increased. Belarbi et al. (2008) presented a state-of-the-art report on the behavior of RC columns under combined loading and discussed the scope for further research. They carried out seismic analyses of bridge models for various earthquake motions. The results of their study clearly show that bridge columns in the bents closest to the bridge abutments are subjected to a significantly higher torsion-to-bending moment ratio (T/M) of between 0.33 and 0.52 compared with the bents that were farther to the abutments. They also concluded that the effects of the softening of concrete strength in the presence of shear load and torsional moment and of the confinement of concrete due to transverse reinforcement are significant in determining the strength of concrete sections under combined loading. They suggested that simplified constitutive models be developed that incorporate softening and confinement effects.

RESEARCH SIGNIFICANCE

A review of previously published work indicates that very few studies have addressed the behavior of circular RC columns under combined loading including torsion. The results of the current study will be a useful contribution in this field, supporting the development of analytical models for circular sections under combined loading. The experimental results will be used to develop and calibrate the design interaction equations and to develop damage and ductility models taking into account the combined loading effects.

EXPERIMENTAL TESTING PROGRAM

Circular RC bridge columns were tested under various loading conditions: cyclic bending, cyclic torsion, and combined cyclic bending and torsion. The main variables being considered in this study are: 1) the ratio of torsion-to-bending moment (T/M); and 2) the level of detailing for high and moderate seismicity. Eight columns were tested: one under cyclic bending and shear, two under cyclic pure torsion, and five others tested under various combined T/M ratios of 0.1, 0.2, and 0.4, including two different spiral reinforcement ratios.

Test specimen details

The half-scale test specimens were designed to be representative of typical existing bridge columns. Figure 1 shows the cross sectional details of the columns. Each circular RC column specimen had a diameter of 610 mm (24 in.) and clear concrete cover of 25 mm (1 in.); they were fabricated in the High Bay Structures Laboratory at Missouri University of Science and Technology (Missouri S&T). The total height of each column was 4550 mm (179 in.), with an effective height of 3650 mm (144 in.) from the top of the footing to the centerline of the applied loads. The axial load simulating the superstructure dead weight was assumed to be 7% of the capacity of the columns. Twelve 25.4 mm (1 in.) diameter bars provided longitudinal reinforcement. The spiral reinforcement was 9.5 mm (0.37 in.) in diameter spaced at 70 mm (2.75 in.) center-to-center for five columns with a low spiral reinforcement ratio of 0.73%. The longitudinal and spiral reinforcement ratios were 2.1 and 0.73%, respectively. The volumetric reinforcement ratio of longitudinal reinforcement and spiral reinforcement are calculated as shown in Eq. (1) and (2), respectively. To permit evaluation of the effectiveness of spiral reinforcement ratio under combined torsion and bending moments, the spiral reinforcement ratio was increased from 0.73 to 1.32% by increasing the spiral size from 9.5 to 12.7 mm (0.37 to 0.5 in.) in diameter and keeping the same spacing. The volumetric spiral reinforcement ratio ρ_t was chosen to satisfy the confinement criteria of CALTRANS (2004) according to Eq. (3). This requirement also satisfies the minimum required spiral reinforcement ratio according to AASHTO (1998) and ACI (ACI Committee 318 2005). The material properties of the specimens on the day of testing are given in the Table 1. The sectional details of the specimens are given in the Table 2.

$$\rho_l = \frac{100A_l}{A_g} \tag{1}$$

$$\rho_t = 100\frac{\pi d_c A_{sp}}{sA_c} \tag{2}$$

$$\rho_{t,\min} = 0.45\left(\frac{A_g}{A_c} - 1\right)\frac{f_c'}{f_y}\left(0.5 + \frac{1.25P}{f_c' A_g}\right) \tag{3}$$

In the above expressions, ρ_t is the spiral reinforcement ratio, ρ_l is the longitudinal reinforcement ratio, $\rho_{t,min}$ is the minimum required spiral reinforcement ratio, P is the applied axial load, f_y is the specified yield strength of the spiral reinforcement, f_c' is the specified compressive strength of concrete, A_l is the total area of longitudinal bars, A_g is the gross cross sectional area, A_c is the confined area enclosed by centerline of the spiral reinforcement, d_c is the diameter of the confined core of the concrete section measured with respect to the centerline of the spiral reinforcement, s is the spacing of the transverse reinforcement, and A_{sp} is the cross sectional area of the spiral reinforcement.

Material properties

The concrete was supplied by a local ready-mix plant. It had a requested 28-day cylinder strength of 34 MPa (5 ksi). The average compressive strength of all the test specimens was 31 MPa (4.5 ksi) on the day of testing. Deformed bars were used in all specimens. Standard tests were conducted for compressive strength, modulus of rupture of concrete, and tension tests on steel coupons. The actual material properties on the day of the testing are given in Table 1. The yield strengths of spiral and longitudinal reinforcement are listed in Table 2.

Test setup and instrumentation

Cyclic uniaxial bending and shear, torsion, and combined bending, shear, and torsion were generated by controlling the two horizontal servo-controlled hydraulic actuators shown in Fig. 2. Cyclic uniaxial bending was created by applying equal forces from the two actuators; pure torsion was created by applying equal forces in opposite directions. Combined cyclic torsion and uniaxial bending were imposed by applying different forces from each actuator. The ratio of applied T/M 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. The hydraulic jack transferred the load to the column via seven unbonded high-strength prestressing steel strands running through a duct in the center of the column and anchored to a plate beneath the column. A target 7% axial load ratio was applied to simulate the dead load on the column in a bridge. The column was heavily instrumented to measure the applied loads, deformations, and internal strains. Load cells in the horizontal hydraulic actuators measured the applied force. The axial load in the steel strands was measured using a load cell placed between the hydraulic jack and the top of the load stub. The twist and horizontal displacement of the column at the top were measured using string transducers at multiple heights above the column footing. Electric strain gages placed on the longitudinal and transverse reinforcement were used to measure the strains in the bars in Sides A, B, C, and D.

Loading protocol

Columns tested under bending-shear and combined bending and torsion were conducted in load control mode until first yielding of the longitudinal bars. The load was applied in load control mode at intervals of 25, 50, 75, and 100% of the predicted yielding force, corresponding to the yielding of the first longitudinal bar (F_y). The loading protocol for the column under bending and shear is shown in the Fig. 3(a). Displacement ductility μ_Δ is the ratio of displacement at any instant during loading to the corresponding displacement at first yielding of longitudinal bar. Hence, the horizontal displacement corresponding to yielding of the first longitudinal reinforcement was defined as displacement ductility μ_Δ of one. The column under pure torsion was loaded under load control at intervals of 25, 50, 75, and 100% of the estimated yielding of the first spiral (T_y). The typical loading protocol for the column under pure torsion is shown in Fig. 3(b). Twist ductility μ_Δ is the ratio of twist at any instant to the corresponding twist at first yielding of spiral reinforcement. Hence, the twist corresponding to yielding torque, which in turn corresponded to the first yielding of spiral reinforcement, was defined as twist ductility μ of one. After the first yield, tests were continued in displacement control at specified levels of ductility and with T/M ratio controlled at desired levels up to failure of the specimens. Application of symmetric loadings at ductility levels higher than 12 was not possible for the column Specimen T/M (∞)/0.73% because of the actuator stroke limitation. The torsional moment was applied only in the negative direction after ductility level of 12. Three loading cycles were performed at each ductility level to assess the degradation of column strength and stiffness. The loadings were applied along Direction A-C following the sign convention shown in Fig. 1. The loadings along Directions A-C and C-A were defined as positive (unlocking) and negative (locking) cycles, respectively.

TEST RESULTS AND OBSERVED BEHAVIOR

Column Specimen *T*/*M* (0.0)/0.73% under bending and shear

After cyclical loading to 50% of F_y, the column tested under bending and shear exhibited flexural cracks near the bottom on Sides A and C (Fig. 1). With higher levels of ductility, these cracks continued to grow, and new cracks appeared on both sides of the column. The concrete cover started spalling at a drift of about 3.2% corresponding to ductility level of 4.5 at a displacement of 117 mm (4.6 in.). Application of symmetric loadings at ductility levels higher than eight were not possible because of the actuator stroke limitation. Spacers were attached between the actuators and the column; and the displacement was applied only in the A-C direction after a ductility level of eight. 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 displacement of 460 mm (18 in.) at a ductility level of 18. The typical progression of damage in the columns under bending and shear is shown in Fig. 4. The flexural hysteresis is shown in Fig. 5. The flexural resistance was maintained at more or less constant levels between displacement of 110 mm (4.3 in.) and 460 mm (18 in.), with a nearly constant bending strength of 850 kN-m (627.8 kip-ft). During the last cycle of loading, a longitudinal bar started buckling while unloading. The yielding zone of the longitudinal bars was about 610 mm (24 in.) from the base of the column. Longitudinal bars on Sides A and C both reached the yield strain at the predicted ductility level of one. The spirals remained elastic up to a ductility level of six, after which they yielded. Soon after cracking and spalling at the location of the spiral gages, these gages were damaged and data could no longer be collected.

Column Specimens *T/M* (∞)/0.73% and *T/M* (∞)/1.32% under cyclic pure torsion

In practice, pure torsion is rarely present in structural members. Torsion usually occurs in combination with other actions, often bending and shear. Understanding the behavior of members subjected to pure torsion, however, is necessary for the analysis of a structural member. Only very few studies have reported on the behavior of RC circular sections under pure torsion. Hindi et al. (2005) proposed the use of two cross spirals to enhance strength and ductility characteristics under 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. Some of the columns tested in this study had a relatively low transverse reinforcement ratio (0.73%). This factor must be considered when interpreting the results for columns under pure torsion.

***Column Specimen* T/M *(∞)/0.73% with hoop reinforcement*—Columns with hoop and spiral were tested under pure torsion to study the locking and unlocking effect of spiral reinforcement on hysteresis behavior. The torsional moment versus twist hysteresis curves of the column with hoop reinforcement is shown in Fig. 6(a). Significant diagonal cracks started developing near mid-height on the column due to the applied torsion at lower cycles of loading up to 75% T_y. Cracking began after cyclically loading the column to 50% of the predicted spiral yield moment. As the test progressed, the cracks lengthened as the applied torsion was increased. The first yielding of spiral reinforcement was observed at torsional moment T_y of 275 kN-m (202.8 kip-ft) at the predicted ductility level of one. The peak torsional moment was achieved in the next ductility level of three. Peak torsional moment was higher in the positive cycle than in the negative cycle because the test was started in the positive loading direction. This could be unlocking in the case of column with spiral reinforcement. The longitudinal bars on all sides remained elastic until a rotational ductility of six. Dowel action of the longitudinal bar was not observed during the higher loading cycles. The test was stopped after torsional strength dropped significantly, corresponding to a twist of 18 degrees.

***Column Specimens* T/M *(∞)/0.73% and* T/M *(∞)/1.32% with spiral reinforcement*—** The torsional moment versus twist hysteresis curves of columns with spiral reinforcement ratios of 0.73 and 1.32% are shown in Fig. 6(b). These curves were approximately linear up to cracking and thereafter become nonlinear with a drop in the torsional stiffness. The post-cracking stiffness decreased proportionally with an increase in the cycles of loading until the dowel action took effect. The behavior of columns with spiral reinforcement differed significantly from that for columns with hoop reinforcement due to the locking and unlocking effects of the spiral reinforcement. During the positive cycles of twisting, the spiral reinforcement was unlocked, which caused significant spalling and reduced the confinement effect on the concrete core. On the other hand, during the negative cycles of loading, the spirals were locked, and they contributed with additional confinement of the concrete core. This effect is reflected in the asymmetric nature of the observed hysteresis loop at higher levels of loading. As expected, locking effect was not observed in the column with hoop reinforcement (Fig. 6(b)). At higher ductility levels, the load resistance on the negative cycles was higher than that on positive cycles of loading due to the added confinement generated by the locking effect of the spiral reinforcement. Dowel action contributed significantly to the load resistance at higher cycles of loading. The longitudinal bars on Sides A and C remained elastic until ductility four. The spirals, however, reached the yield strain at the predicted ductility level of one. Differences were observed in the strain levels on Sides A and C due to the effect of locking and unlocking of the spirals. In the column with hoop reinforcement, higher ultimate strength was obtained in the positive cycle because the test was started in this cycle. The damage pattern in columns with hoop and spiral reinforcement is compared in Fig. 7. Concrete core degradation was more significant in the column with the hoop reinforcement compared with the column with the spiral reinforcement (Fig. 7(b)). This difference was mainly due to the confining effect of spiral in the locking direction, which helped to reduce the damage level in the concrete core. The column with a spiral reinforcement ratio of 1.32% had higher post-cracking stiffness and strength. The yielding strength increased up to 20% and the ultimate strength by 30% due to an increase in spiral reinforcement ratio from 0.73 to 1.32%. More importantly, a significant increase in twist ductility was achieved due to an increase in the spiral reinforcement ratio.

***Comparison of torsional strengths with AASHTO equations*—**The cracking strength under torsional moment is given by Eq. (4) in metric system as:

$$T_{cr} = 0.33\sqrt{f_c'}\left(\frac{A_{cp}^2}{P_{cp}}\right)\sqrt{1+\frac{f_{pc}}{0.33\sqrt{f_c'}}} \tag{4}$$

where f_c' is the specified compressive strength of concrete at 28 days, T_{cr} is torsional cracking moment, A_{cp} is the total area enclosed by outside perimeter of the concrete section, P_{cp} is the length of perimeter of the concrete section, and f_{pc} is the compressive stress in concrete after prestress losses have occurred either at the centroid of the cross-section resisting transient loads or at the junction of the web and flange where the centroid lies in the flange.

Torsional resistance was assumed to be provided only by the spiral reinforcement as shown in Eq. (5) in metric system. Based on the thin tube analogy, the torsional resistance is given by

$$T_n = \frac{2A_o A_t f_y}{s} \cot\theta \tag{5}$$

where A_t is the area of one leg of closed torsion reinforcement within a spacing s, A_o is the area enclosed by shear flow path taken as $0.85A_{oh}$, A_{oh} is the area enclosed by the centerline of outermost closed transverse torsion reinforcement, and θ is the angle of diagonal compressive stress. The value of θ depends on the level of strain in the section ε_x and the level of applied shear stress v/f_c'. The cracking strength and ultimate strength of columns with hoop and spiral reinforcement are compared with AASHTO equations, as shown in Table 3. These equations are conservative compared with experimental values.

Comparison of longitudinal and transverse reinforcement strains—The strain distribution in the transverse reinforcement and longitudinal reinforcement is compared in Fig. 8. Both types of reinforcement experienced tensile strains under pure torsion. The strains in the spiral reinforcement increased significantly after torsional yielding moment. The longitudinal strains, however, remained well within the yield strain limit even at the peak torque. Thus, although spiral reinforcement satisfies confinement requirements from a flexural design point of view, the ratio is very low from torsional design perspective.

Comparison of twist profiles along the height—Twist distribution along the height of the columns is shown in Fig. 9. Torsional stiffness did not show significant degradation until the transverse reinforcement (both spiral and hoop) yielded. The twist distribution, however, clearly shows that stiffness degradation (in the damage zone) was more prominent at the middle height of the column under pure torsion after the yielding of transverse reinforcement. There was less degradation at the top and bottom to the boundary conditions of the loading block and the foundation.

Columns under cyclic combined bending and torsion

Three columns were tested under combined bending and torsional moments by maintaining a constant T/M ratio of 0.1, 0.2, and 0.4 throughout the loading history, respectively. One column was tested at a T/M ratio of 0.1 to validate the consideration of minimum torsional moment from a design point of view. The ACI and AASHTO codes suggest ignoring the presence of torsional moment if it is less than 25% of cracking torque T_{cr}. This level of cracking torque T_{cr} in a column with spiral reinforcement of 0.73% is calculated to be about 50 kN-m (36.8 kip-ft). According to ACI code calculations, the theoretical flexural strength is 786 kN-m (579.6 kip-ft), resulting in a T_{cr}/M_u ratio of about 0.065. Hence, the column was tested at a T/M ratio of 0.1 to understand the effect of the simultaneous application of a relatively small torsional moment along with bending and shear from a design point of view. The results of tests on columns under bending and shear and pure torsion were used as the benchmarks for analyzing the behavior of other specimens tested under combined bending-shear and torsion. In all the columns under combined bending and torsion, the actuator with lower force had displacement going in the same direction as the other actuator with a higher force. Under pure torsion, the direction of displacement in the actuators was in the opposite direction. Pressure force calibration of actuators was checked and found to be consistent with behavior observed during the testing.

In general, three failure modes are possible under combined bending, shear, and torsion for an RC member with longitudinal and transverse reinforcement: under-reinforced (longitudinal and transverse steel yield before concrete crushes), partially over-reinforced (only longitudinal steel yields or only transverse reinforcement yields), and over-reinforced (concrete crushing before any of the longitudinal or transverse steel yields). One column was tested at a *T/M* ratio of 0.4 to establish the balanced point in the interaction diagram by reaching the yield strain of longitudinal reinforcement and spiral reinforcement simultaneously. The bending moment M_y = 497.9 kN-m (367.2 kip-ft) corresponding to first yielding of longitudinal bar under bending-shear was calculated from theoretical calculation based on flexure. The torsional moment T_n = 220 kN-m (162.3 kip-ft) corresponding to yielding of spiral reinforcement was calculated using the AASHTO equation. The ratio of M_y/T_n was calculated to be 0.44. Hence, it was decided to test at a ratio of 0.4 to investigate the sequence of longitudinal bar yielding and spiral yielding. The other column was tested at an intermediate *T/M* ratio of 0.2 to understand the strength and stiffness degradation for *T/M* ratios between 0.1 and 0.4. The maximum *T/M* ratio based on seismic analysis of bridges was found in the previous studies to be up to 0.5 (Belarbi et al. 2008). The torsion-bending moment loading curves for the tested columns at the peak of each cycle is shown in Fig. 10.

Column Specimen* T/M *(0.1)/0.73%—In all 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 foundation with increasing cycles of loading and depending on the *T/M* ratio. The flexural hysteresis and torsional hysteresis are shown in Fig. 11; the behavior of the specimen was dominated by flexure. The specimen failed at low twist ductility, mainly due to the application of very low torsional moment at a *T/M* ratio of 0.1, and it could not resist the applied torsional moment at a displacement ductility level of 9.0. The corresponding torsional ductility at failure was 1.25, indicating that torsional moment corresponding to spiral yielding and peak torque occurred simultaneously.

Column Specimen* T/M *(0.2)/0.73%—Figure 12 shows the flexural hysteresis and torsional hysteresis of the column tested at a *T/M* ratio of 0.2. The behavior of the specimen was dominated by both flexure and torsion. The specimen reached the peak shear at a displacement ductility of 7.0, and finally failed at a displacement ductility of 9.5. The corresponding torsional ductility was 1.76; however, the peak torsional moment was reached at rotational ductility of one. The locking and unlocking effect of spiral reinforcement was clearly reflected in the torsional hysteresis as observed in the pure torsion specimen (Fig. 12(b)).

Column Specimen* T/M *(0.4)/0.73%—The flexural hysteresis and torsional hysteresis of the column tested at a *T*/*M* ratio of 0.4 is shown in Fig. 13. The behavior of the specimen was dominated by torsion. A significant difference due to the locking and unlocking effect of spiral is also apparent in the asymmetric behavior of the hysteresis curve under both flexure and torsion (Fig. 13). Yielding of longitudinal and spiral reinforcements occurred relatively close to each other for the column tested at a *T*/*M* ratio of 0.4. The specimen reached the peak shear at a displacement ductility of 4.5 and failed soon after. The corresponding torsional ductility at failure was 4.0; however, the peak torsional moment was reached at twist ductility of 1.0. Control of the *T*/*M* ratio was lost soon after the column reached its torsional strength. Spalling and core degradation were observed up to a maximum height of 910 mm (35.8 in.) from the base of column for a *T*/*M* ratio of 0.4, demonstrating that the torsional damage location changes due to the effect of bending. The specific location of the damage zone, however, depends on the applied *T*/*M* ratio. Typical damage to the column under combined bending and torsion is shown in Fig. 14. In all columns under combined bending and torsion, failure began due to severe combinations of shear and flexural cracks leading to progressive spalling of cover concrete. The columns under combined loading finally failed due to severe core degradation followed by buckling of the longitudinal bars on Side C.

EFFECT OF SPIRAL REINFORCEMENT RATIO

The torsion-bending loading curves for the specimens tested under combined bending and torsion are shown in Fig. 15. As shown by the curves, all specimens reached their torsional capacities prior to reaching their flexural capacities. However, the longitudinal reinforcement yielded before the spiral reinforcement. Hence, the failure sequence in all specimens was flexural cracking followed by diagonal cracking, longitudinal reinforcement yielding, spalling, spiral reinforcement yielding, and then final failure by buckling of the longitudinal reinforcement after severe core degradation. Spiral reinforcement yielding and longitudinal reinforcement yielding occurred in quick succession for the specimen with a spiral ratio of 0.73%. An increase in spiral ratio significantly improved torsional and bending strength. More importantly, significant twist ductility could also be achieved in torsional behavior. To study the effectiveness of increasing the spiral reinforcement ratio, columns under combined loading were tested under *T*/*M* ratios of 0.2 and 0.4 with spiral reinforcement ratios of 0.73 and 1.32%, respectively.

Column Specimen *T*/*M* (0.2)/1.32%

The flexural hysteresis and torsional hysteresis of the column with a spiral reinforcement ratio of 1.32% and tested at a *T*/*M* ratio of 0.2 are shown in Fig. 16. The behavior of the specimen was dominated by both flexure and torsion. The specimen reached the peak shear at a displacement ductility of 7.0 and finally failed at a displacement ductility level of 9.5. The corresponding twist ductility at failure was 1.76; however, the peak torsional moment was reached at a twist ductility of 1.0. The locking and unlocking effect of spiral reinforcement was clearly reflected in the torsional hysteresis as in the pure torsion specimen (Fig. 16(b)).

Column Specimen *T*/*M* (0.4)/1.32%

Figure 17 shows the flexural hysteresis and torsional hysteresis of the column with a spiral reinforcement ratio of 1.32% and tested at a *T*/*M* ratio of 0.4. The behavior of the specimen was dominated by torsion. The asymmetric behavior of the hysteresis curve under both flexure and torsion revealed a significant difference due to the locking and unlocking (Fig. 17). The specimen reached the peak shear at a displacement ductility level of 4.5 and failed soon after. The corresponding twist ductility at failure was 4.0; however, the peak torsional moment was reached at a twist ductility of 1.0. Control of the *T*/*M* ratio was could not be maintained after the column reached its torsional strength. Spalling and core degradation occurred up to a maximum height of 910 mm (35.8 in.) from the base of column for a *T*/*M* ratio of 0.4, indicating that the torsional damage location changes due to the effect of bending. The specific location of the damage zone, however, depends on the applied *T*/*M* ratio. In all columns under combined bending and torsion, failure began due to severe combinations of shear and flexural cracks, leading to progressive spalling of the concrete cover. The columns under combined loading finally failed due to severe core degradation followed by buckling of the longitudinal bars on Side C.

COMPARISON OF PERFORMANCES

Lateral load-displacement envelopes

The lateral load-displacement envelope curves under combined loading are compared in Fig. 18(a). Due to the effect of combined loading, torsional and bending strengths dropped considerably according to the applied *T*/*M* ratio. Marginal strength and stiffness degraded only marginally for the column tested at a *T*/*M* ratio of 0.1. For the other columns tested at higher *T*/*M* ratios of 0.2 and 0.4, strength and stiffness degraded significantly with an increase in the loading cycles at each ductility level. The yielding displacement increased and the lateral load corresponding to the first yielding of longitudinal reinforcement decreased with an increase in the *T*/*M* ratio.

Torsional moment-twist envelopes

The torsional moment-twist envelopes are compared in Fig. 18(b). Strength and stiffness degraded significantly with an increase in the loading cycles at each ductility level for all the columns. The asymmetric nature of the torsional envelopes is due to the locking and unlocking effect of the spiral reinforcement. Combined loading caused the secondary torsional stiffness to degrade faster than that under pure torsion.

Bending moment-curvature behavior

Bending moment curvature analyses are widely used as the basis for assessing the nonlinear force displacement response of an RC member subjected to inelastic deformation demands under seismic loads. For this work, the curvature was calculated at 240 mm (9.45 in.) from the top of foundation. The yield curvature increased with respect to increases in the applied *T*/*M* ratio. Although flexural strength was attained earlier for the column under a *T*/*M* ratio of 0.4, there was a reduction in flexural stiffness, which in turn resulted in more curvature due to the simultaneous application of a higher level of torsion (Fig. 19). Also, torsion changes the damage location in a column, which changes the behavior under combined loading. Methods for estimation of plastic hinge lengths proposed by Priestley et al. (1996) are not accurate in the presence of torsional loadings because they do not yield practical results Also, the yield moment increased and yield curvature dropped considerably with increase in the spiral reinforcement ratio (Fig. 19(b)).

Cracking and spalling distribution

Under combined torsion, bending, and shear, the inclination of principal compressive stresses and the strain distribution in longitudinal and spiral reinforcement vary across the depth of the cross section and along the height of the column. Figure 20 shows that with an increase in the T/M ratio, the angle of diagonal compression measured with respect to longitudinal axis increases. Test results show that these values varied from 134 degrees under pure torsion to 90 degrees for the column tested under bending and shear, indicating that spirals will be highly strained with an increase in the applied T/M ratio, and longitudinal reinforcement will be highly strained with a reduction in applied T/M ratios.

Spalling of the cover concrete has been shown to be of concern for columns with high axial loads and subjected to combined loading. Spalling occurs at loads lower than the theoretical strength under bending and shear, and the capacity of the column is limited to that of the spalling load in the presence of torsional loads. Two processes are prerequisites for the spalling of cover away from the core. The first involves interface cracking between the cover and the core; and the second requires a driving mechanism to push the cover away from the section. Although, strength may or may not be affected by spalling, it definitely affects the serviceability requirements. A minimum thickness of concrete cover is recommended by various design codes to protect the reinforcement from fire and to prevent or limit corrosion. This minimum thickness depends on the fire rating and on the type and exposure of the member. Greater cover thickness, however, can also have adverse effects if the member is subjected to shear or combined shear and torsion. If the principal tensile stress due to shearing stresses from torsion and shear exceeds the tensile strength of the concrete, spalling of cover concrete will occur along the plane of weakness formed by the transverse reinforcement. A thick concrete cover increases the possibility of spalling and leads to large crack width and spacing (Rahal and Collins 1995).

The spalling distribution along the height of the column is shown in Fig. 21. Under bending and shear loads, the spalling is influenced by the cover to lateral dimension ratio, the amount of transverse reinforcement, the axial load ratio, and the aspect ratio. Under torsional loadings, the concrete cover is assumed to spall off before the ultimate torsional capacity is reached; the shear flow path is related to the dimension of the stirrups. The timing of spalling is important from a design point of view whether it occurs before or after reaching the peak load determines the effective cross-sectional dimensions to be used in the design calculations. If spalling occurs before the peak load is reached, then the clear concrete must be subtracted from the actual dimensions during design calculation. Researchers have modeled spalling in several ways for RC rectangular and box sections. Hsu and Mo (1985) suggested a simple model based on cover thickness and thickness of shear flow to determine the effect of