Journal of Constructional Steel Research 112 (2015) 373–386

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Experimental and numerical study of unstiffened steel plate shear wall structures

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ARTICLE INFO

Article history:
Received 13 March 2015
Accepted 6 May 2015
Available online 20 June 2015

Keywords:
Unstiffened thin steel plate shear wall structure
Hysteretic behavior
Energy dissipation capacity
Ductility
Finite element method (FEM)
Column stiffness

ABSTRACT

In order to investigate the seismic behaviors of unstiffened thin steel plate shear wall structure, tests of four three-story unstiffened steel plate shear wall specimens under cyclic loads were carried out. Parameters of the specimens included height-to-thickness ratio, span-to-height ratio and middle brace. The carrying capacity, hysteretic behavior, degraded characteristics, ductility, failure modes, energy dissipation capacity were analyzed and compared deeply. Besides, the nonlinear finite element method of shear wall structure was also established, which was verified by test results. Finally, the effect of column stiffness on load-carrying capacity was studied. The practical requirements of in-plane and out-of-plane stiffness of edge column were suggested. The experimental and numerical results showed that: this kind structure exhibits high strength, good energy dissipation capacity, and good ductility (the ductility coefficients are more than 3.0). When the inter-story drift angle reaches 1/50, the strength degradation is no more than 5%, indicating that the structure has good seismic behaviors. The span-to-height ratio has little effect on load-carrying capacity, while slightly affects the initial stiffness and ductility. The effect of height-to-thickness ratio (thickness) on load-carrying capacity is relatively larger than other factors. The middle braces do not improve the behaviors of structures. The stiffness of edge column has great effect on lateral load-carrying capacity of shear wall structures. The value of column stiffness index could be within 2.0–2.5 to achieve the sufficient constraints and economical benefit.

1. Introduction

The steel plate shear wall structure has relatively good ductility, energy dissipation capacity and seismic performance with large initial stiffness, which can effectively limit the structural lateral displacement and can overcome the deformation coordination defect and the matching problem (ductility, stiffness and connection) of steel frame with concrete shear wall [1]. The qualitative overall form of steel plate shear wall is similar to the vertical cantilever plate beam whose base is fixed, vertical edge component is equivalent to the flange, infill steel plate corresponds to the web, and horizontal edge component is equivalent to the transverse stiffener rib. The typical steel plate shear wall structure is shown in Fig. 1. However, the stiffness of boundary members has great effect on the capacity of structure, which is different from plate beam [2].

Application of steel plate shear wall structure is gradually promoted from the thick wall to the thin wall economically. Thorburn et al. [3], Timler and Kulak [4], and Tromposch and Kulak [5] firstly found that the unstiffened thin steel plate walls had high post-buckling strength with good ductility behavior. These structures have larger height to thickness ratio λ of infill panel (typically $\lambda > 150$). Early buckling of thin steel plate shear wall occurs under lateral force, and the structure still has high potential of load-carrying capacity after buckling, which is caused by "tension fields" of infill plate. Meanwhile, the yielding infill wall can be treated as plastic hinge to dissipate energy of earthquake effectively.

Based on the important role of "tension field", the unstiffened thin steel plate wall has been studied by many researchers. For instance, Thorburn et al. [3] proposed a tension strip model to simulate the post-buckling behaviors of unstiffened thin steel plate wall. Caccese et al. [6] carried out six single-span three-story steel plate shear wall model tests with 1:4 ratio under cyclic loading, including a pure frame, three thin steel plate wall structures with rigid frame and different thicknesses of wall, and two thin steel plate wall structures with hinged frame and different heights. The results showed that: structural nonlinear performance of thin wall was caused by tension field. And the load-carrying capacity was controlled by the edge column. The thick wall had limited post-buckling strength, compared with thin wall. Driver and Kulak [7] tested a single-span four-story unstiffened steel plate shear wall specimen with rigid frame subjected to cyclic loading. The results indicated that the specimen had high initial stiffness, good ductility and energy dissipation capacity and large deformation capacity under cyclic loading (the story drift ratio reached 4%). Lubell et al. [8]

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http://dx.doi.org/10.1016/j.jcsr.2015.05.002
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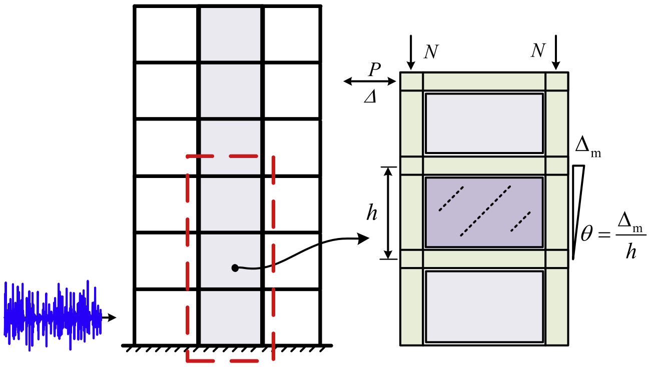

Fig. 1. Typical steel plate shear wall.

conducted experimental studies on two single-span and four-story steel shear wall specimens under cyclic loading. Good energy dissipation and displacement ductility were also achieved. Astaneh-Asl [9] reported the cyclic loading tests of two three-story rigid frame — steel plate shear wall with 1:2 ratio. The stiffness, strength, ductility and failure modes of steel plate shear wall were studied. The results indicated that the system had good lateral resistance capacity and hysteretic performance. Choi and Park [10,11] respectively tested 5 + 3 single-span three-story unstiffened steel plate shear wall specimens with different height to span ratio. The effects of height to thickness ratio and column stiffness on cyclic performance of unstiffened steel plate shear wall were investigated. The results showed that: the edge column should have enough stiffness to ensure the hysteretic performance of steel plate wall. Chen et al. [12,13] carried out the tests of two-story low-yield-point (LYP) steel plate shear walls under cyclic loading. Excellent deformation and good energy dissipation capacity were also obtained. The story drift angle of the LYP steel plate shear wall system exceeded 5%. In 2014, three-span and two-story specimens of unstiffened steel shear wall structure with link beams were tested under monotonic and cyclic loads by Dubina and Dinu [14]. The specimens exhibited good and stable behaviors. Zirakian and Zhang [15] determined the limiting plate thicknesses of unstiffened LYP steel plates with various support and loading conditions. All these researches indicate that the unstiffened thin steel plate wall has wide application prospects, especially in high-intensity seismic region.

Because most infill plates of practical engineering are intermediate layers, which are influenced by the tension fields of upper and lower adjacent layers, therefore, more experimental studies on multi-story shear wall structure should be carried out. In this study, tests of four three-story unstiffened steel plate shear wall with 1:3 ratio under lateral loads were carried out to investigate the seismic behaviors of intermediate layer. Test parameters of the specimens included height-to-thickness ratio, span-to-height ratio and middle brace. The carrying capacity, hysteretic behavior, degraded characteristics, ductility, failure modes, energy-dissipating capacity were studied. Besides, the established nonlinear finite element method of shear wall structure was verified by test results. Finally, the column stiffness effect on load-carrying capacity was studied. The practical suggestions of in-plane and out-of-plane stiffness of edge column were also proposed. This study provides the reliable experimental basis for proposing a practical design method for actual engineering.

2. Experimental program

2.1. Specimen design

The purpose of the tests is to study the seismic behaviors of unstiffened thin steel plate shear wall under cyclic horizontal forces [16]. The research object is middle layer panel, on which tension fields of upper and lower adjacent panels are imposed. Considering the practical engineering application experiences and published researches [11], the chosen size range of thin steel plate shear wall: the span to height ratio is $L/h = 1.5–2.0$, and height to thickness ratio is around $\lambda = 200–400$. Based on these principles, four three-story unstiffened steel plate shear wall specimens with 1:3 ratio are designed. Steel plate shear wall structure generally consists of edge beams, edge columns, infill panel, beam-to-column connections, and fish plates. The welded steel frame is used as boundary members. The width of the fish plates is 60 mm, and the thickness is 8 mm. The dimensions are shown in Fig. 2 and Table 1.

The capacities of panels are predicted by Refs. CAN/CSA-S16-01 [17] and ANSI/AISC 341-05 [18], as shown in Table 2. The shear capacities of the middle layer panels are the smallest according to the calculation method. The values in Table 2 are the shear capacities of middle layer panels.

In which, t_i is the thickness of the wall, f_{py} is the yield strength of panel, α is the angle of tension stripe and column, obtained by Eq. (1). h_s is the center distance between edge beams, I_c is the in-plane bending stiffness of edge column, L_s is the center distance between edge columns, A_c is the area of column, A_b is the area of beam, and h is the height of the panel.

$$\tan^4\alpha = \frac{1 + \dfrac{L_s t_i}{2A_c}}{1 + \dfrac{h_s t_i}{A_b} + \dfrac{h_s{}^4 t_i}{360 I_c L_s}}. \tag{1}$$

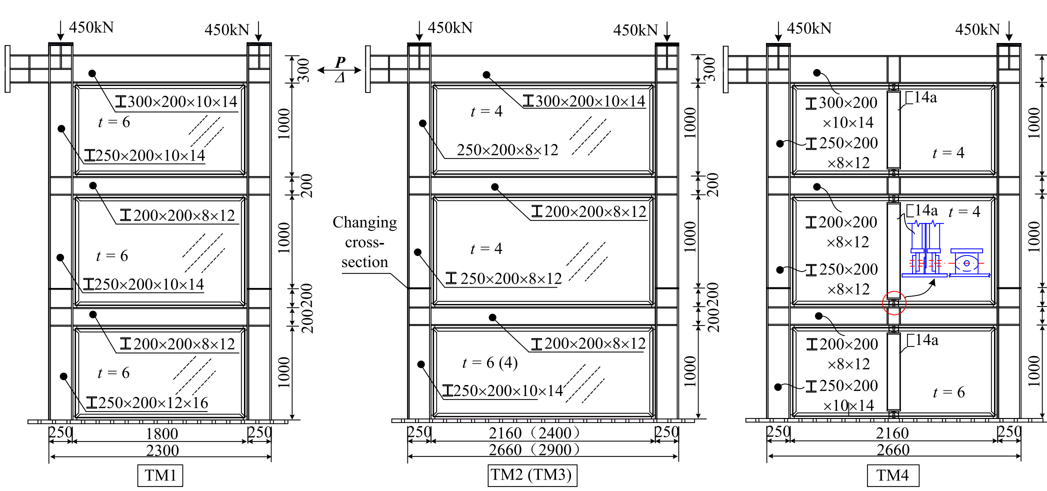

Fig. 2. Construction details of specimens.