on Seismic Behavior of CFT-Frame-Buckling Restrained Steel Plate Shear Wall Structures Using Recycled Aggregate Concrete

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Abstract. Several studies on steel plate shear walls (SPSWs) systems have revealed that the seismic demand on the vertical boundary elements (VBEs) is relatively high for ordinary structures. To resolve this problem and boost the application of concrete-filled steel tubes, two types of concrete-filled steel tubes (CFT) columns (square and L-shaped sections) for SPSWs, consisting of one span and two stories, were designed and tested under quasi-static load. Four corner and double sides connections welding form between frame elements and the shear wall were used to enhance the bearing capacity and stiffness. On the other hand, four corner and double sides fish plates were connected to the steel plate using high-strength bolts to improve the ductility and reduce the local buckling of the steel plate. In terms of buckling restrained, recycled aggregate concrete (RAC) and autoclaved lightweight concrete (ALC) were used as panels to minimize the buckling of steel plates. RAC was also used as a concrete infill. The specimens were evaluated based on hysteretic and skeleton curves. The bearing capacity and stiffness of both types VBEs using four-corner connections were enhanced while the double-sides connections improved the ductility of the SPSWs. Furthermore, connecting the frame elements by high-strength bolts improves the ductility but reduces the bearing capacity and stiffness compared with the welding ones. Finally, both RAC and ALC contributed almost the same buckling restraint in this study.

Keywords: Buckling-restrained steel plate shear walls (SPSWs) · Seismic behavior · Type of columns (square and L-shaped) · Connections forms (four-corner · Double-sides) · Type concrete panels · Recycled aggregate concrete (RAC) · Autoclaved lightweight concrete (ALC)

1 Introduction

For several decades, reinforced concrete (RC) shear walls have been widely used as lateral load resistance in high-rise buildings. Due to continuous increasing the height of high-rise buildings, the shear force, bending moment, and self-weight of the top structures affecting on lower stories that lead to increase the cross-sectional size of RC

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core shear walls while the axial compression ratio of these kinds of shear walls was restricted to obviate cause damage during earthquakes [1, 2]. Therefore, this increased cross-sectional area of RC shear walls would reduce the amount of leasable space in structures while also increasing the mass of the shear walls, which would amplify the horizontal base shear force under earthquake loads. Additionally, increasing the ductility of the RC shear wall requires raising the amount of steel reinforcement that increases the reinforcement details. Prefabricated Steel plate shear walls SPSW could exceed all these drawbacks of RC shear wall structures and provide practical solutions to raise ductility, minimize structural self-weight, and increase deformation ability. Furthermore, SPSW can be easier and more expeditious in construction and repair. Consequently, SPSW has been used in the last 30-years in high rise-building to bear the lateral load, such as earthquake and wind load [3].

Prefabricated SPSW system comprises infill steel plates surrounded by boundary elements, as shown in Fig. 1 [4–10]. Some researchers have been conducted on the traditional SPSW. Astaneh et al. [3, 11] proposed and studied SPSW composing precast concrete panels embedded with thin steel plates connected with shear bolts. The precast concrete panel aims to restrain the buckling of the thin steel plates, thereby improving the bearing capacity and energy dissipation capacity of the structure. Nevertheless, the concrete panel edge gets deformed frequently once the panel touches the boundary frame due to the deformation. Thus, the restraint impact of the concrete panel on the steel plate turns to be very weak. Based on this, Astaneh et al. [12]. Suggested an innovative steel plate shear wall that separates the concrete panel from the frame, in which the concrete panel is only connected with the steel plate by shear bolts. In this way, the concrete panel will not contribute to the role of external restraint on the steel plates but also effectively constrain the buckling of steel plates and avoid the lateral deformation concrete panel caused by the frame.

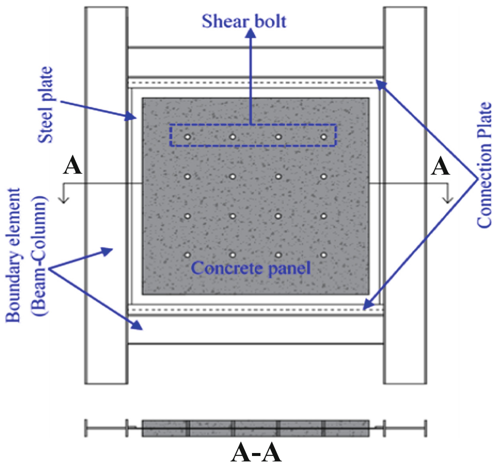


Fig. 1. Steel plate shear wall [10]

2 Influence of Using Different Types of Columns

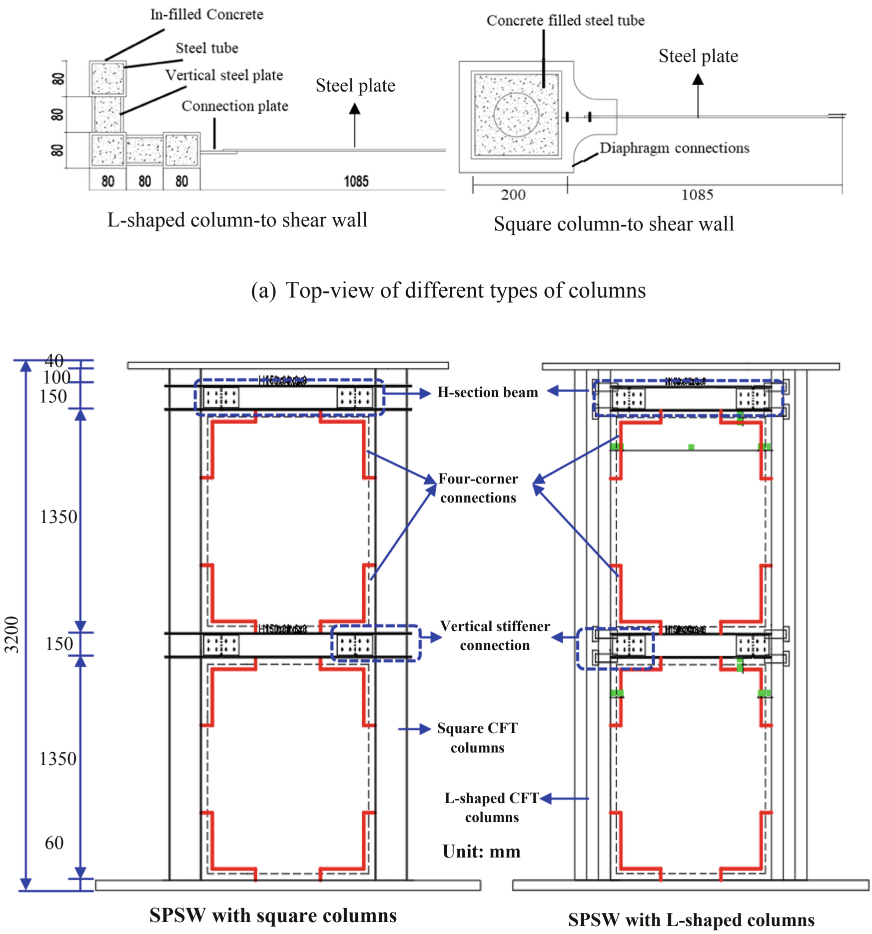
Concrete-filled steel tube (CFT) structures have the advantages of both steel and concrete structures. These structures can effectively minimize the cost of construction, enhance the fire resistance behavior, enhance building comfort and construction speed. However, the common CFT column's sections columns may decrease the available space of the buildings, so recently, some innovative special-shaped columns such as L-shaped, T-shaped and cross-shaped were proposed and investigated by Chen et al. (see Fig. 2) [13–16]. Several experimental research was conducted on the seismic behavior of special-shaped CFT columns. Zhuo et al. experimentally carried out that the L-shaped column has an excellent bearing capacity ductility under axial load, bending load and cyclic load [14–17]. Besides, the research indicated that within increasing the length-width ratio, the ductility and energy dissipation capacity are increased, but the bearing capacity and stiffness are decreased.

In terms of using the special-shaped column in frame systems, a quasi-static test on a special-shaped column-frame system has been carried out by Zhuo el at. the results showed that the system has a stable behavior, good bearing capacity, and ductility. Additionally, Zhoa et al. investigated the seismic performance of a braced-frame using a special-shaped CFT column, and the results revealed a significant enhancement in bearing capacity and energy dissipation compared with an unbraced-frame. Accordingly, a combined special-shaped CFT column-frame buckling restrained steel plate shear wall was proposed and studied. This system's bearing capacity and stiffness are significantly improved compared to a braced frame [18–20].

Based on all of the above, and due high demand for seismic behavior of steel plate shear wall, two sets of 1:2 scaled specimens were designed to study seismic performance and mechanical properties of frame shear walls using two types of columns, including square and L-shaped CFT columns. Four gusset corner welding connections were used to connect the steel plate to the boundary frame, as shown in Fig. 2. The design approach and geometrical details of these specimens were derived from actual Engineering projects in China. Both specimens were named SPSW-1 and SPSW-2 corresponding square and L-shaped CFT columns. An H-section beam is used to fabricate the boundary beams. Besides, this design provides a fixability for applying steel plate shear walls on-site engineering.

3 Influence Connection Forms

On the other hand, it was found that the seismic performance of SPSW is affected by connections between the boundary elements (beam and columns) and the frame's stiffness. In spite of all of the data supplied by researchers that it is appropriate and ductile against lateral loads, it is not widely used [21–26]. It is well known among scholars that the main reason for the shortage application of this system is the abnormal size of the columns [27]. Consequently, many scholars proposed different connection forms such as perforated SPSW panels [28], low yield point and light-gauge SPSW [26, 29], steel plate shear with slits SPSW [30], partially connected to horizontal members SPSW [31], bound-columns with buckling-restrained SPSW [32], buckling-restrained steel SPSW



(a) Top-view of different types of columns

(b) Elevation view of SPSW different VBEs and four corner connection

Fig. 2. Details of SPSW with different types of CFT-columns

with inclined-slots [33] and partially connected bucking SPSW [34]. However, these connections have complicated fabrication and construction processes, resulting in poorer materials and economic efficiency. Additionally, some scholars recently suggested a novel partially connected inner buckling-restrained SPSW to create an unbreakable system that can resist lateral load with low stiffness requirements for columns [35–38]. Furthermore, it was found that the steel plate is more likely to buckle diagonally at an early stage. To prevent the local buckling, innovative precast concrete panels were proposed by Astaneh el at [11]; however, when this precast concrete touched the boundary frame, it early cracked. Thus, later on it was suggested to separate the concrete panels from boundary beam because it did contribute on the bearing capacity and stiffness of the structure. Steel plate shear walls structural system with L-shaped column required an extensive study, so double-side connection form with and without concrete panels.

Then compared with four corner connections forms, as shown in Fig. 3. The aim of this using double-side connection forms with and without concrete is to improve the ductility, energy dissipation and restrained the buckling waves.

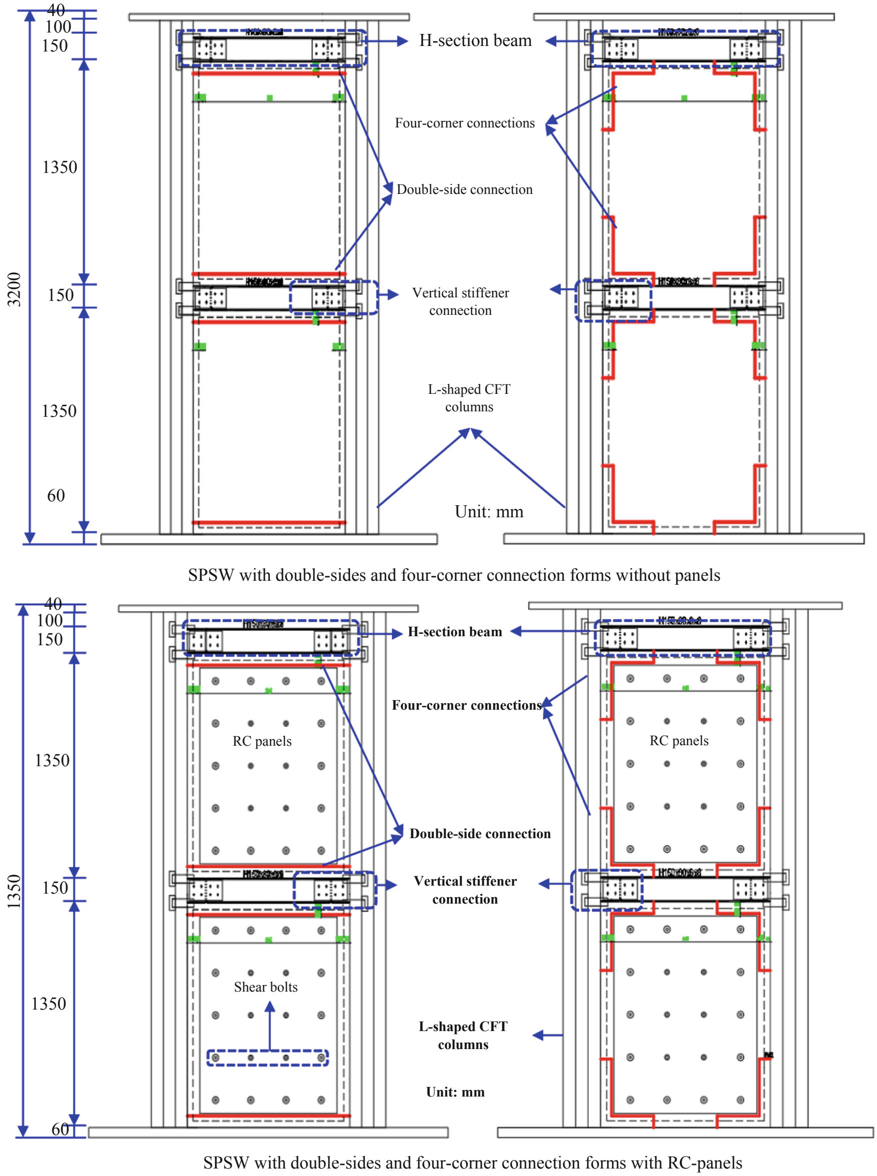


Fig. 3. Details of SPSW with different connections forms

4 Influence of Types of Concrete Panels

The dimensions of the inner steel plate play a significant factor in local buckling and the overall seismic performance of SPSWs. There are two types of SPSWs (thick and thin) categorized based on the height-to-thickness (H_p/t_s) of inner steel plates. The thick steel plate yield before buckling when the ratio of height-to-thickness is small, and the steel plate fully uses lateral stiffness. In contrast, the thinner steel plate has a larger height-to-thickness ratio, so the steel plate expedites buckling before it reaches its yield. Based on JGJ/J 380-2015 [39], the height-to-thickness ratio of SPSW must be in the following range $100 < H_p/t_s\sqrt{235/f_y} < 600$. In addition, Du al el. carried out experimental and numerical research on buckling column frame-buckling restrained SPSW welding connection forms [38]. The results revealed that the connection forms greatly influence failure modes, bearing capacity, stiffness, and buckling behavior. Accordingly, to overcome the buckling the early buckling of the steel plate and enhance the ductility of the structures, two specimens were designed with four corner gusset connection forms. The gusset plates were connected to the steel plate using high-strength bolts. Besides, two types of concrete panels were used to restrain the buckling of steel plate, including recycled aggregate concrete (RAC) panels and autoclaved lightweight concrete (ALC), as shown in Fig. 4.

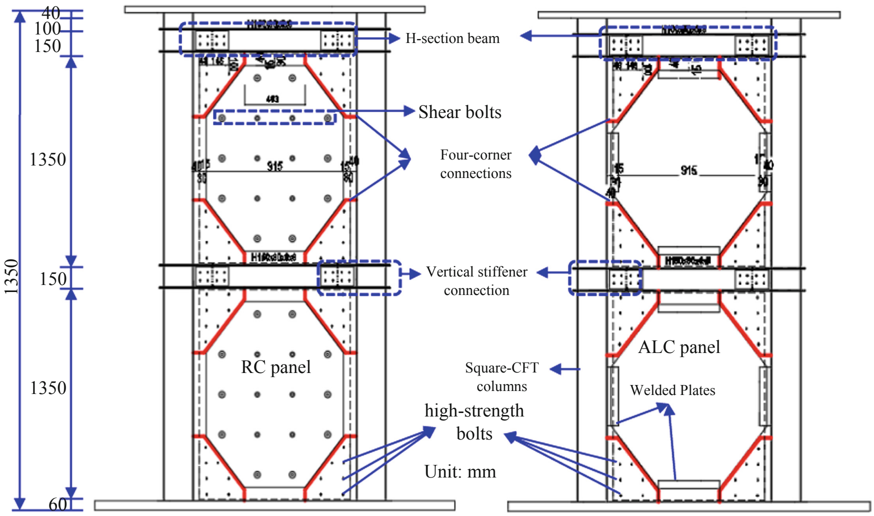


Fig. 4. Details of steel plate shear wall with different types concrete panels

5 Influence of Types of Restrained Steel Plate

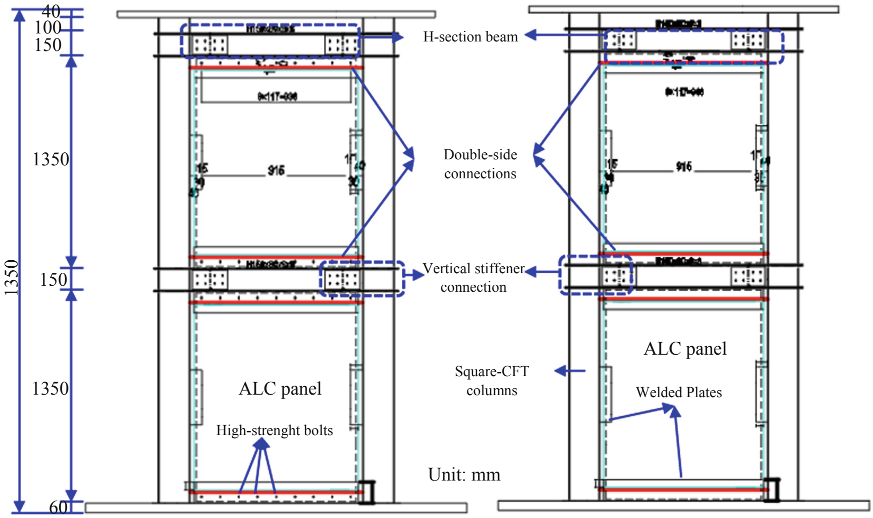
As mentioned above, the steel plate is sandwiched by two precast concrete and connected by shear bolts, and the main purpose of the precast concrete is to groove the local buckling with any contribution on bearing capacity and stiffness. Besides, the precast concrete was cracked in the early stage when it touched with the boundary elements. Later on, scholars conducted that the concrete panel gets partially damaged due to shear deformation caused by shear bolts. As a result, Guo et al. [10]. Designed the buckling restrained shear wall based on Astaneh' model that provides slippage space for shear bolts, placing ellipse holes on the concrete panel in order to avoid excessive local deformation on the concrete panel around bolts. The concrete panel prevents the steel plate from out-plan large deformations. The obtainable study illustrated that the buckling restrained steel plate shear wall has excellent static lateral and seismic performance due to its rotationally of structures [40]. Accordingly, to provide an economical, structural and architectural panel, autoclaved lightweight concrete (ALC) was used as panels in this structural system, as shown in Fig. 5. In addition, double-side guests' plates were connected to the steel plate using welding and bolts to improve the stiffness and ductility of SPSWs.

6 The Innovation and Aims of SPSWs

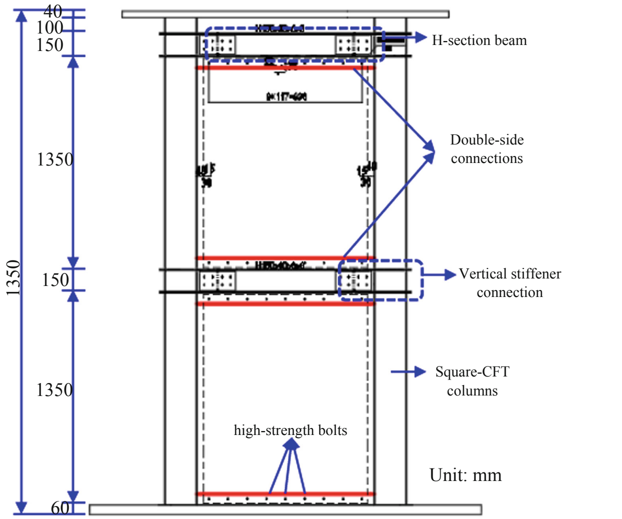
Polite research on L-shaped CFT column frame-buckling steel plate shear wall with different connection forms, including four-side, four-corner and groove connections, was carried out by Du el at [38]. It was found that concrete crackling on the corner of concrete panels and column fracture and damage finally appeared using four-side connections. It is also noticed that the using four-sides connection dropped quickly to lower than 85% of the lateral resistance, and the boundary columns were totally damaged in the bottom because of the full connection between frame and shear wall, which is not favorable in buckling restrained SPSW system, as shown in Fig. 6(a). Local buckling of the inner steel plate and concrete cracking in the corner of concrete panels were captured with concrete separation between the inner steel plate and concrete panels when four-corner connections were used, as seen in Fig. 6(b). However, there was no damage to the boundary columns due to reducing the connections between the shear wall and boundary frame. It can be seen that there are several failures of using groove connections, such as local buckling of steel plate, cracking of concrete panels, and fracture and tearing on inner steel plate and boundary columns, as seen in Fig. 6(c).

Furthermore, the results revealed that the frame shear wall system has excellent seismic behavior, bearing capacity and stiffness. Additionally, due to local buckling of the steel plate, the pinch behavior appeared on the hysteretic curves affected by connection forms. In other words, BRSW-1 was the fullest among all specimens due full connection with the frame element, while BRSW-3 was the clearest one among all due less connection with frame elements and high-buckling of the steel plate, as seen in Fig. 7(a). Furthermore, the connection forms greatly influenced the bearing capacity and stiffness. They were reduced with reduced the connection between the frame elements, as shown in Fig. 7(b). Consequently, the CFT L-shaped columns frame-buckling SPSW reflects a goof seismic behavior, but it observed damage and failure on the frame elements, increasing the connection with them, which is not favorable in seismic design even though the bearing capacity and stiffness were increased.

Accordingly, to exceed all damage and failure on the frame element and enhance seismic behavior of frame-buckling restrained SPSW, this paper explores the overall



SPSW with double side-bolt/welding connection forms



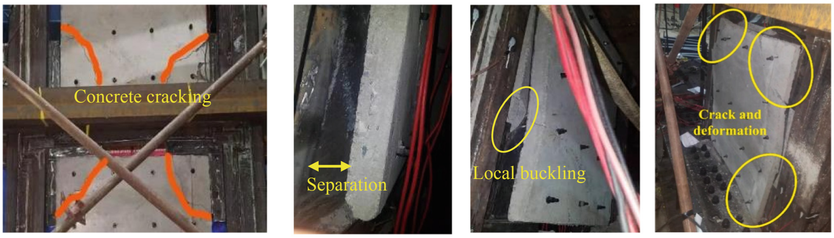
SPSW with double side-bolt connection forms without ALC

Fig. 5. Details of steel plate shear wall with different types of restrained connections

performance of CFT-column Frame buckling restrained steel plate shear wall. It has several features, including assembling on-site, easy to fabricate, increased useable space, and improved overall structural performance compared to reinforced concrete structures. The main objective and aims of this paper can be listed as follows;

1. To investigate the CFT-column frame-buckling restrained steel plate shear wall based on column section types, including L-section and square-section.

(a) Deformation and damage of the BRSW-1



(b) Deformation and damage of the BRSW-2

(c) Deformation and damage of the BRSW-3

Fig. 6. Samples of failure modes

2. To investigate the most effective connections forms in order to enhance the bearing capacity and stiffness of the CFT-frame buckling restrained steel plate shear wall.
3. Study the buckling restrained of steel plates by providing two types of panels, including RAC and ALC concrete panels, with innovative connection forms for steel plates.
4. Compare the connection forms between the gusset and steel plates in terms of welding and bolts.
5. To provide a cleaner production, eco-friendly and sustainable application of material, iron ore tailings sand (IOTs) and recycled coarse aggregate (RCA) are adopted to manufacture concrete in this study.

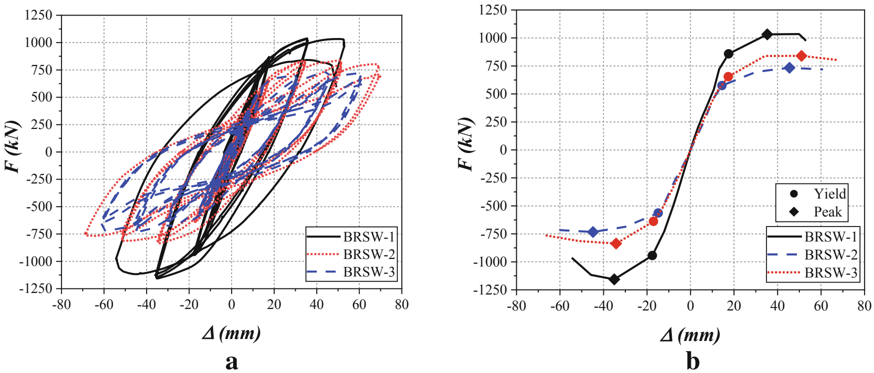


Fig. 7. Load displacement curves

7 Conclusion

Steel plate shear wall has been recently used in a high-rise building, which comprises from infill steel plate surrounded by frame elements (beam and columns). To extend the application of CFT-columns, including square and L-shaped, ten sets 1:2 scale structural model specimens with a single span and two stories were designed to study the cyclic behavior of frame-buckling steel plate shear wall (SPSW). Several parameters were covered in this design to understand this structural system's features and drawbacks, including types of boundary columns, connection forms, types of concrete panels, and types of steel plates restrained. An eco-friendly and sustainable recycled concrete (RC) was adopted in this research to manufacture the concrete infill and concrete panels.

1. Investigate the seismic performance of SPSW using two types of CFT columns, including square and L-shaped, that would extend their application in the high-rise building in different positions. This structural system reduces the useable space and increases stiffness and bearing capacity.
2. The connections forms between the shear wall and boundary frame, including double-sides and four-corner connections, were designed to improve the seismic behavior and mechanical properties of the SPSWs. On the other hand, with and without concrete panels were covered in these specimens using the connections forms to analyze the welding connections' buckling behavior.
3. Previous research showed that the concrete panels do not contribute to the seismic performance of frame-buckling SPSW, and the main aims of the concrete panels are to restrain the steel plate. Therefore, RAC and ALC concrete panels were adopted in this study to delay the local buckling of the steel plate and increase the ductility.
4. The connection forms between the steel plate and gusset plates significantly influence the ductility, stiffness, and buckling behavior. Therefore, welded and bolts connections were used. In addition, using normal precast concrete panels to sandwich the steel plate does not meet economical and architectural requirements, so ALC panels were designed and compared with none panels in order to study their structural effect.

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