# TORSIONAL EFFECTS ON SEISMIC PERFORMANCE OF SQUARE vs. CIRCULAR RC BRIDGE COLUMNS

A. Belarbi[1], Q. Li[2], and S. Suriya Prakash[3]

## Abstract

Reinforced concrete (RC) bridge columns could be subjected to combined flexural, axial, shear, and torsional loading during earthquake excitations. This combination of seismic loading can result in complex flexural and shear failure of bridge columns. Several researchers have investigated and proposed various models for predicting seismic performance; however, knowledge of the interaction between flexure, shear, and torsion in RC bridge columns is still limited. An experimental study is being conducted at Missouri S&T to understand the behavior of circular and square RC columns under combined loading including torsion. The main variable being considered is the ratio of torsion-to-bending moment (T/M). The differences in behavior between RC columns of square and circular cross section under combined loading are discussed in this paper. The main difference between the behavior of circular and square sections under combined loadings including torsion is related to confinement characteristics due to transverse reinforcement arrangement as well as warping effect in square cross sections due to torsion. In particular, the effect of cross-sectional shape on hysteretic torsional and flexural response, damage distribution, and ductility characteristics under combined flexure and torsional moments are discussed.

## Introduction

RC bridge columns can be subjected to multi-directional ground motions which result in the combination of axial force, shearing force, flexural and torsional moments. The addition of significant torsion is more likely in skewed or horizontally curved bridges, bridges with unequal spans or column heights, and bridges with outrigger bents. In addition, structural constraints due to a rigid decking, movement of joints, abutment restraints, and soil conditions also lead to combined loading effects. This combination of seismic loading can result in complex flexural and shear failure of bridge columns. Moreover, the cross-sectional details also affect the seismic behavior of RC bridge columns, such as damage distribution and ductility characteristics. The effect of cross section on the behavior of RC columns under combined loading including torsion is investigated. Test results of four square and four circular columns under cyclic flexure and shear, pure cyclic torsion, and combined cyclic flexure and shear and torsion are presented and discussed.

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[1]Distinguished Professor, [2,3] PhD Candidate, Missouri University of Science & Technology, USA.

## Previous Research

Several experimental studies have been performed to investigate the behavior of columns under bending and shearing with and without axial compression. There are rational and accurate models available for analyzing the interaction between axial compression and flexure for columns. Park and Ang (1985), Priestly and Benzoni (1996), Priestly et al. (1998) and Lehman et al. (1998) have all investigated and proposed various models for predicting the seismic response under flexure. However, knowledge of the interaction between flexural and torsional moments in behavior of RC bridge columns is limited. Few researchers have investigated the effects of combined loading on the seismic performance of bridge columns. The effect of combined flexure and torsion with compression has also not been studied intensively, and most of the tests were focused on static monotonic loads. Otsuka et al. (2004) conducted cyclic loading tests on nine rectangular RC columns under pure torsion, flexure and shear and different ratios of combined flexural and torsional moments. The authors found that the hysteresis loop of torsion was significantly affected by the spacing of the transverse reinforcement. Tirasit and Kawashima (2005) tested reinforced concrete columns under combined cyclic flexure and torsion with three different rotation-to-drift ratios and formulated a nonlinear torsional hysteretic model. The authors concluded that the flexural capacity of reinforced concrete columns decreases as the rotation-drift ratio increases and the damage tends to occur above the flexural plastic hinge region. Recently, Belarbi et al. (2008) presented a state of the art report on behavior of RC columns under combined loadings and scope for further research. They found that the effect of degradation of concrete strength in the presence of shear and torsional loads and confinement of core concrete due to transverse reinforcement significantly affected the ultimate strength of concrete sections under combined loading. They also suggested developing simplified constitutive models to incorporate softening and confinement effects. Prakash and Belarbi (2009) reported test results of several circular columns under combined loadings with different spiral ratios and T/M ratios. They reported that the effects of combined loading decrease the flexural and torsional capacity and affect the failure modes and deformation characteristics. They also concluded that the transverse reinforcement which might be adequate from the flexural design point of view could be inadequate under the presence of torsional loadings.

## Research Significance

A review of previous literature revealed that there have been few studies reporting on the behavior of RC circular and square columns under combined loading. The effect of cross-sectional shape on the interaction between flexure and torsional moment in the presence of axial compression has not been investigated adequately. The seismic behavior of circular and square columns is significantly different under combined loading due to the transverse reinforcement configurations and its effect on confinement of concrete, variation of shear stress flow, and warping effect. For circular columns, the spirals provide significant confinement to the core concrete which could result in higher strength. In addition, the locking and unlocking effect of the spiral significantly affects the behavior of circular columns due to their winding and unwinding action during cyclic loading. The spirals when unlocked during torsional loads cause significant spalling due to the reduced confinement effect on the concrete core. On the other hand, the locking effect of the spirals contributes more to the confinement of the concrete core resulting in higher strength and deformational capacity. However, for the square column, the efficiency of transverse reinforcement is somewhat lesser in confining the core concrete compared to circular columns. And there is no effect of locking and unlocking of transverse reinforcement. Thus, the behavior of circular and square columns needs to be clearly understood to avoid brittle failure modes under combined loading. In addition, shear stress flow due to combined torsional moment and shear force on the square and circular section causes difference in damage distribution and ductility characteristics. The results from the current study will provide useful contributions to establishing rational interaction diagrams for circular and square sections under combined loading and outline differences in behavior between the two models. The above information is essential to develop equations for interaction surfaces and design guidelines for circular and square RC columns subject to combined loading including torsion.

## Experimental Program

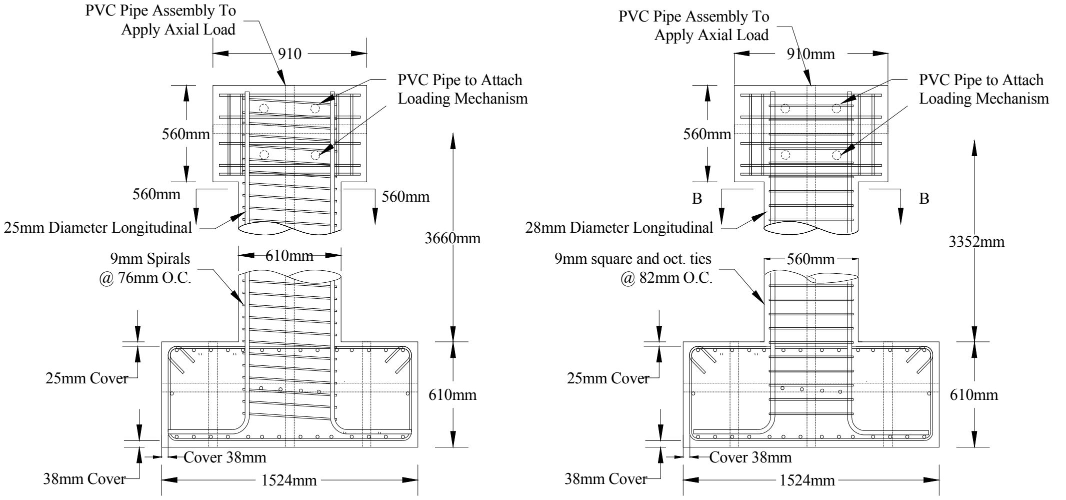
### Specimen Details

Half-scale test specimens were designed to be representative of typical existing bridge columns. Circular specimen dimensions and reinforcement layout are shown in Figure 1(a) and (c). Each of the circular RC column specimens had a diameter of 610 mm. and a clear concrete cover of 25 mm. Sectional details of square columns are shown in Figure 1 (b) and (d), which had a width of 550 mm and clear concrete cover of 38 mm. All these specimens were fabricated in the High Bay Structures Laboratory at Missouri University of Science and Technology (Missouri S&T). Both the circular and square columns had the same aspect ratio (H/D=6). The total height of the circular column was 4.5 m. with an effective height of 3.66m measured from the top of the footing to the centerline of the applied forces; the total height of the square columns was 4.2 m with an effective height of 3.35 m.

Table 1 Mechanical Properties of Concrete and Steel used in Columns

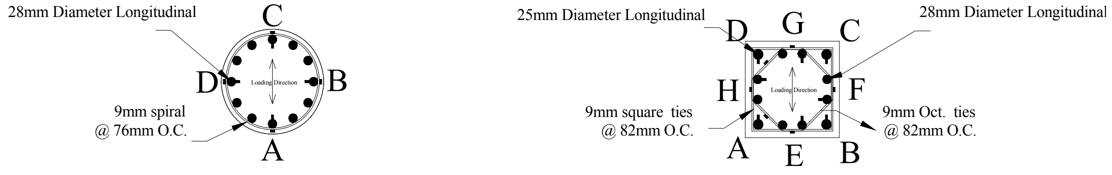
| PROPERTY | CIRCULAR COLUMNS | | | | SQUARE COLUMNS | | | |
|---|---|---|---|---|---|---|---|---|
| | H/D(6)-T/M(0) | H/D(3)-T/M(∞) | H/D(6)-T/M(0.2) | H/D(6)-T/M(0.4) | H/B(6)-T/M(0) | H/B(6)-T/M(∞) | H/B(6)-T/M(0.2) | H/B(6)-T/M(0.4) |
| Compressive Strength ($f'_c$, MPa) | 33.4 | 28.0 | 41.2 | 41.2 | 36.27 | 34.63 | 40.5 | 40.43 |
| Modulus of Rupture ($f_{cr}$, MPa) | 3.52 | 3.42 | 3.86 | 3.93 | 3.73 | 3.57 | 3.68 | 3.64 |
| Spiral Reinforcement Ratio (%) | 0.73 | 1.32 | 1.32 | 1.32 | 1.32 | 1.32 | 1.32 | 1.32 |
| Transverse Yield Strength ($f_{ty}$, MPa) | 450 | | | | 454 | | | |
| Longitudinal Yield Strength ($f_{ly}$, MPa) | 457 | | | | 512 | | | |

Typically, the axial load due to the superstructure dead load to bridge columns varies between 5% and 10% of the capacity of the columns. Therefore, an axial load equivalent to 7% of the concrete capacity of the columns for both circular and square columns was applied during testing. For circular columns, twelve No.8 bars (25 mm diameter) were designed as the longitudinal reinforcement. The longitudinal reinforcement ratio was 2.1% for all the circular specimens. Spiral reinforcement was designed as No.4 bars (12.5 mm diameter) with the pitch of 70 mm to obtain transverse reinforcement ratios of 1.32%. For square columns, four No.9 bars (28 mm diameter) and eight No.8 bars (25 mm diameter) were employed as the longitudinal reinforcement providing a longitudinal reinforcement ratio of 2.13% similar to the circular columns. To achieve better confinement of the core concrete, rectangular and octagonal No.3 rebars were used as transverse reinforcement with spacing of 83 mm. This resulted in a transverse reinforcement ratio of 1.32% similar to circular columns. In order to compare the seismic performance of square and circular columns, the cross sectional dimension were chosen in a way such that both the square and circular columns would have equal flexural and torsional capacities with similar longitudinal and transverse reinforcement ratio. Columns under combined loadings were tested under T/M ratios of 0.2 and 0.4. The reinforcement details of the test specimens are given in Table 1.



(a) End Elevation

(b) End Elevation



(c) Cross Section A-A

(c) Cross Section B-B

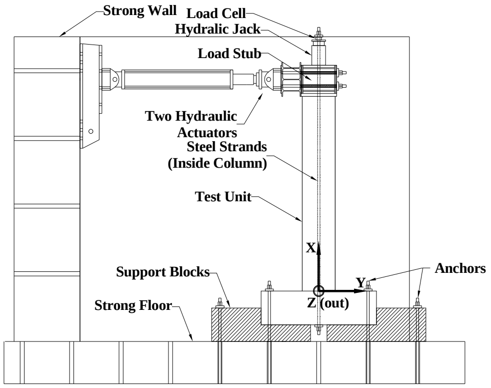
Figure 1 Circular and Square Column Sectional Details

Material Properties

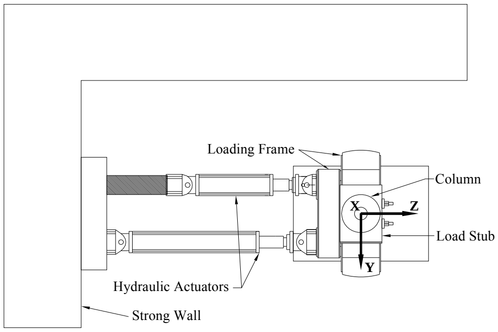
The concrete was supplied by a local Ready Mix Plant with requested 28-day design cylinder compressive strength of 34.5 MPa. Deformed bars were used in all specimens. The design yield strengths of transverse and longitudinal reinforcement are supposed to be 415 MPa. Standard tests for concrete compressive strength, modulus of rupture, and tension tests on steel coupons were conducted. The actual material properties of the circular and square columns on the day of the testing are given in Table 1.

Test Setup and Instrumentation

The axial load was applied by a hydraulic jack on top of the columns which transferred the load to the column via seven un-bonded high-strength pre-stressed steel strands. The strands all ran through a duct which was made of PVC tube in the center of the column and anchored to a steel plate underneath the test specimen. A target 7% axial load ratio was applied to simulate the dead load on the column in a bridge. Cyclic torsion, uniaxial flexure and shear, and combined flexure and shear and torsion were generated by controlling the two horizontal servo-controlled hydraulic actuators shown diagrammatically in Figure 2. Cyclic flexure and shear load were generated by applying equal forces in the same direction with the two actuators. Pure torsion was created by driving equal but opposite directional forces with the two actuators. Combined cyclic torsion and flexural moments were generated by applying different forces/displacements with each actuator. The ratio of the imposing flexural moment to torsional moment was controlled by maintaining the ratio of the forces or displacements in the two actuators. A number of instruments were used to measure the applied loads, deformations, and internal strains. The axial load in the un-bonded pre-stressed steel strands was measured by a load cell between the hydraulic jack and the top of the load stub. Two load cells were installed in the horizontal hydraulic actuators to measure the applied force. Electric strain gages were attached to the surface of the longitudinal and transverse reinforcement to measure strains in order to study the deformation of reinforcement under different loading conditions. The strain gauges were mounted at different heights along the whole column in various patterns based on different loading conditions.



(a) SIDE ELEVATION



(b) PLAN

Figure 2 Test Setup

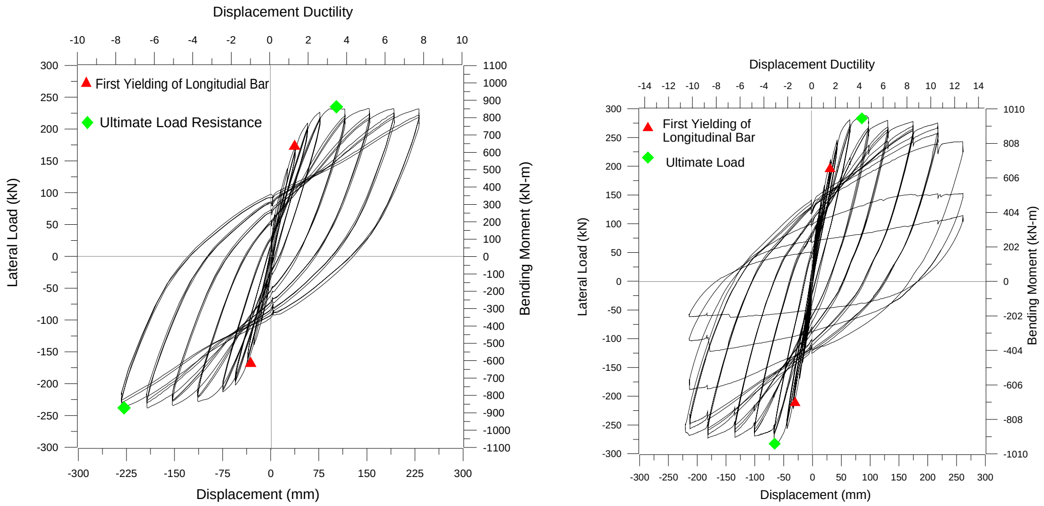
### Loading Protocol

Experimental testing was conducted in load control mode for all columns under flexure and shear, and combined flexure, shear and torsion loading conditions until the first yielding of the longitudinal bars. The load was applied in load control mode for circular columns at intervals of 25%, 50%, 75%, and 100% of the predicted yielding of the first longitudinal bar ($F_y$). The horizontal displacement corresponding to yielding of the first longitudinal bar was defined as displacement ductility one ($\mu_\Delta=1$). The circular column under pure torsion was loaded in load control mode at intervals of 25%, 50%, 75%, and 100% of the estimated yielding of the first spiral ($T_y$). The rotation corresponding to yielding of the first spiral was defined as twist ductility one ($\mu_\theta=1$). For square columns, the load control mode was imposed at intervals of every 10% of the predicted yielding of the first longitudinal bar ($F_y$) under flexure and shear and combined flexure, shear and torsion loading conditions. The square column under pure torsion was loaded at 10% intervals of the predicted yielding of the first transverse bar ($T_y$). More loading steps prior to yielding were implemented in the square column testing to obtain more data for establishing the influence of torsion on curvature of columns under flexure. After the first yield, the tests were performed in displacement control mode until the ultimate failure of the specimens at specific levels of ductility, meanwhile controlling the desired T/M ratios at the same time. Three cycles of loading were performed at each ductility level. The imposed pattern of three cycles was intended to give an indication of degradation characteristics. The loadings were applied along the direction A-C for the circular columns as shown in Figure 1c. The loading along the direction A-C and C-A are defined as positive and negative cycles, respectively. Similarly, for the square columns, the loadings were applied along the direction A-D as shown in Figure 1d. The loading along the direction D-A and A-D are defined as positive and negative cycles, respectively

## Test Results and Discussions

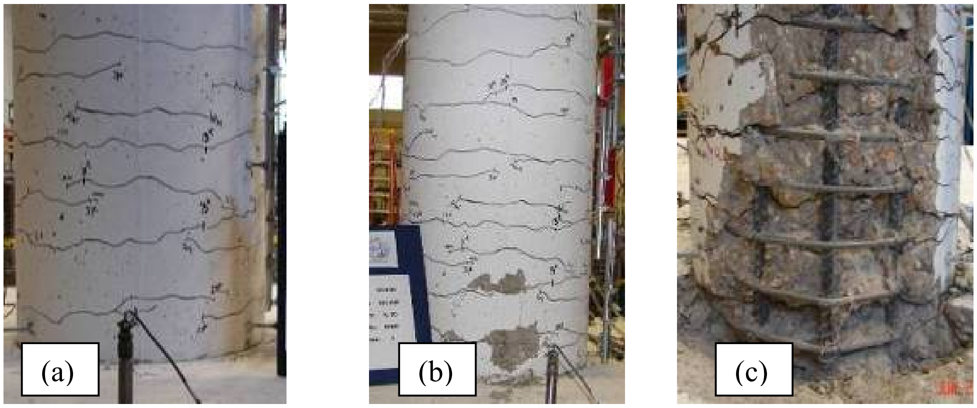
### Columns under Flexure and Shear

Circular Column: The column tested under flexure and shear began exhibiting flexural cracks near the bottom on side A and side C after cyclically loading the column to 50% of $F_y$. These cracks continued to grow and new cracks appeared on both sides of the column as higher levels of ductility were reached. The cover concrete started spalling at a drift of about 3.2%. Spacers were attached between the actuators and the column and the displacement was applied only in the A-C direction after ductility eight. The failure mode of the specimen began with the formation of a flexural plastic hinge at the base of the column, followed by core degradation, and finally by the buckling of longitudinal bars on the compression side at a drift of about 12.7%. The flexural hysteresis is shown in Figure 3 up to ductility level of eight. The flexural resistance was stable between 3% and 12.7% drift with nearly a constant flexural strength of 232.8 kN. During the last cycle of loading, a longitudinal bar started buckling while unloading, as shown in Figure 4c. The yielding zone of the longitudinal bars was about 610 mm from the base of the column. Longitudinal bars on sides ‘A’ and ‘C’ both reached the yield strain at the predicted ductility level one. The spirals remained elastic until a ductility level of six, after which they yielded. Soon after cracking and spalling at the location of the spiral gages, the spiral gages became non-functional.

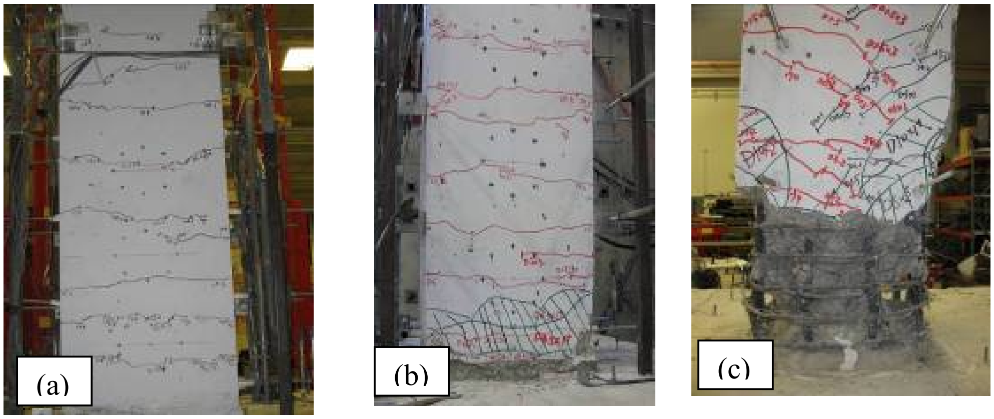


(a) (b)

Figure 3 Hysteresis Curves under Flexure and Shear (a) Circular and (b) Square



(1) Circular Columns



(2) Square Columns

Figure 4 Failure Modes of Columns under Flexure and Shear at (a) Longitudinal Bar Yield, (b) Ultimate, and (c) Final failure

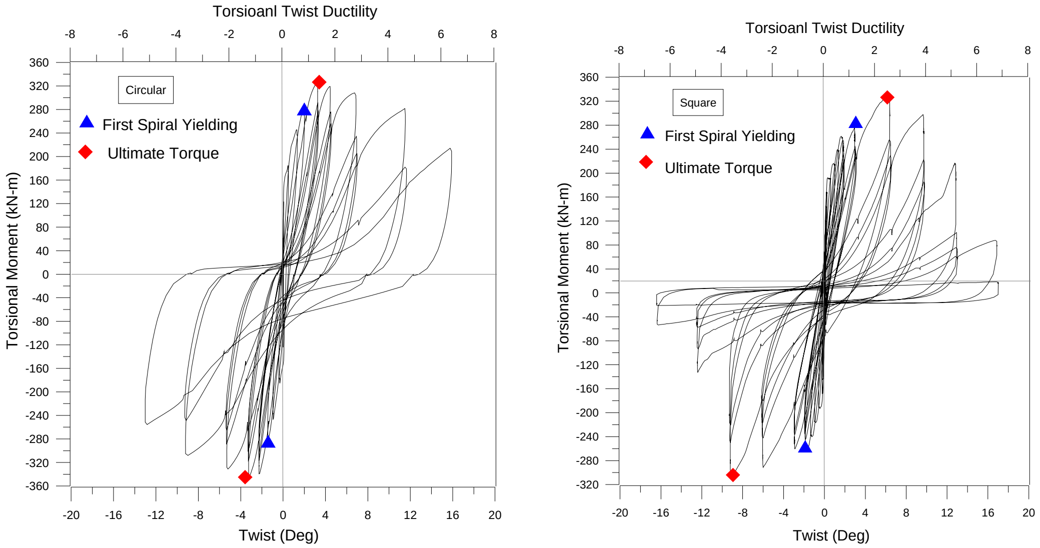
<u>Square Column:</u> The flexural hysteresis of the square column is shown in Figure 3b. The column tested under flexure and shear started to show flexural cracking near the bottom 400 mm above the footing on side AB and side CD after cyclically loading the

column to 40% of Fy. These cracks continued to develop and new cracks appeared on each side of the column in higher position with increasing levels of ductility. Subsequently, the cover concrete started to spall at a drift of about 2% when the column was loaded to ductility three. Application of ductility levels higher than ten were limited by the actuator stroke capacity. After this point, the displacements applied in the A-D direction (Negative) were limited to a smaller value of 210 mm. During the last cycle of ductility 12, almost all the longitudinal bars buckled while unloading as shown in Figure 4c. The yielding zone of the longitudinal bars was about 600 mm from the base of the column. Longitudinal bars on sides 'AB' and 'CD' both reached the yield strain at the predicted ductility level one. The square and octagonal transverse reinforcement remained elastic until a ductility level of eight, after which they yielded. The failure mode of the column began with the formation of a flexural plastic hinge with 580 mm height from the base of the column, followed by core concrete degradation due to crushing of concrete. The column finally failed by the buckling and breaking of longitudinal bars and rupturing of transverse bars on the compression side at a drift of about 8%. The progressing damage of the square column is shown in Figure 4.

## Columns under Cyclic Pure Torsion

In practice, pure torsion is rarely present in structural members. It usually occurs in combination with other actions often flexure and shear forces. And, understanding the behavior of members subjected to pure torsion is necessary for generalizing the analysis of a structural member under combined loadings. However, only very few studies have been reported on the behavior of RC circular and square sections under pure torsion.

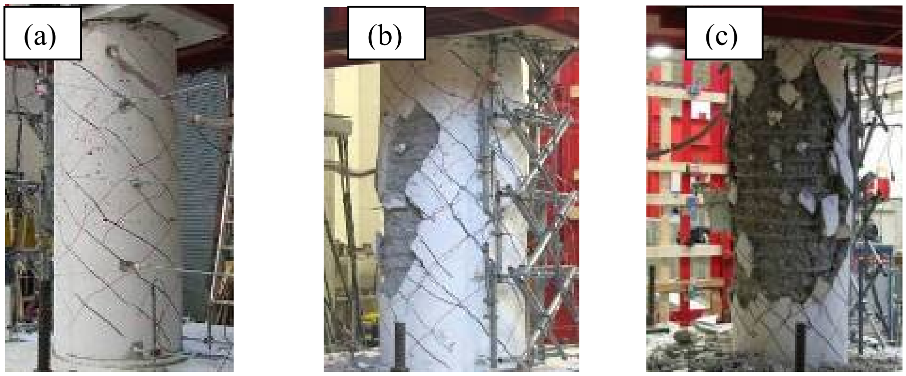
Circular Column: The torsional strength of a member depends mainly on the amount of transverse and longitudinal reinforcement, the sectional dimensions, and the concrete strength. In the post peak behavior, dowel action of longitudinal bars is also reported to significantly affect the load resistance at higher cycles of loading (Belarbi et al., 2008). The torsional hysteresis curve of the column tested under pure torsion is shown in Figure 5a. Under pure torsional loading, significant diagonal cracks started developing near mid- height on the column at lower levels of ductility (Figure 5a). The cracks lengthened when the applied torsion was increased. The progressing damage of the specimen is shown in Figure 6a. Soon after the yielding of spirals, spalling was observed. The angle of diagonal cracks was about 40 degrees relative to the cross section (horizontal) of the column. The post cracking stiffness was found to decrease proportionally with increase in the cycles of loading. The locking and unlocking effect of the spirals was observed in the negative and positive loading cycles. During the positive cycles of twisting, the spirals were unlocked which helped to cause significant spalling and reduced the confinement effect on the concrete core. On the other hand, during the negative cycles of loading, the spirals underwent locking and contributed more to the confinement of the concrete core. This effect is reflected in the unsymmetric nature of the observed hysteresis loop at higher levels of loading (Figure 5a). At higher ductility levels, the load resistance on the negative cycles was higher than that under positive cycles of loading due to the added confinement generated by the locking effect of the spirals. Though, the concrete cover spalled along the entire length of the column, significant spalling led to the formation of a torsional plastic hinge near mid-height of the column (Figure 6c). The damage pattern of the column under pure torsion was significantly different from that of column under flexure and shear.



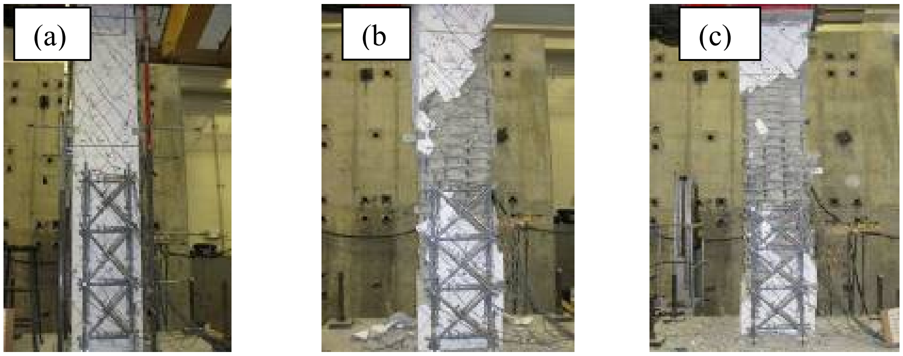
(a) Circular Column (b) Square Column

Figure 5 Torsional Hysteresis under Pure Torsion

Square Column: The torsional moment-twist hysteresis response of the column is shown in Figure 5b. The torsional moment -twist curves are approximately linear up to cracking torsional moment and thereafter become nonlinear with a decrease in the torsional stiffness. The post cracking stiffness decreased proportionally with increase in the cycles of loading. The torsional resistance increased significantly due to the longitudinal reinforcement contribution at higher load levels. Finally, the square and octagonal ties were broken in the plastic hinge zone. Under pure torsional loading, significant shear cracks started developing near mid-height on the column at lower levels of 60% $T_y$. The cracks developed in length and width when the applied torsional moment was increased. The diagonal cracks continued to form at an inclination of 40 to 42 degrees relative to the cross section (horizontal) of the column as the test progressed. Concrete spalling occurred at ductility one and the spalling region appeared along the column from bottom to top when the torsion loading reached ductility eight. At higher levels of loading, a plastic hinge formed near mid-height of the column due to significant concrete spalling. The damage pattern of column under pure torsion was significantly different from that of column under flexure and shear, which was concentrated near the middle of the column height instead of the typical flexural plastic hinge zone within one column cross sectional dimension from the base of the column. Typical damage progress of the columns with square and circular cross section under pure torsion is shown in Figure 6.



(1) Circular Column



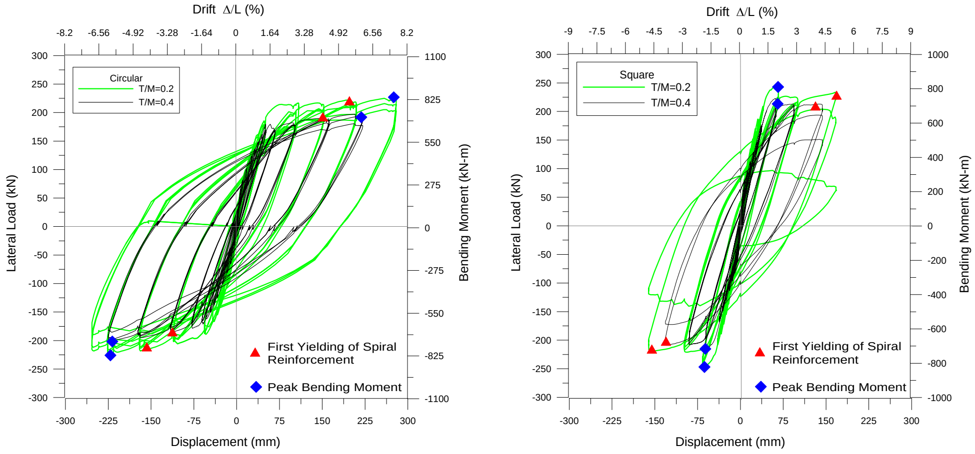
(2) Square Column

Figure 6 Damage of Column under Pure Torsion at (a) Yield (b) Peak Torsional moment and (c) Overall Failure

## Columns under Cyclic Combined Flexure, Shear, and Torsion

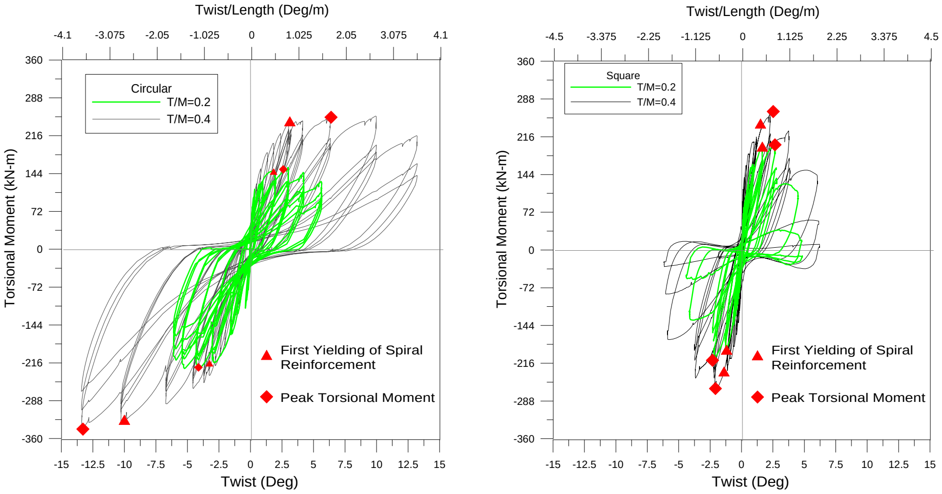
Two circular and two square columns with transverse reinforcement ratio of 1.32% were tested under combined flexure, shear and torsion by maintaining T/M ratios of 0.2 and 0.4. The results from tests on columns under flexure and shear and pure torsion were used as the benchmarks for analyzing the behavior of specimens under combined flexure, shear, and torsion.

Circular Columns: For the two columns tested under combined flexure and torsion, flexural cracks first appeared near the bottom of the column. The angle of the cracks became more inclined at increasing heights above the top of the footing with increasing cycles of loading and depending on the amount of T/M ratio. In all the columns, side ‘A’ of the column exhibited less damage compared to side ‘C’. The main reason for this is that side ‘A’ always experienced smaller displacements compared to side ‘C’ while applying the combined loading. In general, there are three failure modes possible under combined flexure, shear, and torsion for the concrete member reinforced with longitudinal and transverse reinforcement: completely under reinforced (longitudinal and transverse steel yield), partially over reinforced (only longitudinal steel yields or only transverse reinforcement yields), and completely over-reinforced (concrete crushing before steel yields). The flexural and torsional hysteresis behaviors of the column are shown in Figure 7 and Figure 8. The un-symmetric nature of the flexural envelops under combined flexure and torsion is due to both the locking and unlocking effect and the fact that one face is subjected to higher shearing stresses because the components of shear stresses from flexure and torsion are additive resulting in more damage and leading to less load resistance. In all columns under combined flexure and torsion, failure started due to severe combinations of shear and flexural cracks leading to progressive spalling of the concrete cover. The columns under combined loadings finally failed due to severe core degradation followed by buckling of longitudinal bars on side 'C'. The typical damage of circular column under combined flexure and torsional moments is shown in Figure 9.



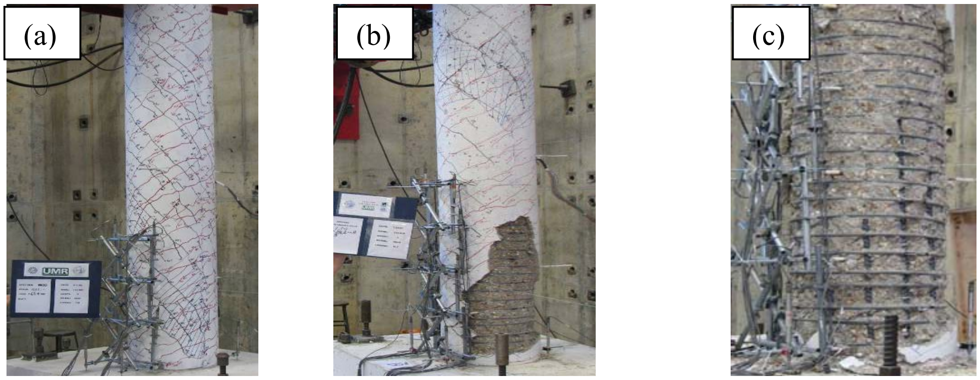
(a) (b)

Figure 7 Comparison of Flexural Hysteresis Behavior under Combined Loading
(a) Circular and (b) Square

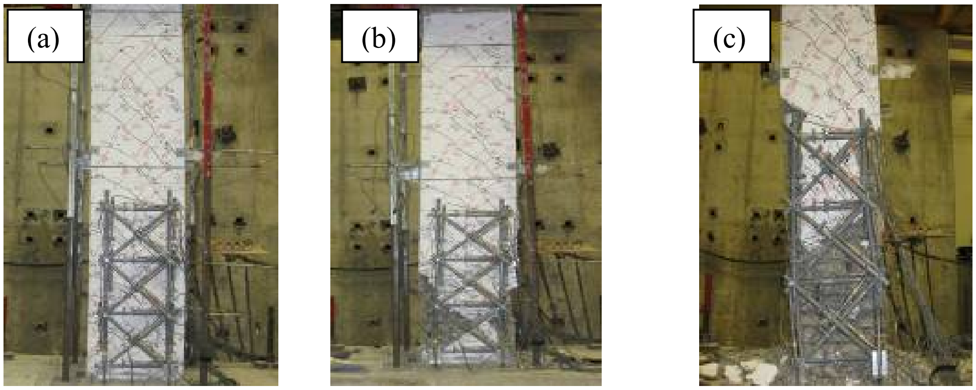


(a) (b)

Figure 8 Comparison of Torsional Hysteresis Behavior under Combined Loading (a) Circular and (b) Square



(a) Circular Column at T/M=0.4



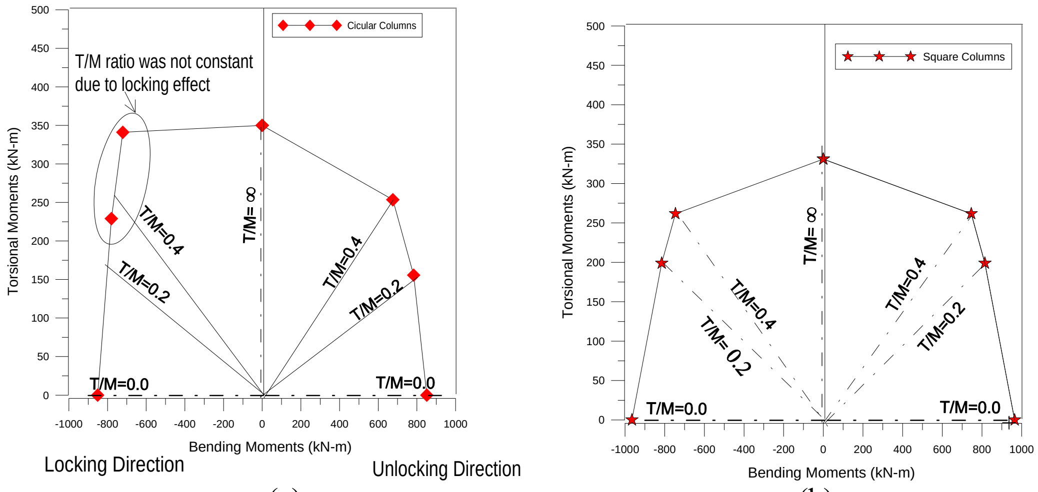
(a) Square Column at T/M=0.4

Figure 9 Comparison of Damages under Combined Loading at (a) Longitudinal Reinforcement Yield (b) Peak Torsional moment and (c) Overall Failure

Square Columns: For the two columns tested under combined flexure and torsion, flexural cracks first appeared near the bottom of the column at 40% of the yield strength, which is a smaller load level compared to the flexure and shear and pure torsion columns. The flexural and torsional hysteresis behaviors of the column are shown in Figure 7 and Figure 8. Strength and stiffness degradation were observed with increases in the loading cycles at each ductility level for the first two cycles, but less significant difference is seen between the curves of the second and third loading cycles. This indicates that the deterioration of the column capacities is substantial in the first loading cycle. It is clearly shown that due to the effect of combined loading, torsional and flexural strength reduces considerably according to the applied T/M ratio as observed in the circular columns. The flexural and torsional capacities as compared to the pure flexure and torsion tests were indeed found to decrease due to the effect of combined loading in this column. With increasing torsional and flexural moments, the angle of the cracks became more inclined at increasing heights above the top of the footing with increasing cycles of loading. The side 'BC' of the column exhibited more damage compared to side 'AD' in the column under combined flexure and torsion. The main reason for this is that side 'BC' always experienced larger shear stress compared to side 'AD' while applying the combined loading. The sequence and severity of damage of concrete and reinforcement lead to three different possible failure modes under combined flexure, shear and torsion as above for circular columns. Core degradation was observed up to a higher level of 1100 mm from the base of the column as compared to 560 mm for flexure and shear loading. This shows that the flexure and shear plastic hinge location changes due to the effect of torsion. However, the specific location of the plastic hinge should depend on the ratio of applied T/M ratio. The location of the plastic hinge shifted to higher location with increasing T/M ratios. Failure of the columns under combined loading, started due to severe combinations of shear and flexural cracks. The column finally failed due to buckling of longitudinal bars on side ‘AB’ and ‘CD’. Typical damage characteristics and failure sequence of the columns under combined flexure and torsion is shown in Figure 9.

## Effect of Cross Section Shape on Flexure-Torsion Interaction

Interaction diagrams between flexural and torsional moments are shown in Figure 10. The locking and unlocking effect of the spiral was significant in circular columns. It can be observed that in circular columns, the torsional strength was reached first and then flexural strength, while the square columns reached their torsional and flexural strength simultaneously. However, the failure sequence in all the specimens were in the order of flexural cracking, followed by shear cracking, longitudinal bar yielding, spalling of concrete cover, spiral yielding and then final failure by buckling of longitudinal bars after severe core degradation. It should be noted that the T/M ratio was close to the desired loading ratio in all the specimens till peak torsional moment. Soon after reaching the peak torsional strength, it was not possible to maintain the desired loading ratio as torsional strength was degrading much faster. Further, experimental research is in progress on behavior of square columns at Missouri S&T. Additional test results at different T/M ratios and further analysis would provide valuable information on the effect of warping and its significance on the torsion and flexural moment interaction diagrams.



(a) (b)

Figure 10 Torsion and Bending Interaction at Peak Torque (a) Circular and (b) Square

## Summary and Concluding Remarks

An experimental study on the effect of combined cyclic flexure and torsion on the behavior of circular and square reinforced concrete columns was presented. Based on the test results presented in this paper, the following conclusions can be drawn:

1) The failure of the circular and square columns under pure torsion was caused by significant diagonal shear cracking leading to the formation of a torsional plastic hinge at middle height of the column. The concrete cover spalled along the full height of the column.
2) The existence of torsion altered the damage patterns of reinforced concrete columns under combined loading. Due to the presence of high shear stresses from shear force and torsional moment, the inclined crack developed significantly resulting in early spalling of concrete cover even before the ultimate shear was attained.
3) The square and octagonal transverse reinforcement for square columns provided confinement to the core concrete similar to the spiral reinforcement for circular columns. This ensured that the square column under flexure and shear obtained nearly the same strength as circular columns. However, their influence on confinement of concrete core under combined loading needs to be investigated further.
4) The ultimate lateral load and displacement capacity of the columns deteriorates with increasing levels of torsion. Similarly, the decrease of T/M ratio resulted in the deterioration of the torsional moment and the ultimate twist capacity.
5) The locking and unlocking effect of spiral reinforcement significantly affected the failure modes of circular columns under combined torsional and bending moments.

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