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Experimental study on seismic behavior of steel strip reinforced CSPSWs in modular building structures

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ABSTRACT

Corrugated steel plate shear walls (CSPSWs) are widely used as exterior walls and efficient lateral load resisting systems in modular building structures (MBS). In practical construction, the CSPSWs are usually accommodated with door or window openings and reinforced with steel strips. The effect of the steel strip reinforcement needs to be evaluated. An experimental study was conducted to investigate the seismic behavior of steel strip reinforced CSPSWs in modular steel structures. Six full-scale specimens were constrained at corners and loaded with cyclic lateral load. The results showed that that failure mode of this lateral load resisting system for the modular building structures was the facture of the weld between the frame beams and columns. The steel strip reinforcement had little effect on the ultimate strength, but could improve the behavior of stiffness, ductility and energy dissipation.

1. Introduction

Corrugated steel plate shear walls (CSPSWs) have been widely constructed as efficient lateral load resisting system in the seismic hazard area. Due to exceptional strength, ductility and light weight, the corrugated steel plate shear walls are ideal for modular building structures (MBS). Corrugated steel plate shear wall usually consists of a rigidly connected frame and a corrugated thin steel plate infill. Compared with flat steel plate shear wall, the trapezoidal corrugations of the CSPSW provide out-of-plane stiffness, bringing higher lateral initial stiffness and avoiding the unpleasant buckling sound under very low load which impairs the living comfortability. Numerous studies have been conducted to investigate the lateral strength, stiffness, buckling behavior and energy dissipation capacity of corrugated steel shear wall systems and to propose prediction models. F. Emami etal. investigated the seismic behavior of horizontal and vertical CSPSWs under cyclic loads and the results showed that the direction of corrugations did not affect the seismic behavior significantly [1–3]. C. D. Zhou etal. [4] and J. Z. Tong [5] investigated the elastic buckling behavior of CSPSWs, giving predictions for the elastic buckling of the CSPSWs. M. Bahrebar etal. investigated the cyclic behavior of CSPSWs with numerical simulation and indicated the effectiveness of the web-plate thickness, corrugation angle, and opening size [6]. Effective non-linear analysis methods was introduced to predict the seismic performance of the CSPSWs [7–9]. The seismic behavior of the CSPSWs in regular structures has been investigated.

For modular building structures, the CSPSWs are usually part of external walls and accommodated with door and window openings. The difference of the CSPSWs in regular and modular structures is the connection. In regular structures, CSPSWs are constrained on both upper and lower edges [10]. However, in modular steel structures, CSPSWs are constrained at corners as shown in Fig. 1. Besides, as the room modules of MBS are connected at corners, most of vertical load is transferred from upper column to lower column. The CSPSWs in modular steel structures mainly work as lateral load resisting system. The behavior of CSPSWs with and without openings has been investigated and the results show that the accommodated openings will significantly impair the performance of the CSPSWs [11]. As the openings are unavoidable in practical use, steel strips are attached on the CSPSWs as reinforcement. Steel strips are perpendicular to the corrugation and welded on each peak of the trapezoidal corrugations. These steel strips will strengthen the out-of-plane stiffness of the CSPSWs. Also these steel strips will improve the ductility and energy dissipation by constraining the deformation between peaks of corrugations. As the behavior of steel strip reinforced corrugated steel plate shear walls has not been investigated, effect of the steel strip reinforcement needs to be evaluated.

This paper presented an experimental study on seismic behavior of steel strip reinforced corrugated steel plated shear walls. Afull-scalequasi-static test program was reported. Six full-scale specimens

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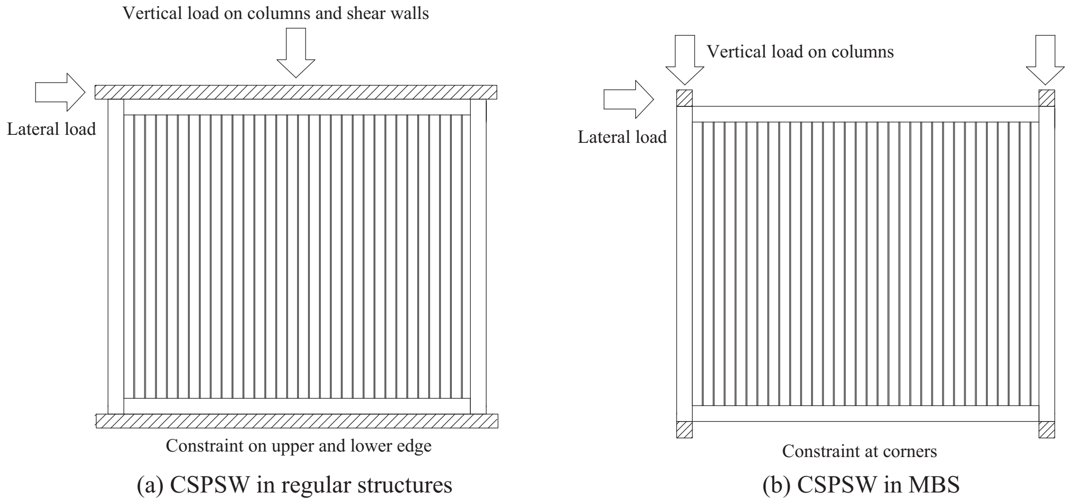

Fig. 1. Comparison of CSPSWs in regular structures and MBS.

were constrained at the lower corners to simulate the boundary conditions in modular steel structures. A cyclic lateral load was applied at the top corners. The results provided useful information on ultimate strength, initial stiffness, ductility and energy dissipation. The comparison was conducted that include variables of opening size and positions. Effect of the steel strip reinforcement was evaluated.

2. Experimental program

2.1. Specimen type

Totally, six specimens were designed and constructed to investigated and distinguish the seismic behavior of the corrugated steel plate shear walls with steel strip reinforcements. The shape of corrugations was shown in Fig. 2. All the specimens were constructed in full-scale, one-story and single-bay as represented in Fig. 3. The specimens were 3.0 m in height and 3.6 m in length. The design of the specimen was based on a CIMC construction project, which was a 19-storeycontainer-shaped modular steel construction. The structure plan was provided by CIMC, but the details were designed by authors. As there is no specialized standard for design of modular steel construction in China, this construction was designed on Chinese standard for steel construction [12]. Considering the corrugated steel plate shear walls was applied in modular building structures in which the sections of the girders and columns were limited, the surrounding frame section of the specimens was steel hollow square (SHS) section with dimensions of 150 × 100 × 6 mm. The thickness of the corrugated steel plate was set as1.6 mm. Two pinned connecting cells were welded at the bottom of each specimen to simulate the connection between upper and lower modules in modular building structures.

All specimens were accommodated with respective openings. Among these specimens, the CSPSW-2, CSPSW-4 and CSPSW-6 were reinforced with steel strips while the rest were not. The steel strip was 100 mm in width, 4 mm in thickness and 360 mm in spacing. 5 rows of steel strips were set in each specimen. The trapezoidal corrugations were in vertical direction and the steel strips were horizontally welded on the peaks of the corrugations with 360 mm-spacings. The specimens' details were shown in Table1.

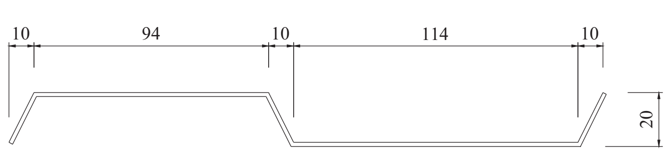

Fig. 2. Shape of corrugations.

2.2. Material properties

Mechanical properties of the steel plates and the steel profiles applied in the construction of the specimens were reported in Table2. The mechanical properties were determined by coupon test performed according to the GB/T 228.1–2010 [13]. The coupons were sampled from different parts of the specimens, i.e.,corrugated steel plates, steel strips, inner frames and outer frames. For each part of the specimens, four coupons were sampled and tested. Average values were taken from the each group of coupon test results. By a proper design, it ensured that the frame would not collapse before the infill corrugated steel plates reached the ultimate strength.

2.3. Test setup

The loading devices and facilities of the specimens were shown in Fig. 4. To simulate the boundary conditions in modular steel structures, the specimens were constrained at the lower corners. Two pinned connecting cells were welded at the bottom of each specimen. The specimens were connected to the fixed steel base with the pinned connecting cells. The steel base was anchored on the ground with six 60 mm-diameter bolts.

A loading hydraulic jack was connected to the top corner of the frame, applying a horizontal load to the specimen. The head of the hydraulic jack was pin-connected to the loading cell at the top right corner of the specimens. The rear of the loading hydraulic jack was fixed on a reaction wall. A dynamic force sensor was applied between the specimen and jack. An out-of-plane limiter was set on the top beam of the frame to prevent global instability by limiting the out-of plane displacement of the top beam. The limiter did not limit the lateral or vertical displacement so that the beam could move smoothly in the plane. No vertical load was applied to the specimens.

2.4. Loading program and measurements

To simulate earthquake load and investigate the seismic behavior of the CSPSWs, quasi-static cyclic load was applied with the loading hydraulic jack. The loading program consisted of pre-loading and normal loading program. During the pre-loading program, a cyclic load was applied and held at the load of 10% of predicted ultimate load for two minutes. The purpose of the pre-loading program was to make sure the specimen and the loading devices close fit. The data of pre-loading