Steel and Composite Structures, Vol. 9, No. 4 (2009) 367-380
DOI: http://dx.doi.org/10.12989/scs.2009.9.4.367

Experimental evaluation on the seismic performance of high strength thin-walled composite members accounting for sectional aspect ratio effect

H. L. Hsu*, J. L. Juang and K. T. Luo

Dept. of Civil Engineering, National Central University, Chung-Li 32054, Taiwan
(Received February 24, 2009, Accepted June 19, 2009)

Abstract. This study focuses on the experimental evaluation of the flexural-torsional performance of high strength thin-walled composite members. A series of tests on composite members with various sectional aspect ratios subjected to eccentric cyclic loads were conducted. Test results show that the composite member's torsional strength could be approximated using a series of linear segments and evaluated using the superposition of the component steel and reinforced concrete responses. It is also validated from the tests that the strength deterioration of members subjected to combined loads is closely related to the aspect ratios of the sections. An interaction expression between the bending and torsion for high strength thin-walled composite members is proposed for engineering practice references.

Keywords : Flexural-torsional performance; thin-walled composite members; high strength concrete; sectional aspect ratio.

1. Introduction

Composite members comprising of steel sections and reinforced concrete are widely used in building and bridge constructions due to their high seismic performance. In such compositions, the steel sections provide high flexural strength and ductility and the reinforced concrete contributes effective lateral support to prevent local buckling of the steel sections. The coupling mechanisms between the steel sections and the reinforced concrete make the composite members suitable designs for earthquake-resistant purposes (Mirza and Skrabek 1991, Ricles and Paboojian 1994, Boyd, *et al*. 1995).

It has been pointed out in the behavior studies on concrete-encased composite members (Chen, *et al*. 2005, Tokgoz and Dundar 2008) that the load-carrying capacity of such members was significant when the members were subjected to cyclic or biaxial loads. Results from the study of Yang, *et al*. (2006) also validated that effective energy dissipating mechanism could be achieved if the cross-sections of the members were adequately detailed. Similar phenomena obtained in the investigations on the seismic behavior of concrete-filled tubes also justified the performance of the composite member designs (Lam and Williams 2004, Han, *et al*. 2004, Ishizawa, *et al*. 2006).

Although the above studies validated the effectiveness of composite members to the seismic designs of structures, design modification for higher structural efficiency using hollow composite sections and high strength concrete to reduce the weight of the structure was considered (Legeron and Paultre 2000,

* Professor, Corresponding Author, Email: T3200178@ncu.edu.tw

Tao, *et al*. 2004). The benefits in using thin-walled composite members include high strength/mass ratios and significant ductility to reduce the demand in lateral load resistance (Mo, *et al*. 2001, Zhao and Grzebieta 2002).

Current studies on the seismic behavior of thin-walled composite members focus primarily on their responses under axial, flexural, or combination loads (Elchalakani, *et al*. 2002, Hossain and Wright 2004, Tao and Han 2006, Uenaka and Kitoh 2008). However, for structures subjected to multi-directional earthquake excitations, combined loads coupled with torsion will be generated on the structural members. Once the torsion-induced shear is presented in the composite members, premature diagonal cracks will appear in the concrete that hamper the sectional integrity and the effective composite mechanism. An increase in the local buckling potential of the encased steel sections subsequently affects the members' seismic performance in the inelastic stages. Therefore, investigation into the member performance, particularly the flexural-torsional responses, under combined loads coupled with torsion is essential in effective earthquake-resistant high strength thin-walled composite member designs (Hsu and Wang 2000).

In addition to the above concerns, it was indicated in the author's previous study (Hsu and Tsao 2007) that the flexural-torsional performances of hollow steel sections were closely related to the sectional geometries, particularly the ratios between the depth (D) and width (B), defined as the sectional aspect ratio hereafter. This concern remains in the seismic design of high strength thin-walled composite members, because various stress states will be induced in composite sections with different aspect ratios when torsion or loads coupled with torsion are presented. As a result, the member performance is affected. To evaluate the effectiveness of high strength thin-walled composite designs, the relationship between the sectional aspect ratios and the member performance must be defined. For these purposes, a series of tests on high strength thin-walled composite members with various sectional aspect ratios subjected to eccentric cyclic loads were conducted in this study.

2. Research significance

The main objectives of this study were: (1) to provide solid experimental information for the evaluation of seismic performance, particularly the flexural-torsional responses, of high strength thin-walled composite members; and (2) to quantitatively define the relationships among member performance, sectional aspect ratios and the magnitude of torsion so that design references can be established.

3. Experimental program

3.1 Specimens

Fourteen specimens, including 12 composite thin-walled members, one steel tube (labeled S) and one hollow reinforced concrete member (labeled RC) were fabricated for testing. The steel tube and hollow reinforced concrete member were used to evaluate the component strengths of the composite member so that the datum for subsequent comparisons could be established. The composite members were composed of reinforced concrete and steel tubes with various cross-sectional geometries. The steel tubes used for composite member fabrications were JIS-SS400 150 × 150 × 6, 200 × 150 × 6 and 200 × 100 × 6 (width × depth × thickness), respectively. The maximum width-to-thickness (b/t) ratios for the three steel tubes were 25, 33.3.and 33.3, respectively. Since these values were all smaller than the limits that governed the tube compact section requirements, adequate strength development in steel tubes would be achieved. Therefore, strength contribution of the comprising reinforced concrete would be the major parameter that affected the behavior of members subjected to combined loads.

The concrete thickness for the hollow reinforced concrete member and all composite specimens was determined at 110 mm. Composite members composed of the above-mentioned steel tubes were labeled series A, B, and C, respectively, and were used to distinguish the sectional aspect ratio effect on the members' flexural-torsional performance. The sectional aspect ratios (depth/ width; D/B) of the three test series were 1, 0.88, and 0.76, respectively. The reinforced concrete of the members was composed of high strength concrete available in the local industry, #5 longitudinal bars and #3 stirrups, respectively. The stirrup spacings in the confined and non-confined zones were 100 mm and 150 mm, respectively. The concrete compressive strength was 55.7 MPa, determined from cylinder tests after 28-days curing. The yield strengths of the steel tube, longitudinal bar and stirrups were 346.5 MPa, 366.9 MPa, and 353.7 MPa, respectively. The specimen labels and cross-sectional details are shown in Fig. 1 and listed in Table 1.

3.2 Test set-up

Four load types were considered in the test program. They included bending tests, pure torsion tests, bending with smaller torsion and bending with larger torsion, respectively. For the bending and pure torsion tests, the specimens were subjected to monotonically increasing deformations until the members reached their ultimate strengths. These tests were designed to evaluate the members' flexural and torsional strengths and set up the datum for subsequent performance comparisons. For members subjected to combined bending and torsion, an eccentric lateral load with desired eccentricity was generated via a series of prescribed increasing cyclic displacement commands. These cyclic combined load tests were implemented to evaluate the performance of members under earthquake excitation. These tests were used to correlate the member's flexural-torsional responses with the member's sectional compositions.

In each test, the bottom of the specimen was fastened to a stiffened base platform. The member top was attached to a stiffened loading beam so that the designated load combinations could be generated and transmitted. For bending tests, a servo-controlled hydraulic actuator was attached to the center of

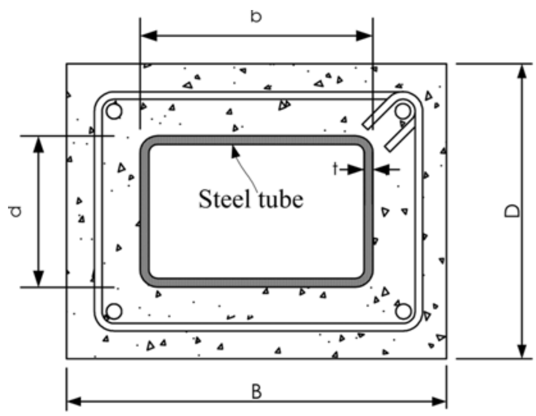


Fig. 1 Cross-sectional details of thin-walled composite members

Table 1 Specimen labels and cross-sectional details

Specimen	Composite section (B × D) (mm)	Steel tube (b × d × t) (mm)	Aspect ratio (D/B)	b/t	Loading type	Eccentricity ($\frac{e}{h}$)
A-M	370 × 370	150 × 150 × 6	1	25	Bending	0
B-M	420 × 370	200 × 150 × 6	0.88	33.3		
C-M	420 × 320	200 × 100 × 6	0.76	33.3		
S-T	----	150 × 150 × 6	----	25	Torsion	0.5
RC-T	370 × 370	----	----	----		
A-T	370 × 370	150 × 150 × 6	1	25		
B-T	420 × 370	200 × 150 × 6	0.88	33.3		
C-T	420 × 320	200 × 100 × 6	0.76	33.3		
A-TM1	370 × 370	150 × 150 × 6	1	25	Combined bending and torsion	0.25
B-TM1	420 × 370	200 × 150 × 6	0.88	33.3		
C-TM1	420 × 320	200 × 100 × 6	0.76	33.3		
A-TM2	370 × 370	150 × 150 × 6	1	25		0.5
B-TM2	420 × 370	200 × 150 × 6	0.88	33.3		
C-TM2	420 × 320	200 × 100 × 6	0.76	33.3		

Note: --- indicates value not concerned.

the loading beam and driven by the prescribed displacement commands. For pure torsion tests, the actuator was moved to one side of the loading beam, and a stiffened strut with both ends hinged was placed at the center of the loading beam. The desired torsion was achieved through the coupled action of the actuator and the strut. For the combined bending and torsion tests, the strut was removed, and the actuator was driven by a series of increasing cyclic displacement commands to generate the required combined loads. The specimen-to-loading-beam connection, the test set-up and the load histories are shown in Figs. 2 and 3, respectively.

4. Experimental observations

4.1 Bending tests

For members subjected to bending, flexural cracks were first observed in the member bottoms where effective confining stirrups were arranged. Spalling in the cover concrete occurred following the growth of flexural cracks in these regions when the member drifts were increased. The flexural damage patterns in the test specimens were similarly governed by the formation of plastic hinges in the confined zones. Fig. 4 shows the damage patterns in thin-walled composite members subjected to bending.

4.2 Torsion tests

For members subjected to torsion, diagonal cracks were first observed at the center portions of the members. Subsequent local buckling in the steel tubes occurred when the twist angles were increased. It was found from the tests that the damage extents for members with same cross-sectional areas, however

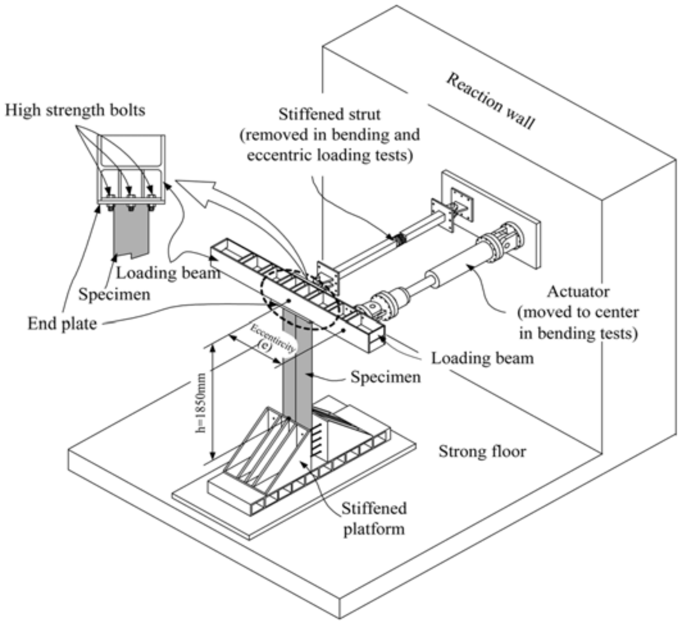


Fig. 2 Specimen-to-loading-beam connection and test set-up

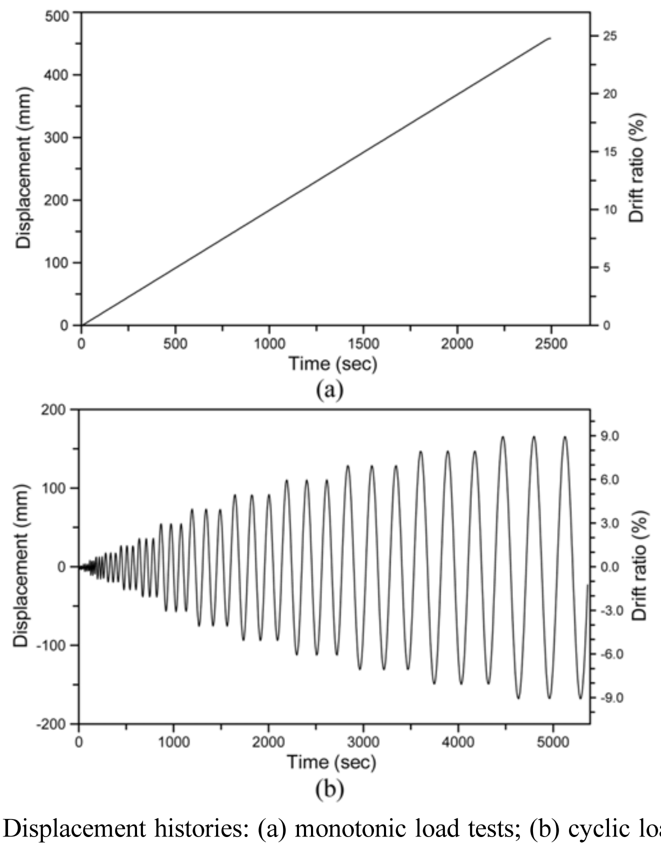


Fig. 3 Displacement histories: (a) monotonic load tests; (b) cyclic load tests

(a) (b) (c)

Fig. 4 Damage patterns in thin-walled composite members subjected to bending: (a) series A; (b) series B; (c) series C

different sectional aspect ratios, were different. This phenomenon can be attributed to the different member torsional rigidity, and subsequently various torsional responses, resulting from the various aspect ratios. Once the above-mentioned damage was exhibited, members with various sectional aspect ratios might result in different performance reductions when subsequent loads coupled with existing torsion were presented. Thus, the effect of the sectional aspect ratios on member performance subjected to earthquake loads must be adequately defined. Fig. 5 shows the damage formation process and the damage patterns for thin-walled composite members subjected to torsion.

4.3 Combined loading tests

For members subjected to combined bending and torsion, both flexural and torsional damage was exhibited. However, major differences in the damage patterns could be distinguished when the ratios between the applied bending and torsion varied. For example, when bending with smaller torsion was applied to the members, minor diagonal cracks were first observed in the lower halves of the members. However, subsequent flexural cracks in the member bottoms combined with the existing diagonal cracks to dominate the damage formation process when the member deformations were increased. In such cases, the members failed in flexural-torsional modes, however, located in the vicinity of the confined zones.

Similar failure patterns were observed in members subjected to bending with larger torsion, except that the centers of the damaged regions shifted from the lower halves to the center portions of the members. These regions were originally arranged with less confining stirrups. Once the damaged regions shifted to these areas, the member performance became susceptible. This phenomenon further validated the necessity for evaluating the members' flexural-torsional responses when they were designed for earthquake resistant purposes. Fig. 6 shows the failure modes for members subjected to various load combinations.

5. Comparisons and interpretations of test results

5.1 Flexural responses of members

Fig. 7 shows the load-deformation relationships for high-strength thin-walled composite members

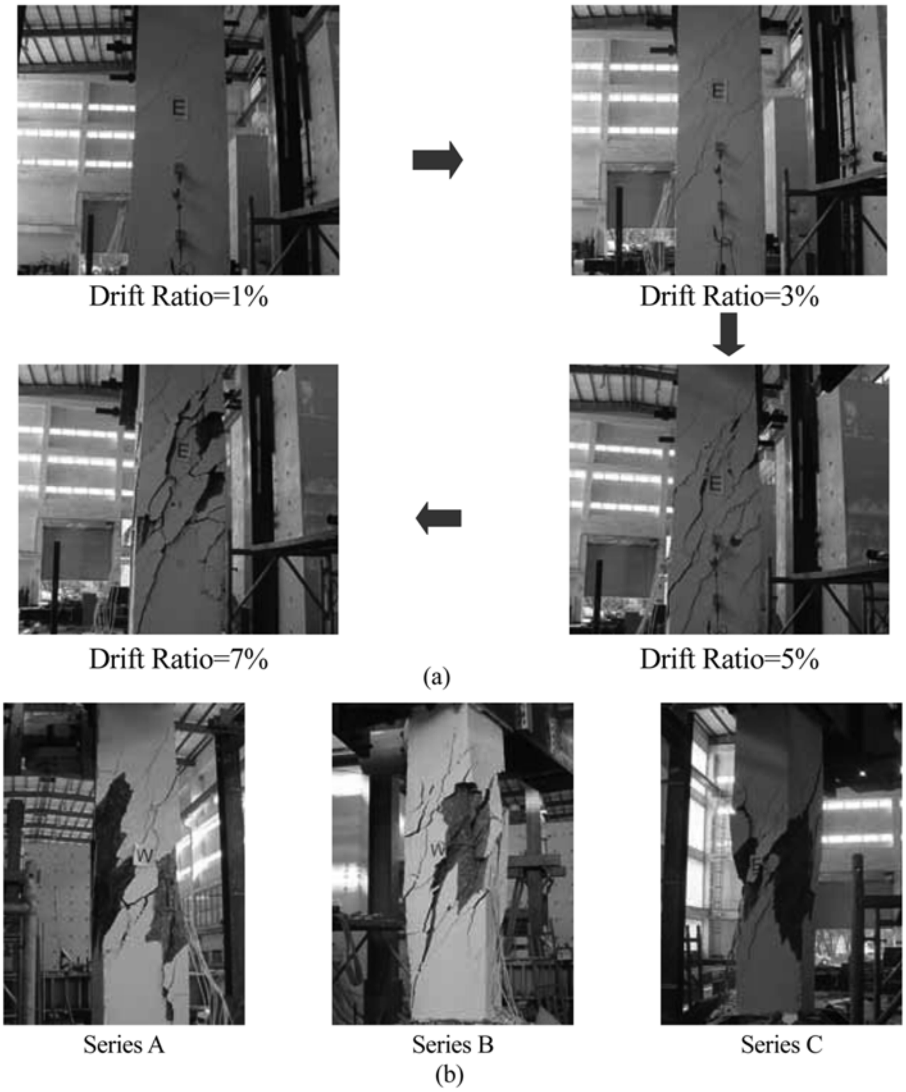


Fig. 5 Members subjected to torsion: (a) damage formation process; (b) comparisons of damage patterns for members with various sectional aspect ratios

subjected to bending. The comparisons show that the flexural behavior for the test specimens was similar, i.e., major strength reduction, about 7% to 13% of the members' ultimate strengths, due to thin-walled concrete crushing when the members reached the ultimate strength, approximately at 3% drift. Following the concrete crushing, the member strength sustained, with minor deterioration, at the post-ultimate-strength stages. This phenomenon could be attributed to the effectiveness of the encased steel tubes because the steel tubes originally possessed high flexural rigidity in the sections' two principal directions. Once the steel sections remained intact the member performance could be sustained. The above characteristics also validated the applicability of high strength thin-walled composite members to the structural designs.

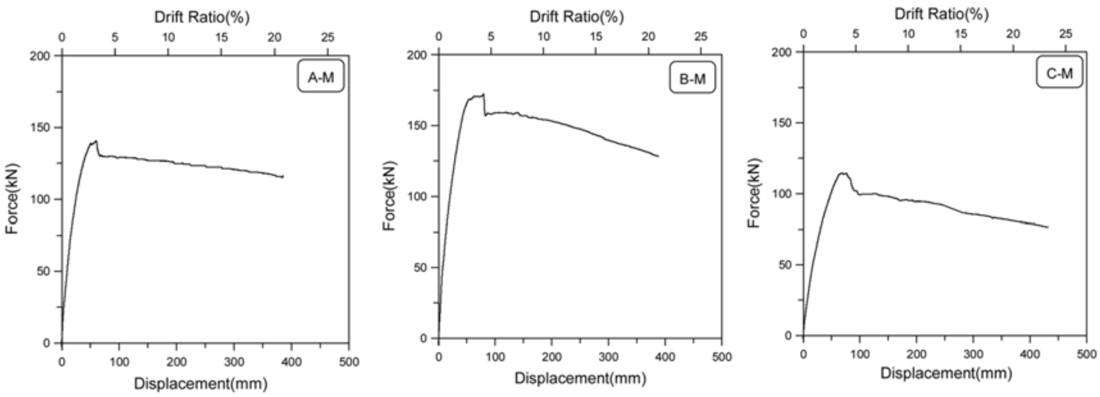
Series A Series B Series C

(a)

Series A Series B Series C

(b)

Fig. 6 Failure modes for members subjected to various load combinations: (a) bending with smaller torsion; (b) bending with larger torsion



(a) (b) (c)

Fig. 7 Load-deformation relationships for high-strength thin-walled composite members subjected to bending: (a) series A; (b) series B; (c) series C

5.2 Torsional behavior of high strength thin-walled composite members

Fig. 8 compares the torsion-twist angle relationships for the steel tube, thin-walled reinforced concrete member and the composite member composed. The figure shows that the torsional responses of the composite members can be approximated using a series of linear segments and can be evaluated using the superposition of the component steel and reinforced concrete responses.

As shown in this figure, the torsional responses of a thin-walled composite member can be distinguished using the following critical points: θ_1, θ_2, θ_3, respectively. In which, θ_1 is the twist angle when the composite member first reaches the crack stage. θ_2 and θ_3 are the twist angles associated with the stages when the thin-walled concrete crushes, and the composite member reaches the ultimate torsional strength, respectively. It can be further observed from the response comparisons among the composite member, component reinforced concrete member, and the steel tube that the above distinguishing points, θ_1, θ_2, θ_3, are close to the twist angles when the reinforced concrete member reaches the crack state, the maximum strength and the steel tube reaches the yielding stage, respectively.

Fig. 9 shows the torsional responses and segmental approximation of the tested composite specimens. It can be observed from the figure that similar response patterns were exhibited. In these tests, the twist angles at which members reached the crack state were close, however, the twist angles when thin-walled composite members reached the ultimate strengths varied. Table 2 lists the twist angles when the composite members reached the crack state (θ_1), concrete crushing stage (θ_2), and the ultimate strength stage (θ_3). It should be noted that the achievable twist angles at the ultimate torsional strengths for thin-walled composite members made of high strength concrete, approximately 0.037 rad/m to 0.039 rad/m, were slightly lower than that achieved in composite members comprised of normal strength concrete, approximately 0.05 rad/m, as indicated in the previous study (Hsu and Liang 2003). This was due to the higher material brittleness.

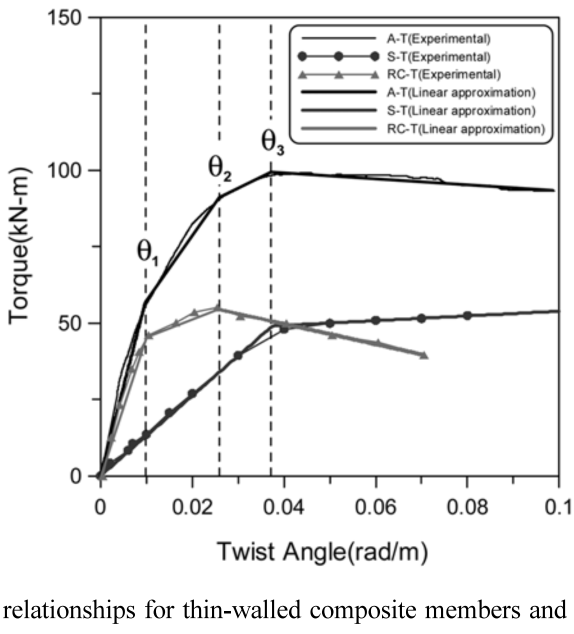


Fig. 8 Torsion-twist angle relationships for thin-walled composite members and the comprising components

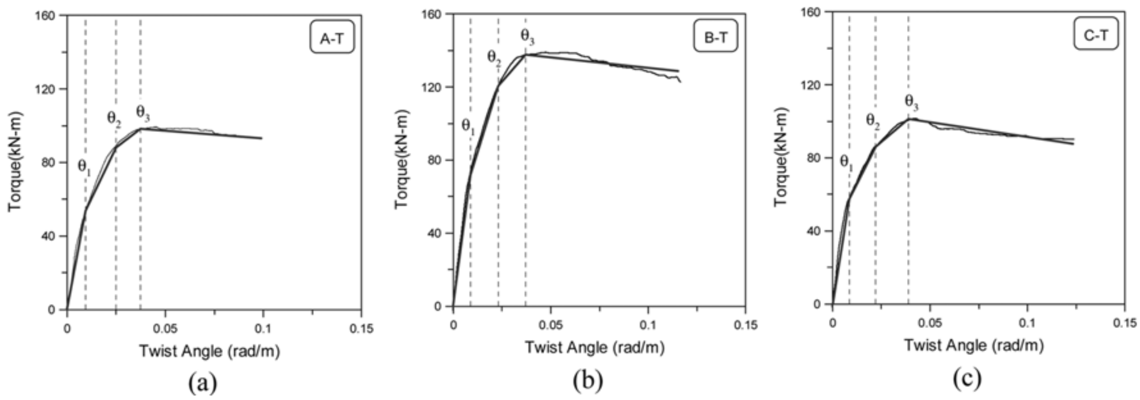


Fig. 9 Torsional responses and the segmental approximation of composite specimens with various sectional aspect ratios: (a) series A; (b) series B; (c) series C

Table 2 Twist angles at which members reached the critical stages

Specimen	θ_1	θ_2	θ_3
RC-T	0.0098	0.026	---
S-T	---	---	0.0372
A-T	0.0094	0.025	0.0374
B-T	0.0090	0.023	0.0371
C-T	0.0087	0.022	0.0390

Note: -- indicates value not concerned.

5.3 Sectional aspect ratio effects on the flexural-torsional performance

Fig. 10 shows the hysteretic relationships for members subjected to various combinations of bending and torsion. The figure shows that the achievable member strength decreased when the torsion magnitude increased. The member strengths for the three test series under combined loads were further normalized with respect to the flexural strength of corresponding members that were subjected to bending alone.

Fig. 11 shows the relationships between the normalized flexural and torsional strengths for the three test series. The figure shows that a linear relationship between the normalized bending strength and the normalized torsional strength existed. It is also found that the effect of torsion on the flexural strength reduction was different when the members' sectional aspect ratios varied. This phenomenon can be explained by the flexural-torsional interaction in members with different cross-sectional compositions. This is because members with various aspect ratios respond to different twist angles and various changes in flexural rigidity, as shown in Fig. 12, when the same magnitude of torsion was applied. These characteristics further justified the necessity for defining the sectional aspect ratio effects on member performance, if the members are designed for earthquake-resistant purposes.

To quantify the interaction between the normalized bending and torsional strengths so that adequate design references can be established, the information shown in Fig. 11 is further approximated using the following expression:

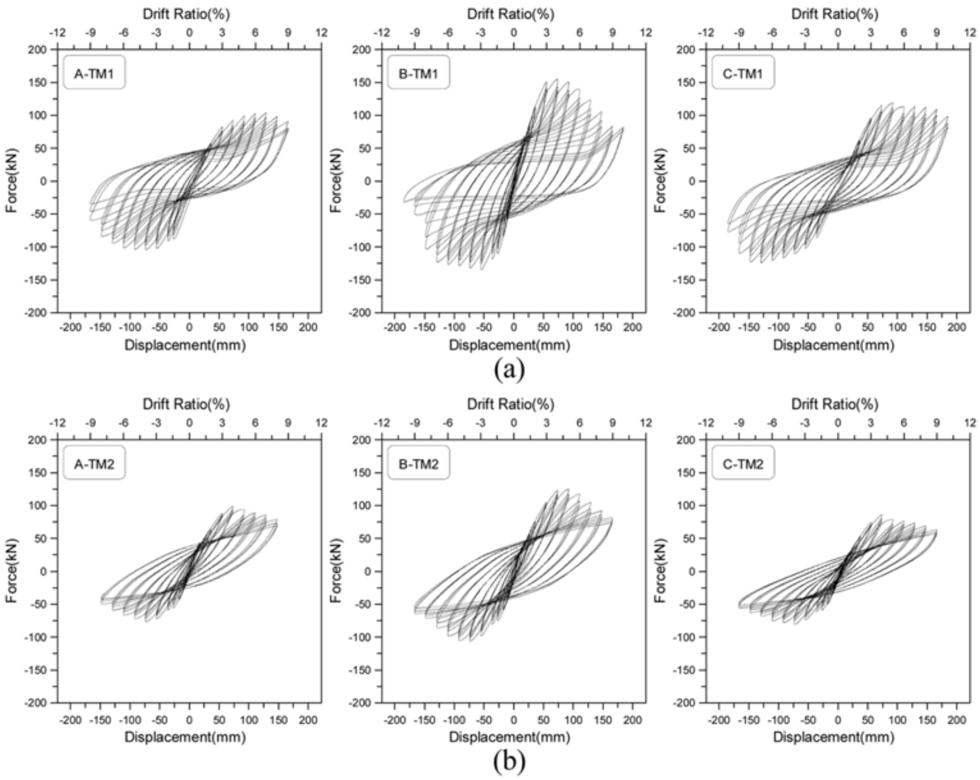


Fig. 10 Hysteretic relationships for members subjected to various load combinations: (a) bending with smaller torsion; (b) bending with larger torsion

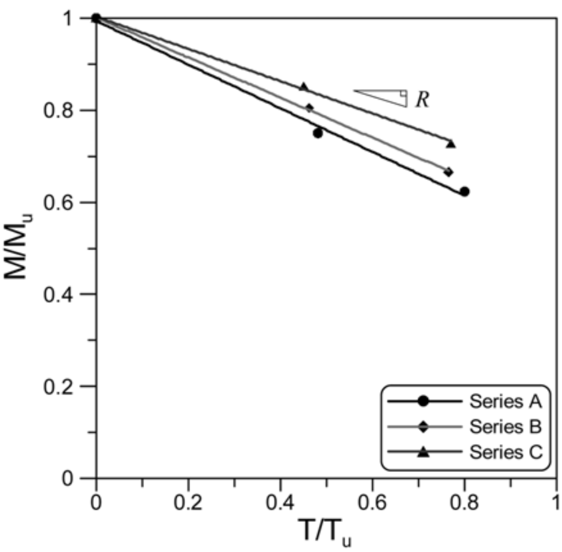


Fig. 11 Relationships between the normalized flexural and torsional strengths for members with various aspect ratios

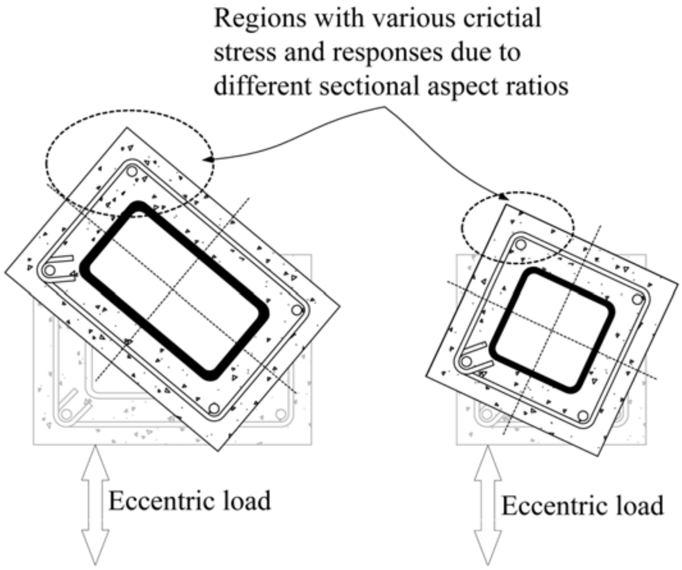


Fig. 12 Different flexural-torsional responses for members with various sectional aspect ratios

$$\frac{M}{M_u} = 1 - R\frac{T}{T_u} \tag{1}$$

In which, *Mu* and *Tu* are the flexural and torsional strengths of the sections, *M* and *T* are the achievable flexural and torsional strengths in the combined loads, respectively. *R* is an interaction coefficient accounting for the influence of the sectional aspect ratios. The values of *Mu* and *Tu* can be evaluated using the following expressions:

$$M_u = M_s + M_{rc} \tag{2}$$

$$T_u = 2\left[\frac{t\sigma_y A_m}{\sqrt{3}} + \frac{A_o A_t f_{ty}}{s}\right] \tag{3}$$

In which, M_s and M_{rc} are the flexural strength of the steel tube and the reinforced concrete, respectively. In Eq. (3), t, and σ_y are the thickness and the yield strength of the steel tube, A_m is the area bounded by the centerline of the steel tube; s, f_{ty}, A_t are the spacing, the yield strength, the cross-sectional area of the stirrup, and A_0 is the area bounded by the shear flow path in the reinforced concrete.

As shown in Fig. 13, the interaction coefficient, R, and the sectional aspect ratios, *D/B*, of the members can be linearly correlated. This relationship can be expressed as follows:

$$R = 0.477\frac{D}{B} \tag{4}$$

Therefore, the interaction between bending and torsion in the combined loads can be evaluated using the following expression:

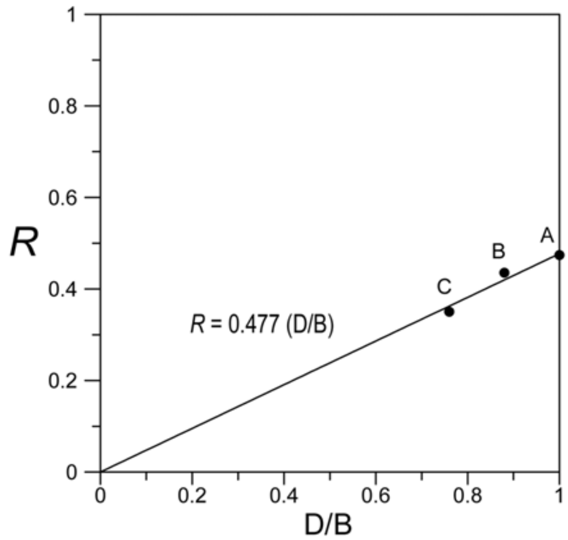


Fig. 13 Relationship between the interaction factor and the sectional aspect ratios

$$\frac{M}{M_u} = 1 - \left(0.477\frac{D}{B}\right)\frac{T}{T_u} \tag{5}$$

The above information provides a simple yet efficient approach for estimating the flexural-torsional performance of high strength thin-walled composite members. This expression can be used for engineering practice for members subjected to combined load coupled with torsion less than 0.8 T_u, and be further refined when more test information becomes available.

6. Conclusions

This paper presented test information on high strength thin-walled composite members subjected to combined bending and torsion. The relationships between member performance and the aspect ratios of the composite sections were evaluated. Test results showed that the composite member's torsional strength could be approximated using a series of linear segments and evaluated using the superposition of the component steel and reinforced concrete responses. The test results also showed that the strength deterioration rates of thin-walled composite members subjected to combined bending and torsion were closely related to the aspect ratios of the sections. An interaction expression between the bending and torsion for high strength thin-walled composite members was proposed for engineering practice references.

Acknowledgments

This study was partially supported by the National Science Council of the Republic of China under Grant No. NSC 95-2221-E-008-099, which is gratefully acknowledged.

References

Boyd, P.F., Cofer, W.F. and Mclean, D.I. (1995), "Seismic performance of steel-encased concrete columns under flexural loading", *ACI Struct. J*., **92**(3), 355-364.

Chen, C.C., Li, J.M. and Weng, C.C. (2005), "Experimental behaviour and strength of concrete-encased composite beam-columns with T-shaped steel section under cyclic loading", *J. Constr. Steel Res.*, **61**(7), 863-881.

Elchalakani, M., Zhao, X.L. and Grzebieta, R. (2002), "Tests on concrete filled double-skin (CHS outer and SHS inner) composite short columns under axial compression", *Thin-Wall. Struct*., **40**(5), 415-441.

Han, L.H., Yao, G.H. and Zhao, X.L. (2004), "Behavior and calculation on concrete-filled steel CHS (circular hollow section) beam-columns", *Steel Compos. Struct*., **4**(3), 169-188.

Hossain, K.M.A. and Wright, H.D. (2004), "Flexural and shear behaviour of profiled double skin composite elements", *Steel Compos. Struct*., **4**(2), 113-132.

Hsu, H.L. and Wang, C.L. (2000), "Flexural-torsional behavior of steel reinforced concrete members subjected to repeated loading", *Earthq. Eng. Struct. D.*, **29**(5), 667-682.

Hsu, H.L. and Liang, L.L. (2003), "Performance of hollow composite members subjected to cyclic eccentric loading", *Earthq. Eng. Struct. D*., **32**(3), 443-461.

Hsu, H.L. and Tsao, J.W. (2007), "Flexural-torsional performance of thin-walled steel hollow box columns subjected to a cyclic eccentric load", *Thin-Wall. Struct.*, **45**(2), 149-158.

Ishizawa, T., Nakano, T. and Iura, M. (2006), "Experimental study on partially concrete-filled steel tubular columns", *Steel Compos. Struct*., **6**(1), 55-69.

Lam, D. and Williams, C.A. (2004), "Experimental study on concrete filled square hollow sections", *Steel Compos. Struct*., **4**(2), 95-112.

Legeron, F. and Paultre, P. (2000), "Behavior of high-strength concrete columns under cyclic flexure and constant axial load", *ACI Struct. J*., **97**(4), 591-601.

Mirza, S.A. and Skrabek, B.W. (1991), "Reliability of short composite beam-column strength interaction", *J. Struct. Eng*. ASCE, **117**(8), 2320-2339.

Mo, Y.L., Jeng, C.H. and Perng, S.F. (2001), "Seismic shear behavior of rectangular hollow bridge columns", *Struct. Eng. Mech*., **12**(4), 429-448.

Ricles, J.M. and Paboojian, S.D. (1994), "Seismic performance of steel-encased composite columns", *J. Struct. Eng.* ASCE, **120**(8), 2474-2494.

Tao, Z., Han, L.H. and Zhao, X.L. (2004), "Behaviour of concrete-filled double skin (CHS inner and CHS outer) steel tubular stub columns and beam-columns", *J. Constr. Steel Res*., **60**(8), 1129-1158.

Tao, Z. and Han, L.H. (2006), "Behaviour of concrete-filled double skin rectangular steel tubular beam-columns", *J. Constr. Steel Res*., **62**(7), 631-646.

Tokgoz, S. and Dundar, C. (2008), "Experimental tests on biaxially loaded concrete-encased composite columns", *Steel Compos. Struct*., **8**(5), 423-438.

Uenaka, K. and Kitoh, H. (2008), "Concrete filled double skin tubular members subjected to bending", *Steel Compos. Struct*., **8**(4), 297-312.

Yang, C., Cai, J., Wu, Y., He, J.G. and Chen, H.F. (2006), "Behaviors of box-shape steel reinforced concrete composite beam", *Struct. Eng. Mech*., **22**(4), 419-432.

Zhao, X.L. and Grzebieta, R. (2002), "Strength and ductility of concrete filled double skin (SHS inner and SHS outer) tubes", *Thin-Wall. Struct*., **40**(2), 199-213.

CC