BEHAVIOR OF RC BRIDGE COLUMNS UNDER CYCLIC FLEXURAL-TORSIONAL LOADINGS WITH MODERATE SHEAR

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ABSTRACT :

Reinforced concrete (RC) bridge columns are subjected to a combined flexural, axial, shear and torsional loading during earthquake excitations. This fact is particularly true for skewed and curved bridges, and bridges with unequal spans or column heights. This combination of geometrical irregularities with seismic loading can result in complex flexural and shear failure of RC bridge columns. An experimental study is being conducted to understand the behavior of RC circular columns under combined loadings. The main variables being considered are (i) the ratio of torsion to bending moment (T/M), (ii) the ratio of bending moment to shear (M/V), and (iii) level of detailing for high and moderate seismicity (low or high transverse reinforcement ratio). The results of four columns with low aspect ratio (height to diameter = H/D=3) tested under cyclic pure bending, cyclic pure torsion, and various levels of combined cyclic bending and torsion in the presence of moderate shear loading are presented in this paper. The effects of combined loading on the hysteretic load-deformation response, spiral and longitudinal reinforcement strain variations, and spalling/damage characteristics are discussed. Torsion-Bending interaction diagrams for tested columns are presented. Based on the test results, it is concluded that the flexural as well as torsional capacity is decreased due to the effect of combined loading and there is also a change in the failure mode and deformation characteristics. The experiments show that the torsional capacity does not change significantly due to the effect of moderate shear compared to the columns under low shear. However, there is a significant reduction in the deformation and energy dissipation capacity due to the application of moderate shear compared to the similar columns tested at low shear.

KEYWORDS: Bridges, RC columns, flexure, torsion, seismic design, combined loadings

1. INTRODUCTION

Reinforced concrete (RC) bridge columns can be subjected to torsional moments in addition to axial, bending and shear forces during earthquake excitations. The addition of torsion is more likely in skewed or horizontally curved bridges, bridges with unequal spans or column heights, and bridges with outrigger bents. Construction of bridges with these configurations is often unavoidable due to site constraints. In addition, multi-directional earthquake motions, significant vertical motions, and structural constraints due to a stiff decking, movement of joints, abutment restraints, and soil conditions may also lead to combined loading effects. This combination of seismic loading and structural constraints can result in complex flexural and shear failure of these bridge columns. There are rational models available for analyzing the interaction between axial compressions and bending. The behavior of columns under bending with and without axial compression has been extensively investigated by a number of researchers. Park and Ang (1985), Priestly and Benzoni (1996), Priestly et al. (1996), Lehman et al. (1998), and Kowalsky and Priestley (2000) have all investigated and proposed various models for predicting seismic performance behavior of circular columns under bending-shear loads.

Shear mode response involves low ductility and poor energy absorption characteristics, accompanied with extremely rapid strength, stiffness and physical degradation under cyclic displacements. The aspect ratio plays an important role in determining the behavior of columns dominated by flexure or by shear. For columns tested in single curvature, the aspect ratio is defined as the ratio of height (M/V=H) to diameter (D) of the column. Columns with higher aspect ratio are long and flexible and attract lesser load during earthquake motions. However, shorter and stiff columns attract much greater portion of the seismic input than more flexible columns. Bridge columns framing in to cap-beam at the top and into a continuous footing pedestal at the base results in shorter aspect ratio with fixed-fixed end condition. Shear failure in bridges have been very common in columns with low aspect ratios. Presence of torsion along with shear and bending increases the possibility of shear failure. The knowledge of interaction between bending, shear and torsion in behavior of RC bridge columns is limited. Very few experimental results are reported in the literature on the behavior of RC columns under combined loadings (Otsuka et al., 2004; Tirasit and Kawashima, 2005; Belarbi et al., 2008a; 2008b; and Suriya Prakash et al., 2008). Though there are few studies reporting on the behavior of circular columns under combined loadings, the behavior is not completely studied owing to various parameters that affect the behavior under combined loadings. The effect of axial compression with combined bending and torsion has not been studied thoroughly. Otsuka et al. (2004) tested nine rectangular columns under pure torsion, bending/shear and different ratios of combined bending and torsion. The authors concluded that the pitch of the hoop lateral tie significantly affected the hysteresis loop of torsion. Later, Tirasit and Kawashima (2005) reported tests on RC columns under three different rotation to drift ratios. The authors reported that the flexural capacity of RC column decreases and the damage tends to occur above the flexural plastic hinge region as the rotation-drift ratio increases. The idea of using two cross spirals to enhance the strength and ductility characteristics and eliminate the locking and unlocking effect was also studied by Hindi et al. 2005. Recently, Belarbi et al. (2008a) presented a state of the art report on behavior of RC columns under combined loadings and scope for further research. They concluded that the effect of softening of concrete strength in the presence of shear and torsional loads and confinement of concrete due to transverse reinforcement play major role in determining the ultimate strength of concrete sections under combined loadings. They also suggested developing simplified constitutive models incorporating softening and confinement effects. Belarbi et al. (2008b) tested several circular columns under combined loadings with different spiral ratios. The authors reported that the spiral ratio which might be adequate from the flexural design point of view may not be adequate in the presence of torsional loadings. The authors proved that the effects of combined loading reduce the flexural and torsional capacity and affect the failure modes and deformation characteristics. The results of experimental studies on the performance of RC circular columns with a low aspect ratio (H/D=3) under a cyclically applied combined loadings including torsion are presented in this paper. Test results of the four columns: one under cyclic bending-shear, one under pure cyclic torsion, and two others under combined cyclic bending-shear and torsion are presented in this paper.

2. EXPERIMENTAL PROGRAM

2.1 Specimen details

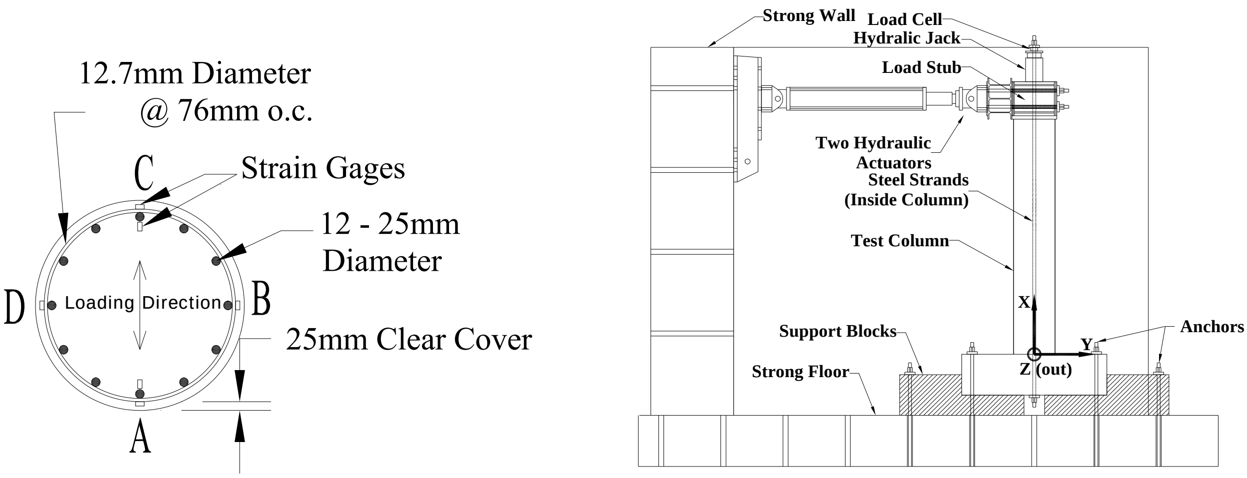
Each of the circular RC column specimens had a diameter of 610mm. and a clear concrete cover of 25mm. These specimens were fabricated in the High Bay Structures Laboratory at Missouri University of Science and Technology. The total height of the column was 2.74 m. with an effective height (from the top of the footing to the centerline of the applied forces) of 1.83 m. Typically; the axial load due to the superstructure dead weight in bridge columns varies between 5 and 10% of the capacity of the columns. Hence, in this study the axial load was taken as 7% of the capacity of the columns. Twelve No.8 bars (25mm diameter) were employed as the longitudinal reinforcement. The longitudinal reinforcement ratio was 2.1% for all the specimens. Columns under combined loadings were tested under torsion/bending ratio of 0.2 and 0.4 with a spiral ratio of 1.32%. Cross sectional details are shown in Figure 1a. As a part of this study, columns were also tested under combined loadings with high aspect ratio (H/D = 6) with different spiral ratios. Test results of these columns can be found elsewhere (Belarbi et al., 2008b and Suriya Prakash et al., 2008).

2.2 Material properties

The concrete was supplied by a local ready mix plant with requested 28-day cylinder strength of 34 MPa. Deformed bars were used in all specimens. The yield strengths of spiral and longitudinal reinforcement are listed in Table 1. Standard tests for compressive strength, splitting tensile strength, modulus of rupture of concrete, and tension tests on steel coupons were conducted. The actual properties of material used in the columns on the day of the testing are given in Table 1.

2.3 Test setup and Instrumentation

The test setup is shown in Figure 1b. Cyclic uniaxial bending was produced by applying equal forces with the two actuators. Pure torsion was created by applying equal but opposite forces with the two actuators. Combined cyclic torsion and bending were imposed by applying different forces/displacements with each actuator. The ratio of the applied bending moment to torsional moment was controlled by maintaining the ratio of the forces in the two actuators. A hydraulic jack on top of the column was used to apply an axial load. A target 7% axial load ratio was applied to simulate the dead load on the column in a bridge. Load cells in the horizontal hydraulic actuators measured the applied force. The axial load in the steel strands was measured using a load cell between the hydraulic jack and the top of the load stub. The twist and horizontal displacement of the columns were measured using string transducers at multiple heights above the column footing. Electric strain gages on the longitudinal and transverse reinforcement were used to measure the strain in the bars.



(a) (b)

Figure 1 (a) Column cross sectional detail and (b) test setup elevation

Table 1 Mechanical properties of concrete and steel used in test columns

Properties	Test Columns			
	M/V(6) T/M(0)	M/V(0) T/M(∞)	M/V(6) T/M(0.4)	M/V(6) T/M(0.2)
Compressive Strength (f'_c, MPa)	25.78	27.97	26.78	28.67
Modulus of Rupture (f_{cr}, MPa)	3.59	3.36	3.19	3.43
Splitting Tensile Strength (f_t, MPa)	2.48	2.50	2.55	2.63
Spiral Yield Strength (f_{ty}, MPa)	65.20			
Longitudinal Yield Strength (f_{ly}, MPa)	66.40			

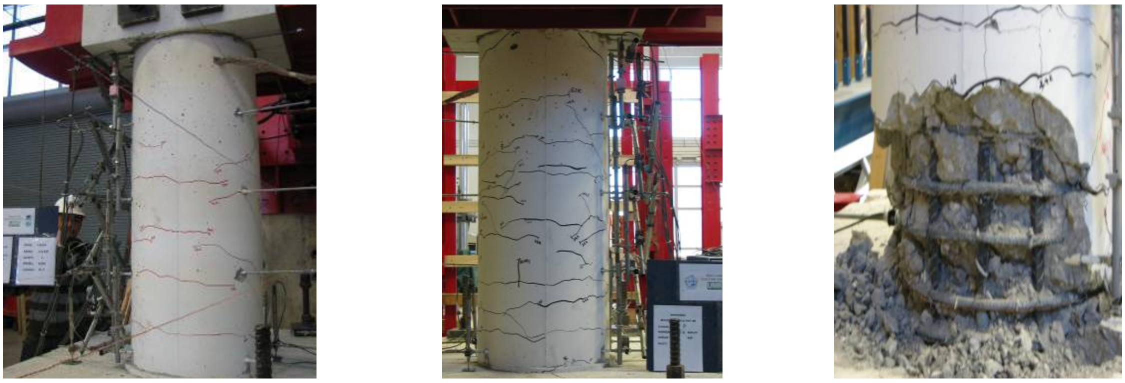
2.4 Loading Protocol

Testing of column under bending shear and combined bending and torsion were conducted in load control mode until the first yielding of longitudinal bar. The load was applied in load control mode at intervals of 25%, 50%, 75%, and 100% of the predicted yielding force (F_y) corresponding to the first yield of longitudinal bars. The horizontal displacement corresponding to yielding of the first longitudinal bar was defined as displacement ductility one (μ_Δ=1). The column under pure torsion was loaded under load control at intervals of 25%, 50%, 75%, and 100% of the estimated yielding torque (T_y) corresponding to the first yield of spiral. The rotation corresponding to yielding of the first spiral was defined as rotational ductility one (μ_θ=1). After the first yield, tests were continued in displacement control until the failure of the specimens at specified levels of ductility. The loading (pushing and twisting) along the direction A-C and C-A (Figure 1a) are defined as positive (unlocking direction) and negative (locking direction) cycles, respectively.

3. TEST RESULTS AND DISCUSSION

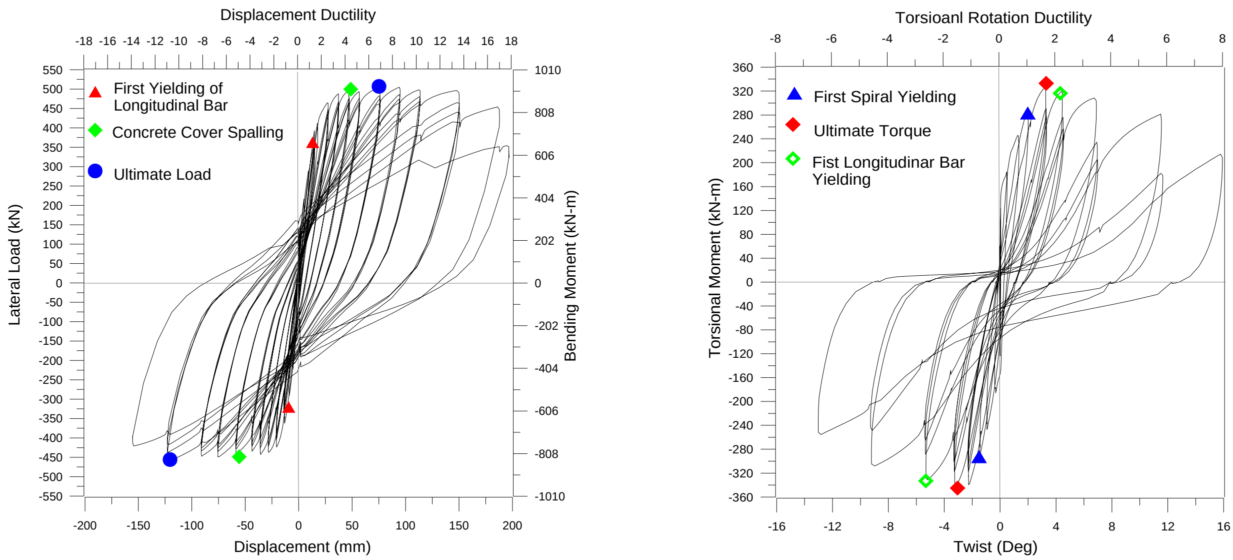
3.1 Column Under Bending-Shear

The column tested under bending-shear exhibited initial flexural cracks near the bottom on sides A and C after cyclically loading the column to 50% of the force F_y. These cracks continued to grow and new cracks appeared on both sides of the column as higher levels of ductility were reached (Figures 2a and 2b). The concrete cover started spalling at a drift of about 1.3%. The failure 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 5.1%. The progress of damage of the column is shown in Figure 2. The flexural hysteresis is shown in Figure 3a. The flexural resistance was constant between 1% and 4.1% drift with a flexural strength corresponding to a lateral load of 500 kN. During the last cycle of ductility 17, the longitudinal bars started buckling in the compression side as shown in Figure 2c. The yielding zone of the longitudinal bars was about 460mm 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 throughout the loading history up to failure. Soon after cracking and spalling at the location of the spiral gages, the spiral gages were damaged and no data was collected after this point. Though the column was tested at a lower aspect ratio of H/D=3, the failure was mainly dominated by flexure due to relatively low longitudinal ratio of the column and increased confinement from spiral reinforcement due to higher spiral ratio of 1.32%.



(a) (b) (c)

Figure 2 Damage of column under bending-shear at (a) cracking, (b) first longitudinal bar yielding, and (c) overall failure



(a) (b)

Figure 3 (a) Flexural hysteresis curves under bending-shear and (b) torsional hysteresis curves under pure torsion

3.2 Column under Cyclic Pure Torsion

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., 2008b). The torsional hysteresis curve of column tested under pure torsion is shown in Figure 3b. Under pure torsional loading, significant diagonal cracks started developing near mid- height on the column at lower levels of ductility (Figures 4a and 4b). The cracks lengthened when the applied torsion was increased. The progressing damage of the specimen is shown in Figure 4. 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 also 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 3c). 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. The spalling over the height of the column continued to increase with higher levels of ductility (Figure 4c). 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. The damage pattern of column under pure torsion was significantly different from that of column under bending-shear. The post-yield and pre ultimate plateau in the torque twist curve of a column with spiral ratio of 0.73% was very small (Belarbi et al., 2008b). Even increasing the spiral ratio from 0.73% to 1.32% did not help in increasing the pos-yield and pre ultimate plateau in the torque twist curve. This shows that strain hardening of spiral reinforcement is not significant under pure torsion.

(a) (b) (c)

Figure 4 Damage of column under pure torsion at (a) spiral yield (b) peak torque and (c) overall failure

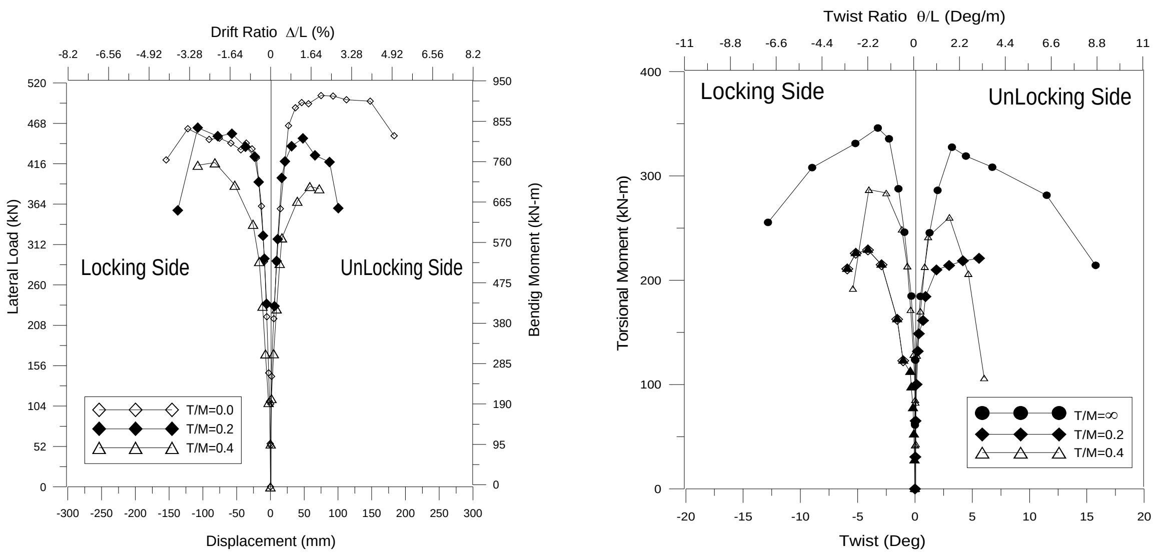
3.3 Columns under Cyclic Combined Bending And Torsion

Two columns were tested under combined bending and torsion by maintaining torsion to bending (T/M) ratio of 0.2 and 0.4 respectively. The results from tests on columns under bending-shear and pure torsion were used as the benchmarks for analyzing the behavior of columns under combined bending-shear and torsion. For the columns tested under combined bending 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 was depending on the level of torsion to bending ratio. In all columns, side ‘A’ of the column exhibited less damage as compared to side ‘C’. The main reason for this is that side ‘A’ always experienced smaller displacements as compared to side ‘C’ while applying the combined loading. In general, there are three failure modes possible under combined bending, 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 crushes before steel yields). Typical damage of the column under combined bending and torsion is shown in Figure 5.

(a) (b) (c)

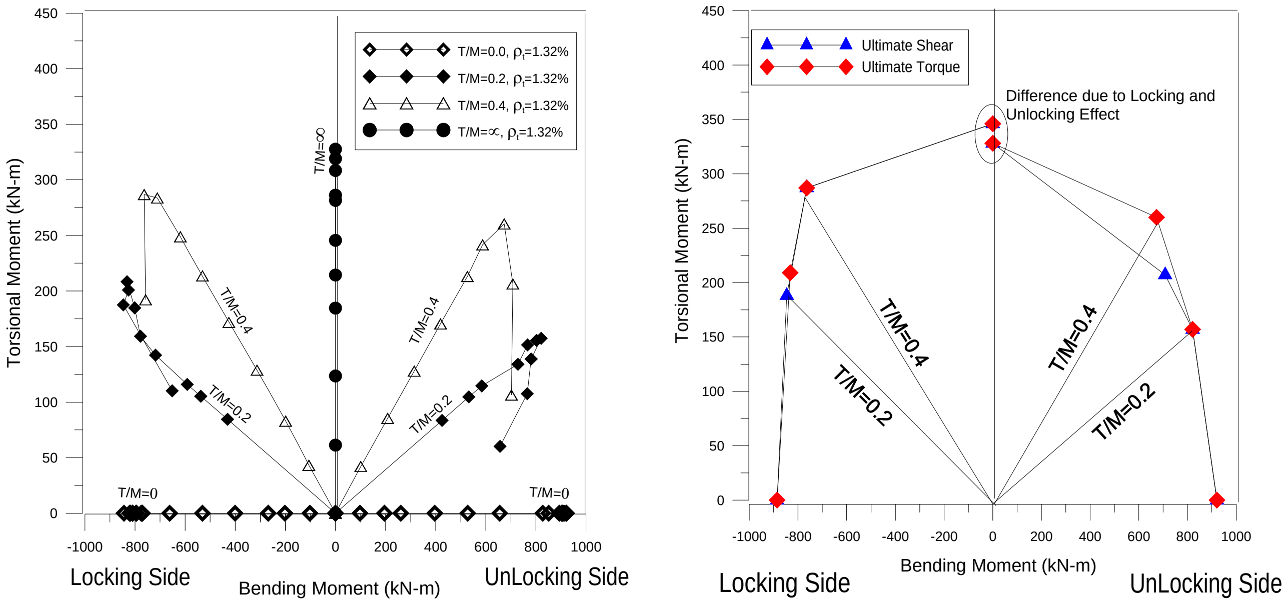
Figure 5 Typical damage of column under combined bending-shear-torsion at (a) spiral yield (b) peak torque and (c) overall failure

The load-displacement curves and the torque twist curves are compared in Figures 6a and 6b respectively. It is clearly shown that due to the effect of combined loading, torsional and bending strength reduces considerably according to the applied torsion to bending ratio. Strength and stiffness degradation were observed with increases in the loading cycles at each ductility level. 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. The unsymmetric nature of the torsional and flexural envelopes is due to the locking and unlocking effect of the spirals. Due to the effect of combined loading, the post-cracking torsional stiffness was found to degrade faster than that observed in pure torsion test. The unsymmetric nature of the flexural envelopes under combined bending and torsion is due to the fact that one face is subjected to higher shearing stresses because the components of shear stresses from shear and torsion are additive resulting in more damage and leading to less load resistance. Torsion-bending moment loading curves for the tested columns are shown in Figure 7a. The interaction of torsion and bending is shown in Figure 7b. It is shown that the torsion to bending (T/M) ratio could not be maintained constant soon after the column reaches its strength under bending or torsion (Figure 7 a). The spalled region of the column and core degradation extended up to a maximum height of 900mm from the top of foundation for torsion to bending (T/M) ratio of 0.4. This shows that the damage/spalling zone location changes due to the effect of torsion. However, the specific location of the damage zone depends on the applied torsion to moment (T/M) ratio. The spalling/damage distribution under different ratios of T/M is shown in Figure 8. In all columns under combined bending and torsion, failure started due to combinations of shear and flexural cracks leading to progressive spalling of concrete cover. The columns under combined loadings finally failed due to significant core degradation followed by buckling of longitudinal bars on the compression side.



(a) (b)

Figure 6 Comparison of (a) lateral load-displacement envelopes and (b) torsional moment-twist envelopes



(a) (b)

Figure 7 (a) Torsion-bending moments loading curves and (b) torsion-bending moments interaction diagrams

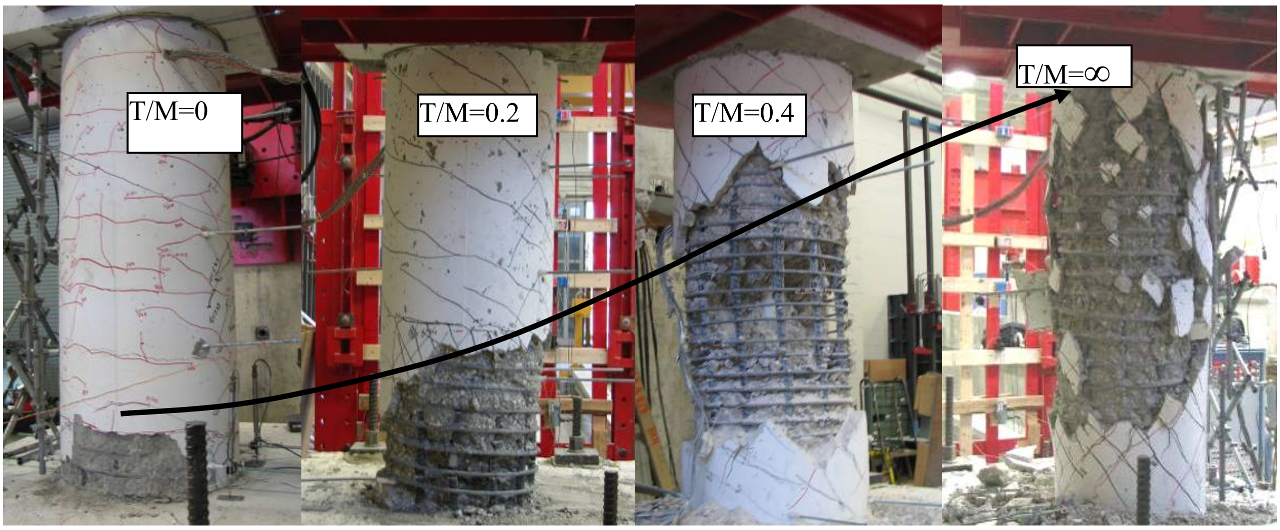


Figure 8 Effect of torsion on damage distribution of test columns under combined loading

3.4. Torsion Bending Moments Interaction

The test results of columns were used to create the interaction diagrams as shown in Figure 7b. Interaction diagrams were created at ultimate torque and bending moment. The interaction curves are slightly different in the positive and negative cycles owing to the locking and unlocking effect of spiral. The torsional capacity as well as bending capacity has been found to reduce due to the effect of combined bending and torsion. The interaction between bending and torsion depends on a number of factors, such as the amount of transverse and longitudinal reinforcement, aspect ratio of the section, and concrete strength. The column tested under T/M ratio of 0.2 failed mainly in flexure. The ultimate strength under bending and torsion were reached simultaneously at the same cycle in the unlocking side. However, the ultimate strength under bending was reached earlier than the torsional strength in the locking side. The column tested under T/M ratio of 0.4 failed mainly in torsion. The ultimate strength under bending and torsion were reached simultaneously at the same cycle in the locking side. However, the ultimate strength under torsion was reached earlier than the bending strength in the unlocking side and hence the control on torsion to bending ratio was lost thereafter.

4. SUMMARY AND CONCLUSIONS

The test results of four columns under bending-shear, pure torsion, and combined bending-shear and torsion were presented and discussed. Based on the preliminary test results from this study, the following major concluding remarks are drawn:

- The column tested under bending shear had a moderate aspect ratio but it still failed in flexure. The degradation in strength of the column was by 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. This is due to low longitudinal ratio considered in this study and increased confinement from spiral reinforcement due to higher spiral ratio of 1.32%.
- The failure of the column under pure torsion was by significant diagonal cracking leading to formation of a torsional plastic hinge along the full-height of the column.
- The location and the length of the damage zone changes with the level of combination of bending and torsion. Due to the presence of high shear, the crack widths were higher and resulted in early cover spalling of concrete even before the ultimate shear was attained.
- The length of plastic hinge zone decreases due to the application of high shear loading and resulted in reduction of the energy dissipation capacity when compared to the columns tested at low shear.

ACKNOWLEDGEMENTS

This study was funded by NEES-NSF, National University Transportation Center (NUTC) and Intelligent Systems Center (ISC) of Missouri S &T. Their financial support is gratefully acknowledged.

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