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Seismic behavior of high strength concrete composite walls with embedded steel truss

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ABSTRACT

Experimental investigation was conducted on three 1:3 scaled high strength concrete composite wall (HSCCW) specimens with embedded steel truss with a medium aspect ratio (1.0–3.0) under cyclic load reversals and constant axial load, to examine the influences of steel usages of embedded truss chord and web brace on the overall seismic behavior of the specimens. The hysteretic characteristics, cracking pattern, failure modes and energy dissipation capacities of the specimens were discussed. Then parametric analysis was carried out on 27 numerical models based on verified finite element modeling techniques to thoroughly evaluate the influences of axial load ratio, steel ratio of embedded truss chord and volumetric ratio of embedded truss web brace on the overall seismic performance of HSCCW with embedded steel truss. Research results indicate that increasing the steel ratio of embedded truss chord can effectively improve the initial stiffness and lateral load carrying capacity. Although the volumetric ratio of embedded truss web brace has little influence on lateral strength, it is beneficial to the energy dissipation capacity of composite walls. Within the maximum allowable limit, higher axial load ratio can result in increased lateral load capacity and stiffness.

1. Introduction

Reinforced concrete (RC) shear walls have been widely used in high-rise buildings located in seismic regions to provide sufficient lateral strength and stiffness to limit nonlinear responses at service level earthquakes and to ensure adequate nonlinear deformation capacity during design and maximum considered earthquakes. Previous experimental studies (e.g., Vallenas et al. [1]; Hines et al. [2]; Thomsen and Wallace [3]; Sayre [4]; Dazio et al. [5]; Lowes et al. [6]) have revealed the complex response characteristics of RC walls under earthquake ground motions largely due to the interaction between nonlinear shear and flexural responses, even though flexure and shear are believed dominant in walls with high (greater than 3.0) and low (less than 1.0) aspect ratios (h_w/l_w), or shear-span-to-depth ratios (M/Vl_w). Satisfactory performance of shear walls can be achieved following stringent design provisions in terms of reinforcement and detailing under normal levels of axial load. However, lessons learnt from the 2010 Chile Earthquake showed the adverse influence of high axial stress level on the seismic performance of RC shear walls [7]. The high axial load ratios up to 0.5–0.6 of the shear wall structures severely damaged in the 2010 Chile Earthquake were mainly resulted from the small thickness of walls of lower stories [8–9]. With the considerable increase of number of stories or structural height, as is the case in the super high-rise buildings in China, the axial stress in walls of lower stories can be hardly maintained at reasonable levels and thus the bottom walls of super high-rise buildings are very susceptible to failure induced by concrete crushing or flexure–shear interaction. In order to ensure the safety of super high-rise buildings under strong earthquake excitations, RC shear walls need to possess even higher load carrying capacity and deformation capacity when subjected to complex stress states caused by high levels of axial load, shear and flexure. The conventional way of improving the load carrying capacity of wall and reducing the wall axial load ratio is to largely increase the wall thickness. However, the significant increase of wall thickness will reduce the usable floor area, increase the structural weight and thus cause more seismic base shear under earthquake ground motions. In addition, constructions difficulty will also be introduced due to large volume concrete. Therefore, increasing the wall thickness is neither effective nor economical.

The recent development of concrete construction in China has exhibited the trend of using steel and concrete composite shear walls in super high-rise buildings. Although there are various types of composite shear walls with different composite forms, the fundamental purpose of combining steel and concrete together is to further increase the load carrying capacity and deformation capacity of shear walls. For example, the 452 m tall main tower of the International Commercial Center in Changsha city, Hunan Province, adopted the RC shear walls with embedded steel plate from basement up to the ninth story. The new TV

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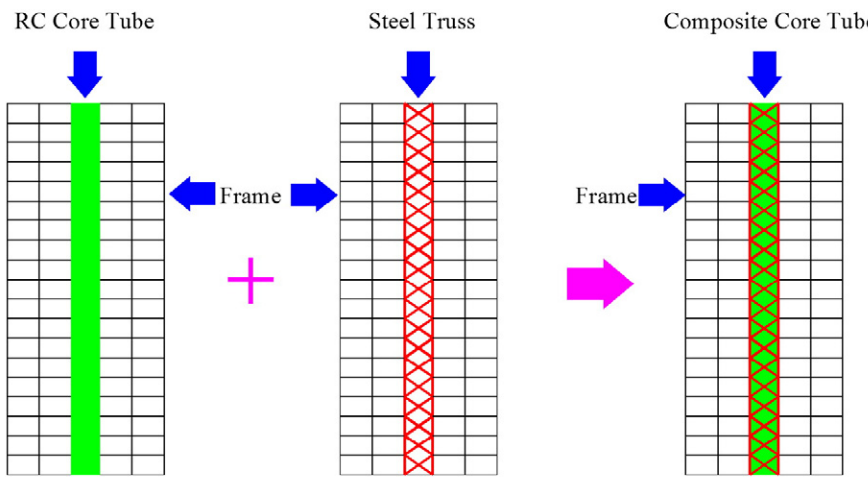

Fig. 1. Composite walls with embedded truss.

tower in Hefei city, Anhui Province, used concrete filled double plate composite shear walls for its lower stories. Furthermore, much research has been conducted on RC composite walls with steel plates in recent years (e.g. Zhao and Astaneh-Asl [10]; Eom et al. [11]; Nie et al. [12]). Efforts have been made to study the seismic behavior of steel plate and concrete composite shear walls (Rahai and Hatami [13]; Brando G. and De Matteis [14]). However, if a steel plate is embedded in the concrete wall, it is difficult to run through the cross ties for the longitudinal reinforcement on the two sides of wall cross section. On the other hand, if concrete is filled into double steel plates, the fire proofing and maintenance of the encasing steel plates may become a problem and cause the increase of cost.

In this research program, an alternative type of composite wall system was studied where the steel truss is used to replace steel plate and embedded in RC walls, as depicted in Fig. 1. The embedded steel truss consists of channel steel chords and equal-leg double angle web braces. By incorporating steel truss instead of steel plate into reinforced concrete wall, considerable saving in steel material and improvement in constructability can be achieved. Such type of composite walls has been used in some well-known buildings in China such as the International Convention Centre in Dalian city, as shown in Fig. 2. However, research has rarely been carried out to thoroughly study the influence of the embedded truss members on the seismic performance of composite walls.

In order to investigate the influences of embedded truss chord and web brace on the overall behavior of high strength concrete composite walls (HSCCWs) with embedded truss, three 1:3 scaled HSCCW specimens with embedded steel truss were tested under constant axial load and reversed cyclic lateral load. Then 27 finite element (FE) models were established and analyzed based on the suggested numerical modeling techniques, which were verified sufficiently accurate and effective by the comparison between simulated and experimental results, to further investigate the influences of axial load ratio, steel ratio of embedded truss chord members and volumetric ratio of embedded truss web braces on the overall behavior of composite behavior.

Fig. 2. Construction of International Convention Centre in Dalian city, China.

2. Experiment program

2.1. Details of specimens

The three HSCCW specimens with embedded steel truss tested in the experimental program were identified by HSCCW-1, HSCCW-2 and HSCCW-3. Each specimen consisted of a 300 mm × 300 mm × 900 mm loading block on top, a 350 mm × 450 mm × 1500 mm base block at bottom and a 800 mm × 100 mm × 1290 mm wall portion in between that was to be vertically and horizontally loaded during testing. The resulted ratio of wall height h_w to wall cross section length l_w was 1.61, indicating that all the three specimens had a medium aspect ratio and shear–flexure interaction would dominate the overall wall behavior. The specimens were fastened to the strong floor at the base block through high strength post-tensioned steel rods. The top of each specimen, or the loading block, was connected to a vertical hydraulic jack for constant axial load and to a horizontal servo controlled actuator for reversed cyclic loading. The specimens were designed based on the Chinese Code for Seismic Design of Buildings (GB50011-2010) [15]. The vertical and horizontal distributed reinforcements for wall portion of each specimen were hot-rolled ribbed bars (HRB) with nominal yield strength of 335 MPa, having the same nominal diameter of 6 mm but different spacing of 120 mm and 100 mm. Six HRB with nominal yield strength of 335 MPa and nominal diameter of 8 mm were used as the longitudinal reinforcement on each side of the wall boundary region. The steel truss embedded in the specimens consisted of C shape or W shape steel chords and equal-leg double angle web braces welded to the chords. The details of the specimens, including the cross section dimensions of embedded truss members were shown in Fig. 3. The main test parameters were the steel ratio of embedded steel truss chord members, ρ_c, and the volumetric ratio of embedded truss web braces, ρ_{vb}. For specimen HSCCW-1, C shape steel C5 was used as the chord members and two equal-leg double angles L25 × 2 as web braces. For specimen HSCCW-2, W shape steel I10 was used as chord members and two equal-leg double angles L25 × 2 steel angles as web braces. The embedded truss chord of specimen HSCCW-3 was the same as that of specimen HSCCW-1 while the web braces were two equal-leg double angles L30 × 4 for HSCCW-3. Therefore, the main test parameters were the steel ratio ρ_c of embedded truss chord, defined as the ratio of total cross sectional area of chord members to the entire wall cross sectional area, and the volumetric ratio ρ_{vb} of embedded truss web braces, defined as the ratio of total volume of web braces to the