Experimental Comparison Study on Cyclic Behavior of Coupled Shear Walls with Steel and RC Coupling Beam

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Abstract

Coupled shear walls are widely used in high rise buildings, since they can not only provide efficient lateral stiffness but also behave outstanding energy dissipation ability especially for earthquake-resistance. Traditionally, the coupling beams are made of reinforced concrete, which are prone to shear failure due to low aspect ratio and greatly reduce the efficiency and ability of energy dissipation. For overcoming the shortcoming of concrete reinforced coupling beams (RCB), an innovative steel coupling beams called two-level-yielding steel coupling beam (TYSCB) is invented to balance the demand of stiffness and energy dissipation for coupled shear walls. TYSCBs are made of two parallel steel beams with yielding at two different levels. To verify and investigate the aseismic behaviour improvement of TYSCB-coupled shear walls, two 1/3 scale, 10-storey coupled shear wall specimens with TYSCB and RCB were tested under both gravity and lateral displacement reversals. These two specimens were designed with the same initial lateral stiffness, thus to be easier to compare. The experimental TYSCB specimen demonstrated more robust cyclic performance. Both specimens reached 1.75% lateral drift, however, the TYSCB-coupled shear wall showed minimal strength degradation and higher bearing capacity. Additionally, a larger amount of energy was dissipated during each test of the TYSCB specimen, compared with the RCB specimen. Based on the experimental results, design recommendations are provided.

Keywords: *experimental comparison study; two-level yielding steel coupling beam; einforced concrete coupling beam; cyclic behaviour.*

1. Introduction

Coupled shear walls have provided a suitable solution for lateral load resisting systems in tall buildings[1-3]. The overall stiffness and damping in these structures are strongly influenced by the mechanical and structural properties of not only the walls but also the coupling beams. Traditional reinforced concrete coupling beams are prone to shear failure due to a large aspect ratio. This shear failure, as a brittle failure, cannot satisfy the high ductility demand of coupling beams. As an alternative, steel coupling beams (SCB) are preferred owing to their excellent capacity of plastic deformation and energy dissipation. With the application of SCBs, traditional coupled shear wall systems turn to be hybrid coupled wall systems (HCW).[4]

Recently an innovative steel coupling beam called two-level-yielding steel coupling beam (TYSCB) was proposed by Li et al[5, 6]. It consists of two components: shear-yielding beam and bending-yielding beam, as shown in Fig. 1. The shear-yielding beam (Fig. 1(a)) is designed to yield at minor earthquakes and the bending-yielding beam (Fig. 1(b)) is to yield at design earthquakes. These two components work independently. Under a minor earthquake, when the shear yielding beam yields, the bending-yielding beam is still in elastic. In this way, the coupling beam may dissipate energy by the yielding of the shear-yielding beam, and at the same time ensures that its stiffness is

maintained by the elastic bending-yielding beam. The proposed steel coupling beam is to provide sufficient lateral stiffness and energy absorption for the whole coupled shear wall structure. The experimental results showed that TYSCB can dissipate energy under a small earthquake. However, at the same time, its stiffness will not deteriorate too fast. When subjected to a major earthquake, TYSCB could perform better energy-dissipation ability than SCBs.
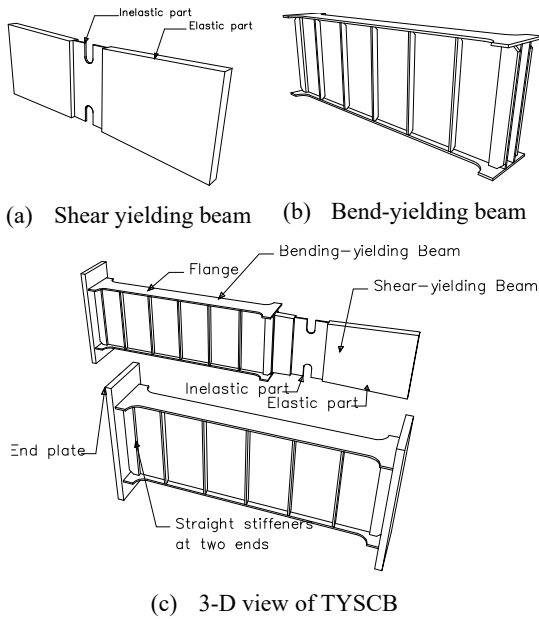

(a) Shear yielding beam   (b)   Bend-yielding beam

(c)   3-D view of TYSCB

Fig. 1 Configuration of TYSCB

Li et al made a series of seismic performance comparisons of coupled shear walls with various coupling beams through numerical analysis. It was found steel coupling beams (SCBs or TYSCBs) could largely improve the energy-dissipation ability of coupled shear wall systems[7]. However, the corresponding experimental verification study is relatively deficient. To this end, two 1/3-scale ten-storey coupled shear wall specimens were tested under both gravity and lateral displacement reversals.

Specimen CW-RC, featuring traditional reinforced concrete(RC) shear walls and RC coupling beams, was designed with the same initial stiffness with Specimen CW-TYSCB, which was featuring RC shear walls and two-level-yielding steel coupling beam.

The wall piers of the two specimens shared the same geometric size and reinforcement configuration. Two full-length H-section (100×100×6×8) structural steels were set as the boundary elements for each wall pier.

The objectives of this research aim to (1) investigate the cyclic behavior of RC and hybrid coupled shear wall syetems that features longitudinally reinforced and two-level-yielding steel coupling beam, respectively; and (2) evluate the performance of using two H-section steel boundary elements for each wall pier.

2. Test specimens

Test specimens were designed to represent a 1/3-scale ten-storey coupled shear wall system. The total height of the specimens was 10 m, and each storey has the same height of 0.8 m. The width of wall piers was 160 mm. The clear length to height ratio, also known as aspect ratio, of the RC and the two-level-yielding steel coupling beam are approximately 2.3 and 2.6, respectively. The specimen was designed to achieve the mechanism in which yielding is assumed to develop over the coupling beams and at bases of the walls. The detailed configuration of the two specimens was shown in Fig. 2.
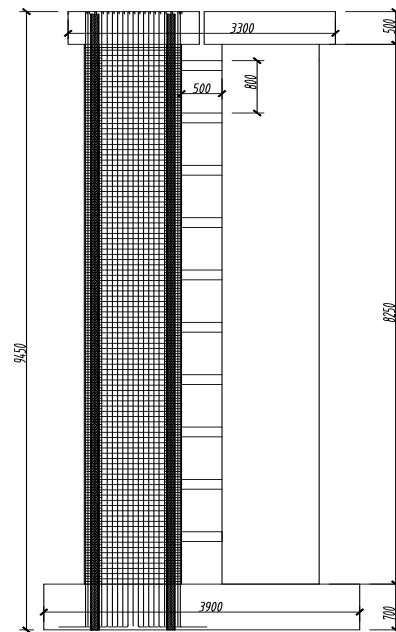
(a)   Configuration of the whole specimen
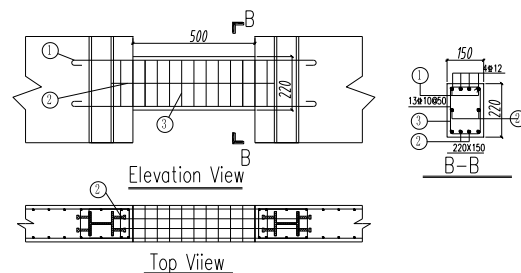
(b) RC-Coupling beam
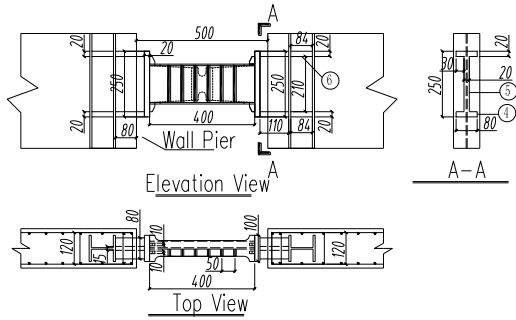
(c) TYSCB-Coupling beam

Fig. 2 Configuration of two specimens

2.1. RC coupling beam

The RC coupling beam is 500 mm long, 220 mm high and 160 mm wide. Four HRB400 (i.e. the nominal yielding strength = 400 MPa) rebars with a diameter of 12 mm were placed at the top and bottom, recpectively. Thirteen reinforcing bars of ϕ10@50mm (in a diameter of 10 mm and spacing of 50 mm) were arranged as stirrups along the length direction of RC coupling beams. The detailed reinforcement layout of the RC coupling beam is presented in Fig. 2(a).

The initial stiffness of RC coupling beam is calculated as 180 kN/mm, with a stiffness reduction coefficient of 0.7 considered.

2.2. Two-level-yielding steel coupling beam

The TYSCB was designed based on the approach proposed by Li et al. The low yield point (LYP) steel LYP 225 (the nominal yield strength was 225 MPa) was used to made up of the inelastic part of the shear-yielding beam of TYSCB. The length of TYSCB is 400 mm, and the height is 150 mm. To keep the same initial stiffness with RC coupling beam, the first yielding level of TYSCB is designed as (0.6 mm, 110kN), and the second yielding level is (1.3 mm, 220kN) .The detailed configuration of TYSCB is shown in Fig. 2(c).

2.3. RC shear wall

The design criteria for RC shear wall are to prevent shear failure, with satisfying the bending capacity first. The shear wall is designed based on an axial force-moment (P-M) interaction diagram. Except for the self-weight of the specimen and the experimental setups, an additional gravity load of 400 kN which accounts for $10\% A_g f_c'$, was applied for each wall pier.

Two 9.41 m long H-steel boundary elements at both ends of the wall pier is reinforced by a total of 4 ϕ10 HRB400 longitudinal reinforcing bars. Two curtains of ϕ10 HRB400 reinforcing bars at 80 mm spacing are provided for shear resistance. The reinforcement layouts of RC shear walls in Specimen CW-RC and CW-TYSCB are presented in Fig. 2(a).

## 2.4. Connection detailings of both specimens

For specimen CW-RC, the longitudinal reinforcements of coupling beams were welded to the flanges of the boundary H-steel. TYSCBs were connected to the H-steel boundary element through a short bracket. In this way, the two H-steels connected with the two ends of TYSCB will have two roles: embedded elements for coupling beam and boundary elements for shear wall. The design method for this 'beam-column' joint was referenced from the researches by Li et al[8, 9]. The detailed configuration of the connetion is presented in Fig. 2(b) and Fig. 2(c) . This bracket configuration made it more easier to replace the TYSCBs.

3. Test setup and test procedure

Specimens are loaded horizontally with one 2000 kN hydraulic actuator at the top rigid beam. A 3-D detailed illustration of the experimental setup is shown in Fig. 3. The whole loading procedure was displacement controlled and the detailed loading history inshown in Fig. 4. This setup provided an approximate first-mode dominant loading profile for the test specimen. The fixed boundary condition at the bottom of the specimens was provided through a heavily reinforced concrete block which was anchored on the strong floor through twelfth 50 mm diameter prestressed rods. Lateral supports are provided using an steel reaction frame to prevent out-of-plane movement of the shear wall.
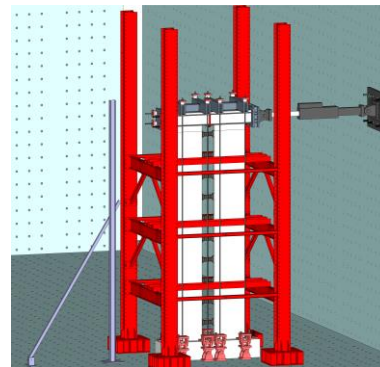
(a) 3D view of testsetup
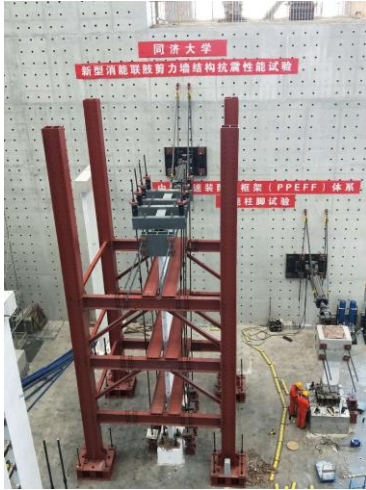
(b) test setup

Fig. 3 Test Setup

The 400 kN additional gravity load was applied to the top of each shear wall using four hydraulic jacks which pulled four 30 mm prestressed rods at the same time before applying lateral displacement.
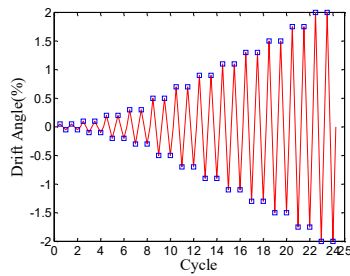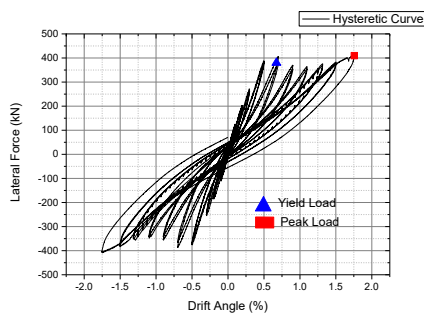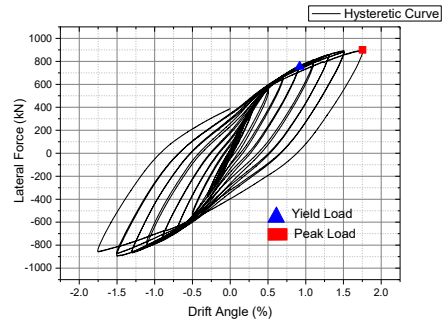

Fig. 4 Loading pattern

4. Test results

Hysteretic responses between the drift and the lateral force of Specimen CW-RC and CW-TYSCB is presented in Fig. 5(a) and (b), respectively. It should be noted that horizontal forces due to horizontal components of the prestressed rods have been cancelled and have no effect on the total lateral force.

(a) CW-RC

(b) CW-TYSCB

Fig. 5 Hysteretic response

The ultimate capacity of CW-RC is 420 kN, and it is about 900 kN for Specimen CW-TYSCB. The results clearly showed that using TYSCB can have a much higher bearing capacity and plumper hysteretic response.

Crack development was traced at bases of the wall piers and all the coupling beams for Specimen CW-RC, and only the wall base for Specimen CW-TYSCB. The first hairline cracks of the two specimens appeared at the same drift angle of 1/1000. With the increasing of loading, the development of cracks of Specimen CW-TYSCB were more rapid, since at the same loading level CW-TYSCB could bear larger lateral forces. The final state of both specimens are presented in Fig. 6.

(a) CW-RC   (b) CW-TYSCB

Fig. 6 Final state of the both specimens

For Specimen CW-RC, all the coupling beams were failed due to shear force, and a very significant X-shape crack could be observed on the first-floor coupling beam. The degree of destruction depended from the 10th-floor to the 1st-floor coupling beam. The roof-floor coupling beams lost a large portion of the concrete core nd some stirrup reinforcements buckled. The same situation appeared on the 6th to 9th –floor coupling beams , but not as significant as the roof-floor.The bases of wall piers damaged little, and the strain gauages on the flanges of the

boundary steels showed the H-steel were still in hardening satge. This result indicated the couling beams failed before the wall base, which was also the expected failure mechanism for coupled shear wall system.

For Specimen CW-TYSCB, the 10th-floor to 4th –floor coupling beams were damaged after completing the first loading cyle of 1.75% drift angle. The width of the crack on the wall base was more larger than that of the Specimen CW-RC. However, the RC wall piers were not failure in the final stage. The preffeered energy-dissipation mechanism was also achieved. Furthrore, the Specimen CW-TYSCB showed better energy-dissipation ability.

The connection between TYSCB and the RC wall piers in Specimen CW-TYSCB appeared to be intact and almost elastic through the whole loading process.

4.1. Energy dissipation

Energy dissipation of each cycle for both specimens was evaluated through equivalent viscous damping ratio, which is determined by the energy dissipation, area enclosed by hysteretic loops, divided by 4π times linear strain energy from origin to maximum deformation point at each cycle. The analysis results of each cycle are presented in Fig. 7. According to that figure, Specimen CW-TYSCB showed more plump and robust hysteretic response at the same drift level. It should be noted that Specimen CW-RC inidicated fairly considerable plump curve under the 1.75% drift angle cycle loading. Based on the gauge readings, this phenomena was caused by the yielding of the H-steel boundary elements. As a result, the better energy-dissipation in Specimen-TYSCB was most attributed to the steel coupling beams.
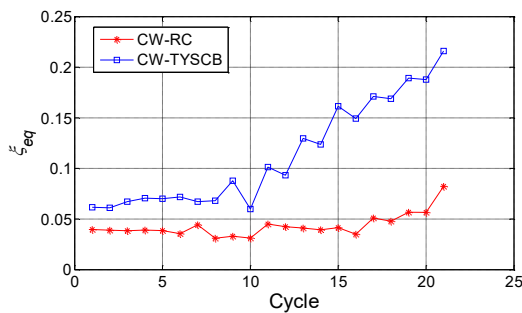

Fig. 7 Equivalent viscous damping ratio

4.2. Stiffness and displacement ductility

A bilinear lateral force-drift model was developed for each soecimen in order to evaluate lateral stiffness and displacement ductility. This idealized bilinear curve was developed in the following way: First, anevelope curve was created by linearly connecting the peak value of the first cycle at each target drift level in the positive direction. Second, the ultimate drift ratio, d_u was selected as the point corresponding to the lateral force with a 20% drop from the peak. The yield point (d_y, f_y) was defined based on theconcept of equal plastic energy so that the area enclosed by theidealized elastoplastic envelope curve was the same as that enclosed by the actual envelope curve.The idealized bilinear lateral force-drift responses of the two specimens are presented in *Fig. 5* and the numerical values of the curves are summarized in Table 1.

Table 1. Bilinear response properties of Specimens CW-RC and CW-TYSCB

Specimen	Yield Load(kN)	Peak Load(kN)	Ultimate drift
CW-RC	380.04	409.8	1.75%
CW-TYSCB	753.77	900.2	1.75%

Stiffness deterioration at each drift cycle for both specimens is presented in Fig. 8. The stiffness ratio for the vertical axis is determined by the peak-to-peak secant stiffness at each cycle divided by the initial stiffness from the idealized curve. It shows that Specimen CW-TYSCB sustains better stiffness both in the repeated cycles at a given drift level and in between different drift levels.
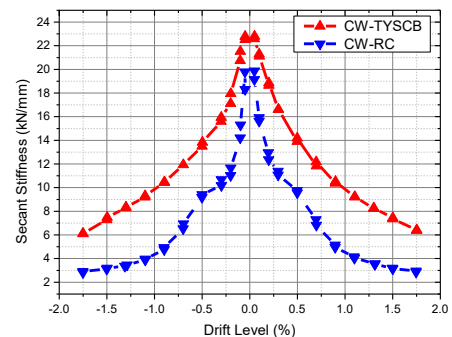

Fig. 8 Stiffness deterioration

5. Conclusions and recommendations

Two 1/3-scale ten-storey coupled shear wall specmens were tested in this research. Specimen-RC consisted of two RC wall piers and ten longitudinally reinforced concrete coupling beams while Specimen CW-TYSCB consisted of two RC wall piers and ten TYSCBs. Based on the experimental results, the following conclusions can be drawn:

(1) Sharing almost the same initial stiffness, the bearing capacity of Specimen CW-TYSCB was two times larger than that of Specimen CW-RC. The earlier shear failure of concretes of RCBs could not guarantee the rebars develop their post-yielding strength, as a result the Specimen CW-RC showed a very low bearing capacity.

(2) At the same drift level, specimen CW-TYSCB suatained better lateral force in the repeated cycle, better stiffness deterioration and better energy dissipation ability.

(3) The energy dissipation ability of Specimen CW-TYSCB is far beyond that of CW-RC, and the equivalent viscous damping ratio for each loading cycle of CW-TYSCB is 2.63 times larger than CW-RC.

6. Acknowledgements

References

[1] El-Tawil S, Harries KA, Fortney PJ, Shahrooz BM, Kurama Y. Seismic Design of Hybrid Coupled Wall Systems: State of the Art. *J Struct Eng* 2010, *136*, 755-769.

[2] Harries KA, Gong B, Shahrooz BM. Behavior and Design of Reinforced Concrete, Steel, and Stee-Concrete Coupling Beams. *Earthq Spectra* 2000, *16*, 775-799.

[3] Harries KA, Mitchell D, Cook WD, Redwood RG. Seismic Response Of Steel Beams Coupling Concrete Walls. *Journal Of Structural Engineering* 1993, *119*, 3611-3629.

[4] Park W, Yun H. Seismic behaviour of coupling beams in a hybrid coupled shear walls. *J Constr Steel Res* 2005, *61*, 1492-1524.

[5] Li G, Sun F, Pang M, Liu W, Wang H. Structural Shear Wall Systems with Metal Energy Dissipation Mechanism. International Journal of High-rise Buildings 2016, *5*, 195-203.

[6] Mengde Pang GLFS. Seismic Behaviour Improvement of Coupled Shear walls using Innovative Steel coupling Beams .Proceeedings of the 11th pacific structural steel conference, Shanghai, China 29-31 October, 2016.

[7] Li G, Pang M, Sun F, Jiang J, Hu D. Seismic Behavior Of Coupled Shear Wall Structures With Various Concrete And Steel Coupling Beams. The Structural Design Of Tall And Special Buildings 2017.

[8] Li G, Gu F, Jiang J, Sun F, Cyclic behavior of steel beam-concrete wall connections with embedded steel columns (I): Experimental study. Steel Compos Struct 2017, *23*, 399-408.

[9] Li G, Gu F, Jiang J, Sun F. Cyclic behavior of steel beam-concrete wall connections with embedded steel columns (II): Theoretical study. Steel Compos Struct 2017, *23*, 409-420.