Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No

PERFORMANCE OF SANDWICH COMPOSITE MEMBERS SUBJECTED TO EARTHQUAKES

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ABSTRACT

This study focused on the experimental evaluation of hollow sandwich composite members subjected to combined bending and torsion. The sandwich composite design is composed of dual steel tubes with concrete filled in-between. Steel tubes with various sectional dimensions were used to fabricate the specimens. A series of combined loading tests, including bending, torsion and their combination, on 14 composite members with various sectional compositions were conducted to investigate the relationship between the sections' compositions and the members' performance. It was found from the test results that the strength and energy dissipation of sandwich composite members with adequate sectional compositions were higher than those of concrete-filled tubes with similar dimensions. A simplified expression for member strength estimation under combined bending and torsion was proposed for engineering practice references.

Introduction

Steel-concrete composite members have been widely used in building and bridge constructions. Typical composite member design can be seen in the fabrication of concrete -filled tubes (CFT). The concrete-filled tubes have been recognized as effective structural forms in earthquake-resistance designs due to their high strength and significant ductility (Ishizawa et. al. 2006; Lam and Williams 2004; Tokgoz and Dundar 2008). However, for CFT constructions designed for extremely heavy loads or designs used for members with large dimension, such as bridge pier with high elevation, the weight of the CFT member will become extremely heavy and the efficiency of the design begins to descend. In order to improve the

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design efficiency, a hollow composite member that comprises of dual steel tubes and in-filled concrete, noted sandwich composite members hereafter, has been introduced.

It has been investigated in previous study that the flexural performance of sandwich composite members is significant compared with CFT members with similar dimensions (Hossain and Wright 2004; Tao and Han 2006; Uenaka and Kitoh 2008; Zhao and Grzebieta 2002). However, for structures subjected to earthquakes, particularly those acting at the non-principal axes of the structures, torsion and combined loads, such as bending and torsion, will be induced. Current studies on the seismic performance of the composite member designs focus mostly on the member behavior under axial load, flexural load or their combinations. Information on the responses of sandwich composite members under combined bending and torsion is still limited (Hsu and Liang 2003). In order to validate the effectiveness of the seismic design of composite members, the torsional effect on the member responses and the flexural-torsional performance of the design must be adequately evaluated.

This study focused on the experimental evaluation of hollow sandwich composite members subjected to combined bending and torsion. A series of combined loading tests, including bending, torsion and their combination, on composite sandwich members with various sectional compositions were conducted. Test results were used to investigate the relationship between the sections' compositions and the members' seismic performance, and to define design reference for engineering practice.

Experimental Program

Specimens

Fourteen specimens, including two CFTs and 12 sandwich composite members were fabricated for testing. All specimens were composed of the same outer steel tubes, however, inner tubes with various dimensions. The outer tube was ASTM A36 300x300x6mm, and the three inner tubes used for fabrication were ASTM A36 100x100x4.5mm, 150x150x4.5mm, and 200x200x4.5mm, respectively. These compositions yielded sandwich composite members with void ratios, defined by the values between voids to the cross-sectional areas, equaling 0.11, 0.25, and 0.44, respectively. The arrangements were used to correlate the relationship between the sectional geometries and member performance, particularly those in the post-buckling stages. Yielding stress of the steel tubes and the compressive strength of the in-filled concrete were 355 MPa and 49.6 MPa, respectively. The dual steel tubes were welded to an end plate on the top. The bottom 900mm of the inner tube was further strengthened with concrete so that a rigid boundary could be achieved. The member categorization was listed in Table 1.

Table 1. Member categorization

Specimen	CFT-M	M100	M150	M200	SE100	SE150	SE200	LE100	LE150	LE200	CFT-T	T100	T150	T200
Void ratio	0	0.11	0.25	0.44	0.11	0.25	0.44	0.11	0.25	0.44	0	0.11	0.25	0.44
Loading type	M	M	M	M	M+T	M+T	M+T	M+T	M+T	M+T	T	T	T	T
e/h	--	--	--	--	0.25	0.25	0.25	0.5	0.5	0.5	0.5	0.5	0.5	0.5

Note: M and T indicate bending and torsion, respectively

Test Set-up

In order to investigate the effect of torsion on the member's performance, four load combinations, including bending, torsion, and bending with small and large torsion, were adopted to test the sandwich composite members. During each test, the member bottom was fastened on a pair of stiffen platforms by high strength rods, and the member top was attached to a stiffened loading beam for load transmission. For bending test, a constant axial load was applied to the member by the action of a hydraulic jack pushing against a reaction beam. The member was then horizontally exerted by a servo-controlled hydraulic actuator driven under a series of increasing displacement commands. For torsional tests, the actuator was moved to one end of the loading beam to generate torsion through the couple action with a stiffened strut that was placed at the center of the loading beam. Combined bending and torsion tests were conducted by simultaneously applying constant axial load with hydraulic jack and lateral load with hydraulic actuator with desired eccentricity on the loading beam. The test set-up and the displacement history are shown in Figs. 1 and 2, respectively.

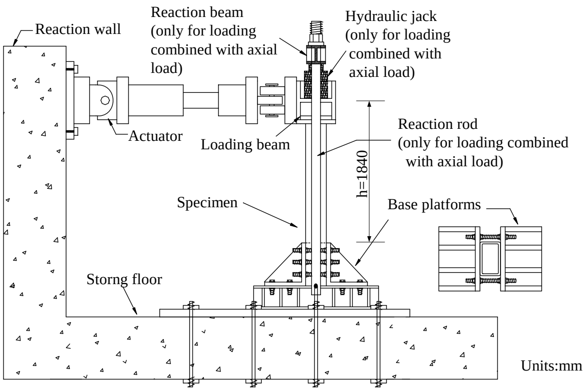


Figure 1. Test set-up

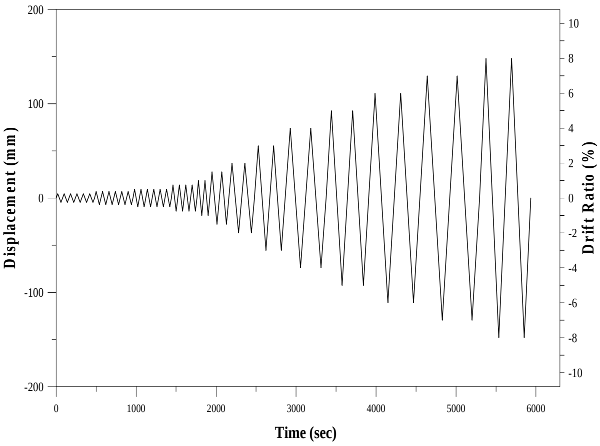


Figure 2. Displacement history

Experimental Observations

Various failure patterns were observed in members subjected to different load combinations. For members failed in flexural loads, the damaged regions were concentrated at the member bottoms where plate local buckling was observed. Strength deterioration leading to the formation of plastic hinge was found when the drift was increased. For members subjected to pure torsion, diagonal plate deformation was observed in the center portions of the members. Minor strength deterioration was exhibited when the member was subjected to large twist angle. This phenomenon could be related to the integrity of the cross section, because the member originally possessed closed section with high torsional rigidity. Once the section remained in tact, the torsional resistance could be sustained.

However, for members subjected to combined loads coupled with torsion, the diagonal plate deformation due to torsion caused changes in the sections' flexural rigidity. The distorted section responded to the subsequent combined loads with larger deformation. This phenomenon yielded significant flexural-torsional deformation in the steel plate and caused larger strength deterioration. The failure patterns of members subjected to combined loads coupled with torsion validated the importance of effect of torsion on the member performance. Fig. 3 compares the failure modes for members subjected to various load combinations.

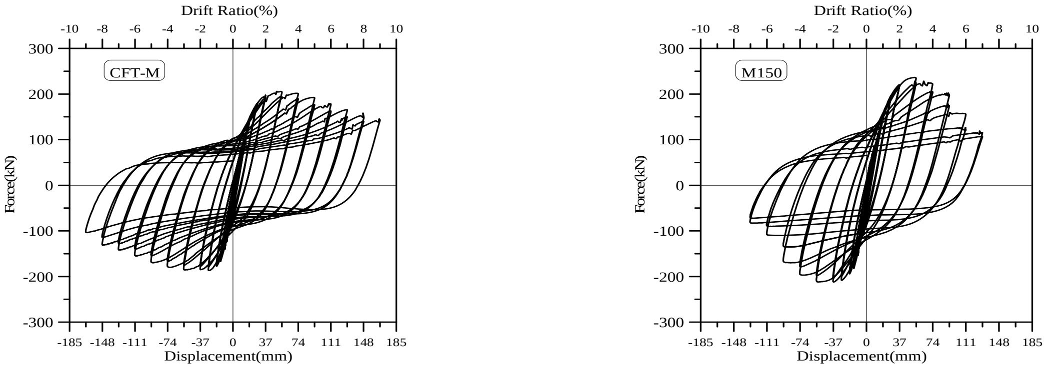
(a) (b) (c)

Figure 3. Comparisons of failure modes: (a) CFT under bending; (b) sandwich composite member under bending; (c) sandwich composite member under combined loading.

Comparisons of Test Results

Strength

In order to evaluate the effects of torsion and sectional compositions on the member performance, the achievable strengths of members were first compared. Fig. 4 shows the typical hysteretic relationships for CFT and sandwich composite member.



(a) (b)

Figure 4. Typical hysteretic relationships: (a) CFT; (b) sandwich composite member

It can be found from the comparison that these two designs exhibited similar hysteresis behavior with difference in ultimate strength and strength deterioration. The backbone curves for the members subjected to axial load and bending were compared in Fig. 5. It can be found from the figure that the strength for sandwich composite member with larger inner tube was higher; however, the strength deterioration at the post-buckling stage was also larger.

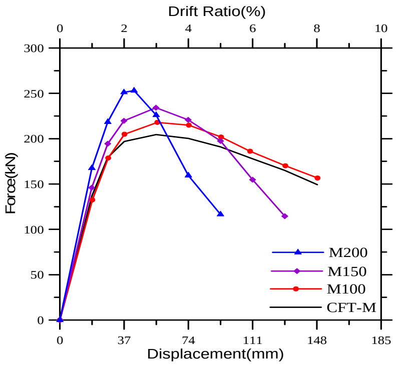
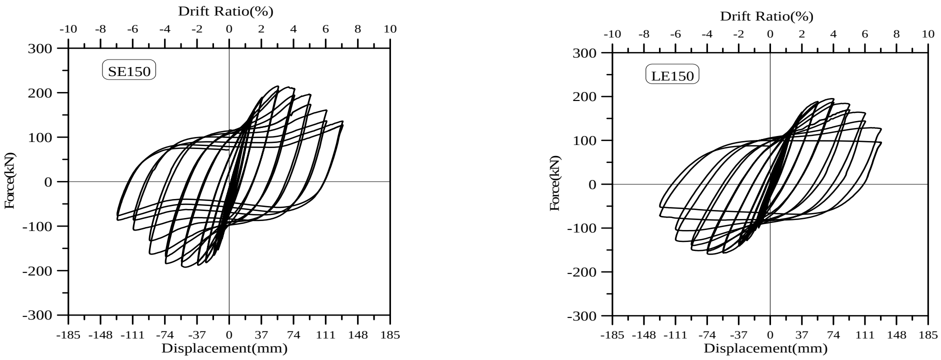


Figure 5. Backbone curves for members subjected to axial load and bending.

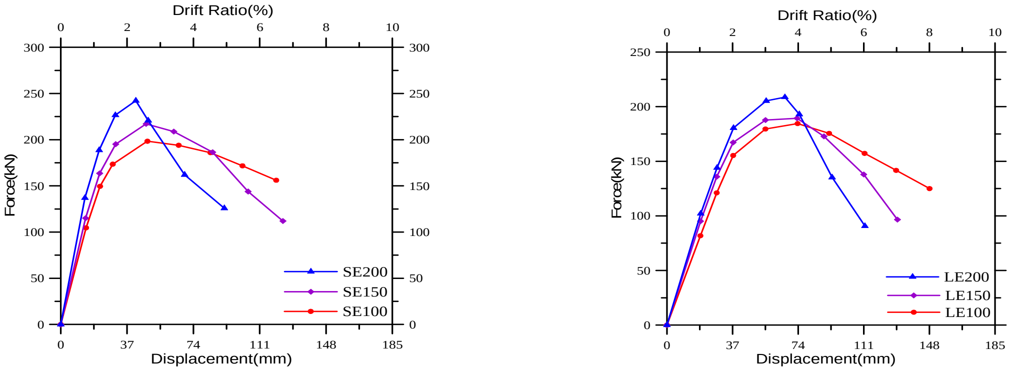
The typical load-displacement relationships for members subjected to various combinations of bending and torsion were shown in Fig. 6. It can be found from the comparison that the achievable strength of member was reduced when the magnitude of torsion was increased.



(a) (b)

Figure 6. Typical load-displacement relationships for members subjected to combined loads: (a) load with small eccentricity; (b) load with large eccentricity.

Fig. 7 compares the flexural-torsional responses of members with various sectional compositions. It can be found from the comparisons that the members with larger void ratios tended to exhibit higher strength deterioration.



(a) (b)

Figure 7. Responses for members with various sectional compositions: (a) load with small eccentricity; (b) load with large eccentricity.

Fig. 8 shows the relationship between the normalized bending strength and the load eccentricity. It can be found from the figure that member's flexural strength was reduced when the magnitude of the eccentricity increased. This relationship could be approximated by a linear expression and could be expressed by the follow:

$$\left(\frac{M}{M_u}\right)=1-0.333\left(\frac{e}{h}\right) \tag{1}$$

In Eq. (1), e is the eccentricity of the applied load, h is the height of the specimen, M_u and M are the achievable strength when members are subjected to bending, and combined loading, respectively.

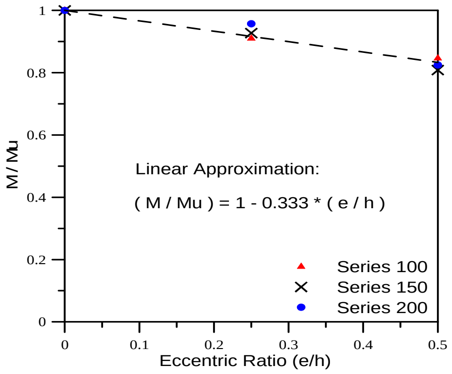
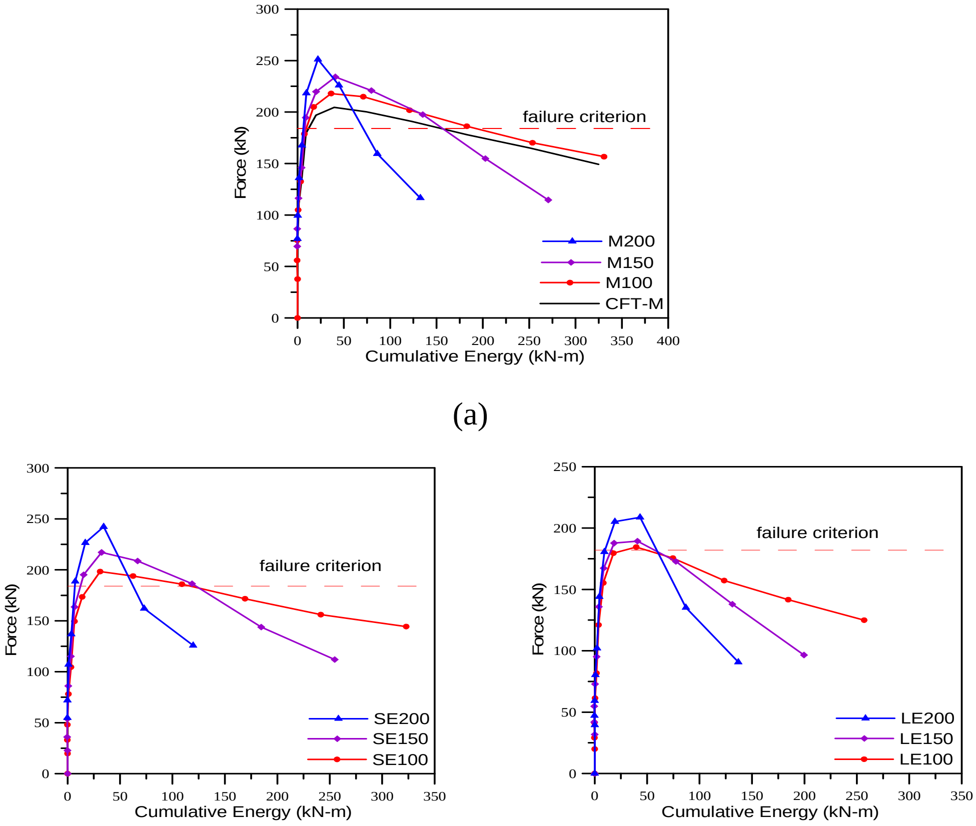


Figure 8. Relationship between the normalized bending strength and the load eccentricity.

Energy Dissipation

In order to further define the seismic performance of the sandwich composite members, the members' energy dissipation capacity was evaluated. Energy dissipation was evaluated by the area bounded by the hysteretic curves. Fig. 9 shows the relationships between strength and cumulative energy for members subjected to various load combinations. Member's energy dissipation capacity was compared by the cumulative energy when the member's strength drops to 80% of the ultimate strength of the corresponding CFT member.

It can be found from the comparisons that the ultimate strengths for the tested sandwich composite members were all higher than that of the CFT. However, the energy dissipation capacity of the former may not necessarily be larger than the latter. Therefore, the void ratios of the sandwich composite members need to be adjusted in order to achieve higher member performance. For this purpose, the energy dissipation capacities of the members were normalized and compared in Fig. 10. It can be found from the figure that higher efficiency could be expected for sandwich composite members with void ratios less than 0.25.



(a)

(b) (c)

Figure 9. Relationships between strength and cumulative energy: (a) bending tests; (b) bending with small torsion; (c) bending with large torsion.

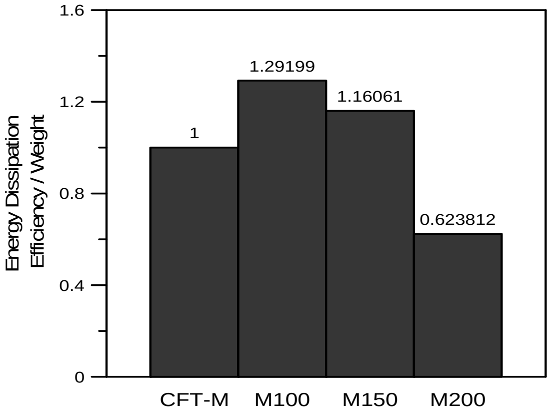


Figure 10. Comparisons of energy dissipation capacities.

Conclusions

This study focused on the seismic performance evaluation of sandwich composite members. A series of combined loading tests on members with various sectional compositions were conducted to investigate the relationship between the sections' void ratios and the members' performance. It was found from the test results that the strength and energy dissipation capacity of sandwich members with adequate sectional void ratios were higher than those of concrete-filled tubes with similar dimensions. Test results also showed that the members' energy dissipation capacities decreased when the sectional void ratios increased. A simplified expression for member strength evaluation was proposed for engineering practice references.

Acknowledgments

This study was partially supported by the National Science Council of Taiwan under Grant No. NSC98-2221-E-008-068, which is gratefully acknowledged.

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