# IMPROVING SEISMIC PERFORMANCE OF HOLLOW COMPOSITE MEMBERS SUBJECTED TO ECCENTRIC CYCLIC LOADS

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**ABSTRACT :**
Hollow composite members possess high strength/mass ratios and sufficient ductility, thus are widely used in buildings and bridges designed for earthquake-resistant purposes. For structures subjected to eccentric cyclic loads, torsion and combined loading coupled with torsion are usually observed on the structural members. These loads often induce unexpected structural responses causing premature failures of the composite members and undesirable structural performance in the inelastic stages. This study is focused on the improvement of seismic performance of hollow composite members subjected to eccentric cyclic loads. Sixteen composite members composed of encased steel tubes and high-strength reinforced concrete with inclined bars were fabricated for testing. Structural responses, such as strength and energy dissipating capacity, were compared to evaluate the member performance. The test results showed that the strength of members with inclined bars were significantly increased when subjected to torsion and combined loading coupled with torsion. Enhancement in energy dissipation further validated the applicability of incline bars to the performance improvement of the hollow composite members.

**KEYWORDS:**
Hollow composite members, eccentric cyclic loads, seismic performance

## 1. INTRODUCTION

Hollow composite members possess high strength/mass ratios and sufficient ductility, thus are widely used in buildings and bridges designed for earthquake-resistant purposes (Zahn et al. 1990 ). In such designs, the member stiffness can be effectively enhanced by the comprising reinforced concrete to reduce structural deformation. Furthermore, performance of members, such as ductility, can be sustained when encased structural steel with adequate sectional details are adopted. Currently, study of composite member behavior is mostly focused on the response under axial load, bending moment and their combinations (Galano and Vignoli 2000; Ricles and Paboojian 1994). For designs according to such concerns, the members are required to place closely spaced stirrups at the member ends so that confined zone requirements can be satisfied.

However, for structures subjected to earthquake excitation, multi-directional loads, such as torsion and combined loads coupled with torsion, will be induced on the structural members. In such cases, unexpected premature diagonal cracks in structural members, particularly the regions in member's mid-span, due to torsion-induced shear will occur, because those areas originally possess less torsional resistance (Ali and White 1999; Hsu and Wang 2000; Mo et al. 2000; Koutchoukali and Belarbi 2001). Therefore, a remedy to improve the member's torsional resistance so that the seismic performance of member during the inelastic stages can be sustained is essential.

This study focused on the seismic performance improvement of hollow composite members subjected to eccentric cyclic loads. A series of composite members composed of encased steel tubes and high-strength reinforced concrete with inclined bars placed in the members' center portions were fabricated for testing.

Member performance was evaluated using the test information. Energy dissipation capacity of members strengthened with inclined bars was compared to validate the effectiveness of the proposed strengthening method.

## 2. EXPERIMENTAL PROGRAM

### *2.1 Specimens*

In order to investigate the effect of the proposed method in improving the member performance, sixteen composite members, including 12 strengthened and 4 unstrengthened members, were fabricated for testing. The composite sections were composed of 150mm x 150mm x 4.5mm steel tubes and high strength reinforced concrete. Dimensions for all composite sections were 350mm x 350mm. The effective length of the members was 1650 mm. Reinforced concrete was composed of four #6 deformed bars in the longitudinal direction, and #3 deformed bars laterally. Yielding stress of the steel tubes and the compressive strength of the concrete were 351 MPa and 55.2 MPa, respectively.

Stirrup spacings for the confined and unconfined zones were 75 mm and 150 mm, respectively. Inclined bars were made from #2, #3, and #4 deformed bars, respectively, by cold-bending the bars at 90 degree. The inclined bars were placed at the sections' four sides in the center portions of the composite members. These arrangements were designed to improve the torsional rigidity of member segments originally possessed less resistance, so that premature cracks could be delayed until members reached desired deformation. The specimen details and the member categorization were shown in Figure 1 and listed in Table 1, respectively.

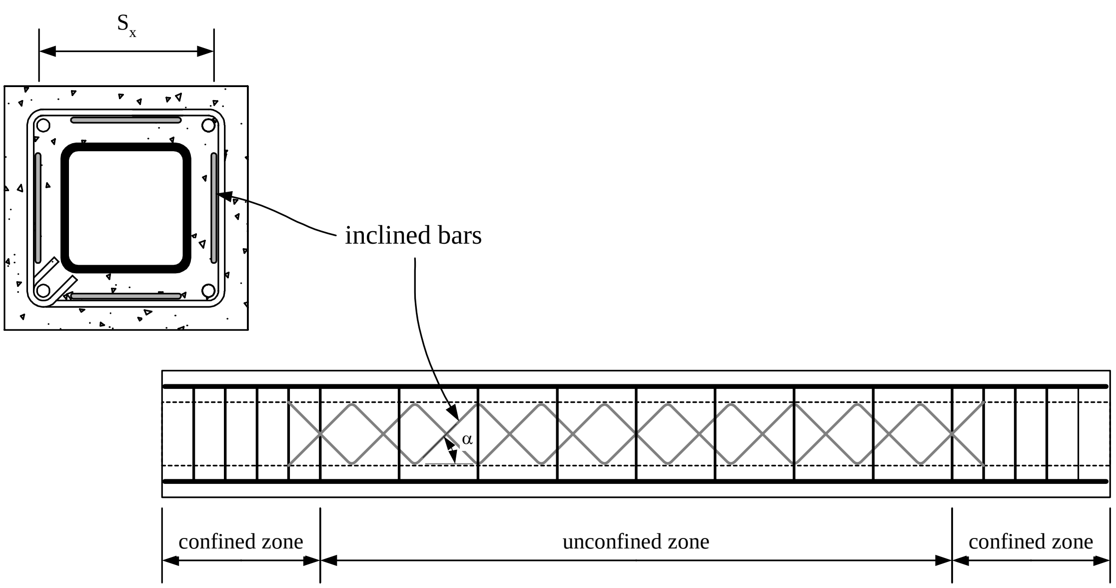


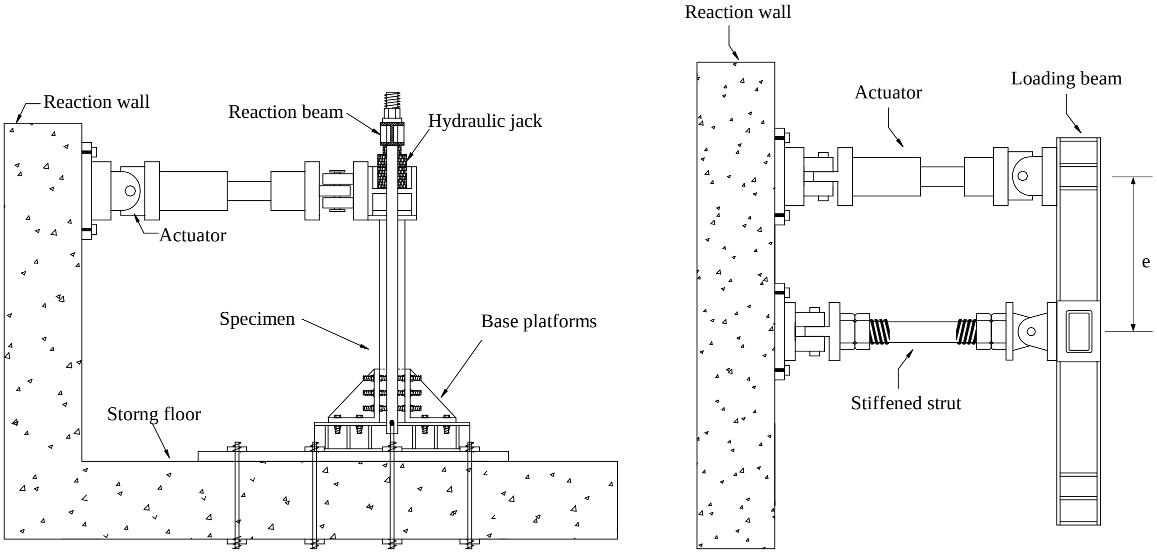

Figure 1 Specimen details

Table 1 Specimen categorization

| Specimen | Inclined bars | Loading type | Eccentricity (e) (mm) |
|---|---|---|---|
| MP-0 | N.A. | Axial load + Bending | 0 |
| MP-2 | #2 | | |
| MP-3 | #3 | | |
| MP-4 | #4 | | |
| T-0 | N.A. | Torsion | 920 |
| T-2 | #2 | | |
| T-3 | #3 | | |
| T-4 | #4 | | |
| TM46-0 | N.A. | Axial load + bending + torsion | 460 |
| TM46-2 | #2 | | |
| TM46-3 | #3 | | |
| TM46-4 | #4 | | |
| TM92-0 | N.A. | Axial load + bending + torsion | 920 |
| TM92-2 | #2 | | |
| TM92-3 | #3 | | |
| TM92-4 | #4 | | |

### *2.2 Test Set-up*

Four types of combined loads were used to investigate the member responses under earthquakes. They were combined axial load and bending, pure torsion, combined axial load and lateral cyclic load with small eccentricity, and combined axial load and lateral cyclic load with large eccentricity. These arrangements generated various combinations of axial load, bending and torsion to assess the members' seismic performance. The axial load was generated using a double-action hydraulic jack pushing against a stiffened reaction beam. Pure torsion and combined bending and torsion were generated by the combination of a stiffened strut and a servo-controlled hydraulic actuator. The test set-up is shown in Figure 2. Lateral load was generated by a series of prescribed cyclic displacement commands. The loading history is shown in Figure 3.




(a) (b)

Figure 2 Test setup: (a) side view; (b) top view

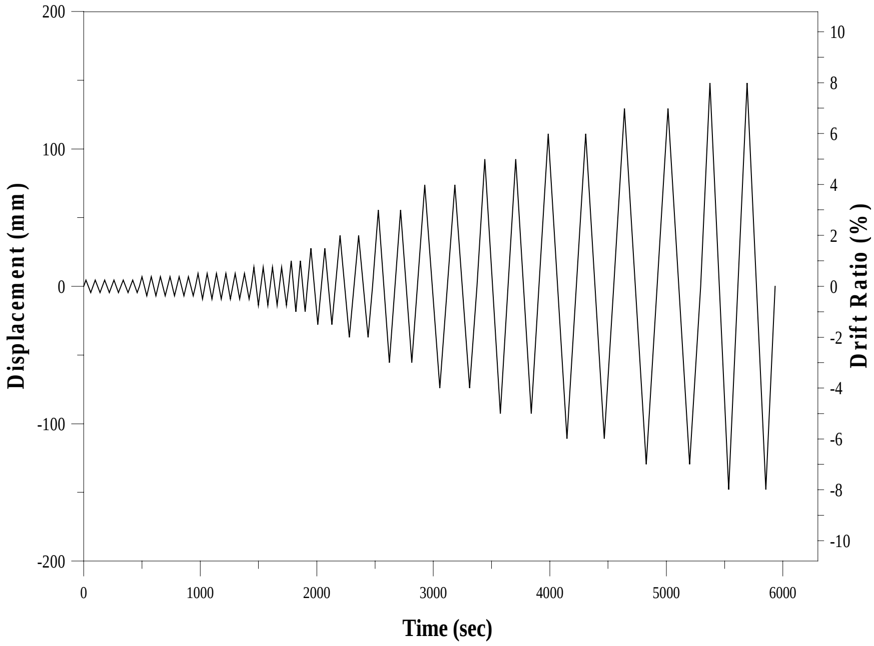
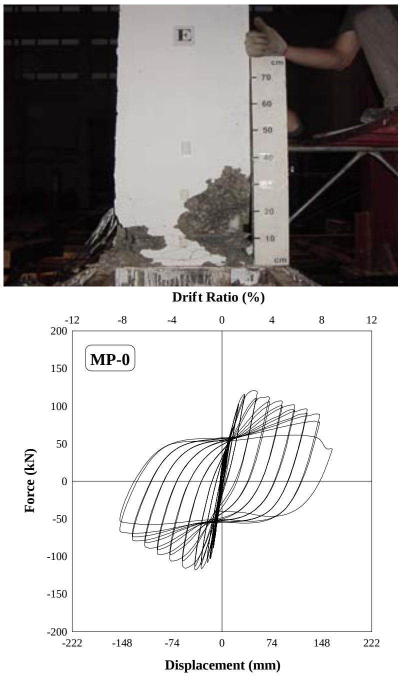



Figure 3 Loading history

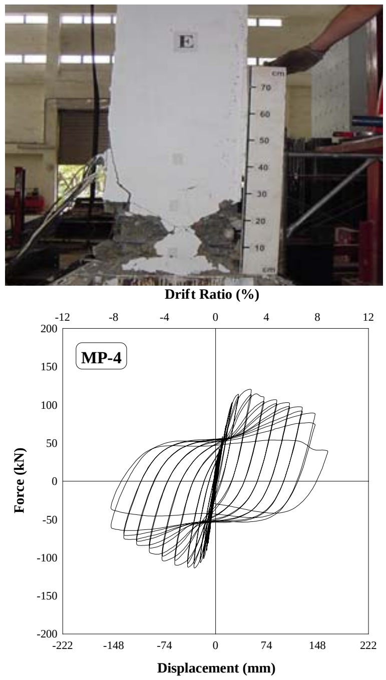
## 3. TEST RESULTS AND INTERPRETATIONS

### *3.1 Failure Modes*

Various failure patterns were observed in members subjected to bending, torsion, and their combinations. For members failed in flexural loads, the damaged regions were concentrated in the member bottoms where well-confined zones were located. Flexural cracks with increasing magnitudes were observed when the member deformation was increased. Plastic hinges formed at large deformation resulted in major strength deterioration when the members reached the ultimate stages. It was observed in this test series that the failure patterns for members strengthened or unstrengthened with inclined bars, as shown in Figure 4, were the same. It can thus be concluded from this phenomenon that the addition of inclined bars did not affect the flexural behavior of the original member. Therefore, no further re-analysis of the member's stiffness is necessary. For members subjected to pure torsion, diagonal cracks were observed in the center portions of the members. Cross diagonal cracks were exhibited and widened when the magnitudes of the cyclic loads increased. Damaged regions concentrated and deteriorated in the less-confined regions leading to major strength reduction when the members reached the ultimate stages. The failure modes of members subjected to torsion are shown in Figure 5.

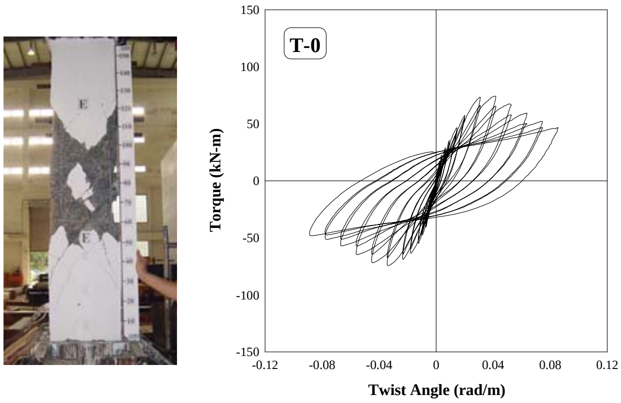


(a)

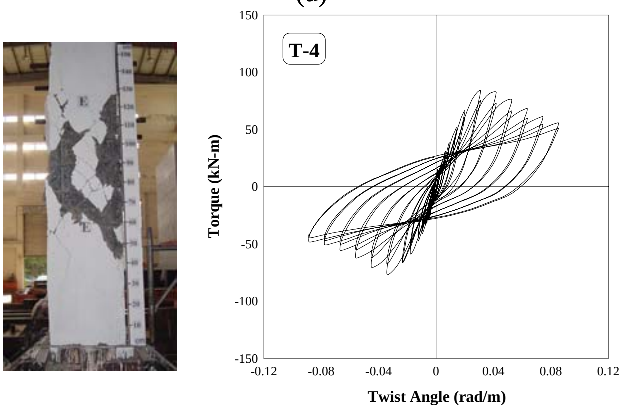


(b)

Figure 4 Failure patterns for members subjected to combined axial load and bending:
(a) unstrengthened member; (b) strengthened member



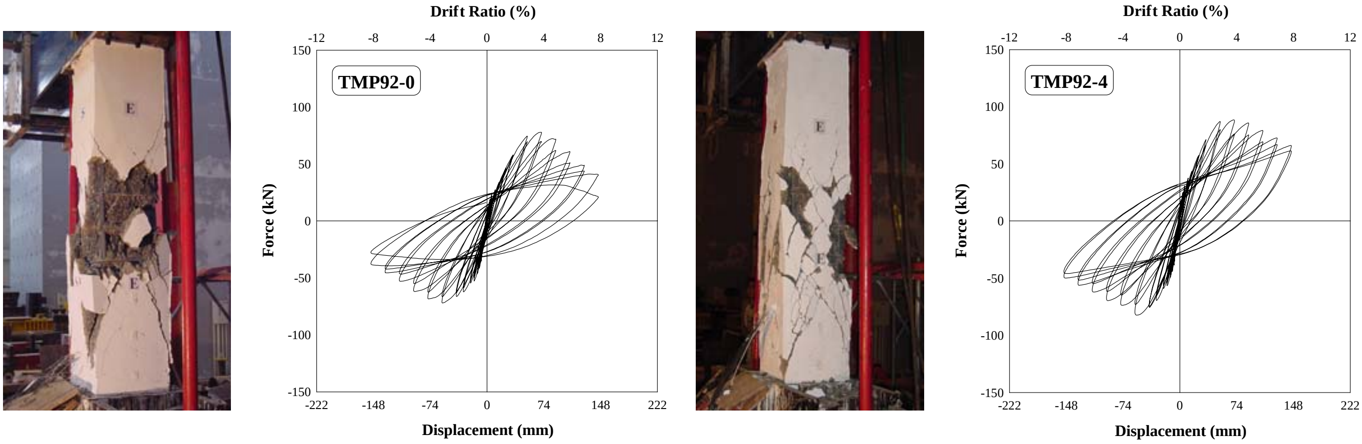
(a)



(b)

Figure 5 Failure patterns for members subjected to torsion:
(a) unstrengthened member; (b) strengthened member

Failure patterns for members subjected to combined bending and torsion varied when the magnitudes of eccentricity was altered. For members tested under lateral load with small eccentricity, flexural cracks were first observed at the member bottoms. Subsequent diagonal cracks developed and interacted with the existing flexural cracks, resulted in the shifting of the damaged regions from the member bottoms toward the member centers. In this test series, failure patterns were still governed by the flexural loads. For members subjected to lateral load with large eccentricity, diagonal cracks were first observed in the member centers, and then followed by the occurrence of the flexural cracks. Similar damage pattern due to combination of flexural and diagonal cracks, as observed in previous loading case, was observed, except that the extent of damage and the reduction of member performance in the latter case were severer. These phenomena validated the significance of torsion in affecting the seismic performance of composite members. Figure 6 compares the failure modes for strengthened and unstrengthened members subjected to various load combinations.




(a) (b)

Figure 6 Failure patterns for members subjected to combined loads:
(a) unstrengthened member; (b) strengthened member

### *3.2 Torsional Responses of Composite Members*

As described in the previous sections, performance of members under earthquake was greatly affected by the presence of applied torsion. In order to evaluate the member's seismic performance, the member's torsional resistance, including strength contribution due to added inclined bars, should be adequately defined. In general, the torsional strength of the strengthened members can be approximated by the superposition of those of the unstrengthened members, *Tsrc*, and the inclined bars, *Tx*, respectively. However, it was observed from the tests that responses of inclined bars located in regions subjected to tension and compression, respectively, were different. For example, inclined bars in both regions functioned to resist the applied torsion when the member was subjected to smaller twist angles. This phenomenon was altered when the member was loaded to larger twist angles, approximately 0.00815 rad/m. At this stage, compressive strains in the added inclined bars exhibited major relaxation, while the tensile strains of the inclined bars showed significant increase. This phenomenon can be attributed and related to the effectiveness of the bonding mechanism between the thin-walled concrete and the inclined bars. Therefore, an inclined-bar-strength-related effectiveness factor, $\lambda$, can be introduced to the evaluation of the strengthened members, as shown in Figure 6, and expressed as follows:

$$\begin{aligned} T_{srcx} &= \mathrm{T_{src}} + \lambda \mathrm{T_x} \\ &= \mathrm{T_{src}} + 2\lambda \mathrm{A_x f_{yx} S_x} \sin\alpha \end{aligned} \tag{1}$$

in which, $T_{srcx}$ and $T_{src}$ are the torsional strengths of the strengthened and unstrengthened members, $A_x$ and $f_{xy}$ are the cross-sectional area and yield strength of the inclined bars, $S_x$ is the distance between the inclined bars, and $\alpha$ is the inclined angle of the inclined bars, which is 45 degree in this study. Table 2 lists the torsional strengths of members strengthened with various inclined bars. It is found from the test results that the torsional strengths of the strengthened members were significantly enhanced, approximately 12% to 16%. The effectiveness factor, $\lambda$, for the #2, #3, and #4 bars were 1.00, 0.924, and 0.620, respectively, calibrated from test results.

Table 2 Torsional strength of members

| Specimen | $T_{src}$ $(kN-m)$ | $T_x$ $(kN-m)$ | $T_{srcx}$ $(kN-m)$ | $\lambda$ |
|---|---|---|---|---|
| T-0 | 66.789 | — | 66.789 | — |
| T-2 | 66.789 | 5.613 | 72.402 | 1.000 |
| T-3 | 66.789 | 9.939 | 76.728 | 0.924 |
| T-4 | 66.789 | 19.243 | 86.032 | 0.620 |

### *3.3 Energy Dissipation*

In order to further define the effectiveness of the proposed method in improving the flexural-torsional performance of members, the energy dissipation capacities of members subjected to cyclic eccentric loads were evaluated. The energy dissipation is defined by the cumulative area in the hysteretic loops when the member's strength drops to 80% of the ultimate strength of the unstrengthened members. Figure 7 shows the relationships between the member strength and the cumulative energy dissipation. It can be observed from the comparisons that the energy dissipation capacities of members strengthened with inclined bars are higher than those of the unstrengthened ones. Further comparisons on the performance enhancements of strengthened members subjected to loads with various eccentricities revealed that the efficiency of the inclined bars in improving member performance was higher when structures were subjected to loads with higher torsion/bending ratios.

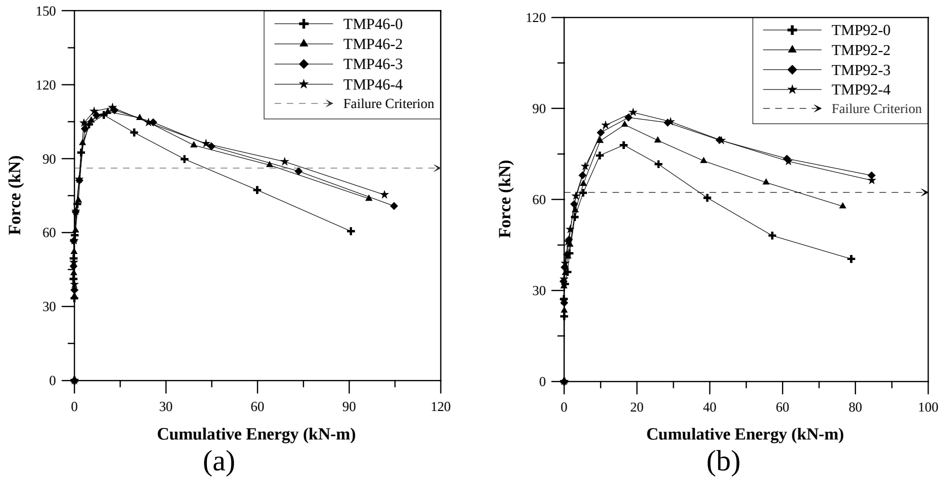



Figure 7 Relationships between member strength and cumulative energy dissipation: (a) members subjected to loads with smaller eccentricity; (b) members subjected to loads with larger eccentricity

## 4. CONCLUSIONS

This paper investigated the flexural-torsional behavior of hollow composite members subjected to eccentric cyclic loads. A series of composite members strengthened with inclined bars were tested under various combinations of axial load, bending and torsion. Strength and the energy dissipation capacity of members were compared to evaluate the effectiveness of the proposed method in improving the members' seismic performance.

The test results showed that the strength of members with inclined bars were significantly increased when subjected to torsion and combined loading coupled with torsion. Enhancement in energy dissipation further validated the applicability of the incline bars to the performance improvement of the hollow composite members.

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