INSIGHT INVESTIGATION OF SEISMIC PERFORMANCE OF RC CIRCULAR BRIDGE COLUMNS UNDER COMBINED LOADINGS

Abdedjelil Belarbi[1†], Suriya Prakash Shanmugam[2†] and Pedro Silva[3††]

Abstract

Reinforced concrete (RC) columns of skewed and curved bridges and bridges with unequal spans and column heights can be subjected to combined loadings including axial, flexure, shear and torsion during an earthquake. Multi-directional earthquake motions with significant vertical excitations, structural constraints due to stiff deck, movement joints, soil condition and foundations may also lead to combined loadings. The combination of axial, bending, shear and torsion can result in complex failure modes of RC bridge columns. In this study, experimental and analytical studies are currently underway to investigate the performance of RC circular columns under combined loadings including torsion. The main variables being considered in the experimental study 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 spiral ratio). The experimental results will be used to develop and calibrate the design interaction equations and develop damage and ductility models taking into account the combined loading effects. An overall summary of the major findings and relevant results from experimental and analytical studies of RC bridge columns under seismic loading are presented in this paper. In particular, the effects of spiral reinforcement ratio, shear span or aspect ratio of columns and its impact on the strength and ductility are discussed. Also, the effect of torsional loading on the bending moment curvature, ductility and energy dissipation characteristics are presented.

Introduction

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 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, structural constraints due to stiff decks, movement of joints, abutment restraints, and soil conditions may lead to combined loading effects including torsion. This combination of seismic loading and structural constraints can result in complex failure modes of these bridge columns. Very few experimental results are reported in the literature on the behavior of rectangular columns under combined loadings. Hsu and Wang (2000) reported the performance of composite columns with H-steel sections under combined loadings. The authors found that the flexural capacity and

---

[1]Distinguished Professor, [2]PhD Candidate, [3]Associate Professor, [†]Missouri University of Science & Technology, USA, [††]George Washington University, USA

ductility of composite columns decreased when a constant torsion was simultaneously applied. Otsuka and his team (Otsuka et al., 2004) studied nine rectangular columns under pure torsion, bending/shear and different ratios of combined bending and torsional moments. The authors concluded that the pitch of the hoop lateral tie significantly affected the hysteresis loop of torsion. Later, Kawashima and his colleagues (Tirasit et al., 2005) reported tests on RC columns under three loading conditions. The authors reported that the flexural capacity of RC column decreases and the region of plastic deformation tend to move above the typical flexural plastic hinge region as the rotation-drift ratio increases. Recently, Belarbi and his team (Belarbi et al., 2008) tested number of columns at different torsion-to-bending moment (T/M) ratios. They observed that the effects of combined loading reduce the flexural and torsional capacities, as well as, affect the failure modes and deformation characteristics. They found that with an increase in torsion-to-bending moment (T/M) ratios, the energy dissipation capacity decreases.

There are rational models available for analyzing the interaction between axial and bending loads. The behavior of columns under bending with and without axial loadings has been extensively investigated by a number of researchers. Park and Ang (1985), Priestly and Benzoni (1996), Priestly et al. (1996) and Lehman et al. (1998) have all investigated and proposed various models for predicting the seismic performance behavior of columns taking into account the axial loading effect on bending capacity. Analytical models for RC columns in the past have primarily focused on inelastic flexural behavior and usually decoupled with shear and torsion. In addition to axial load, shear force and bending moment, bridge columns can be subjected to torsional loadings. Torsional loadings can significantly affect the flow of internal forces and deformation capacity of RC columns. These in turn can influence the performance of vital components of bridges and consequently impact the daily operation of the transportation system.

During the design of bridge systems, columns are typically chosen as the effective system for dissipation of the seismic induced energy. In order to improve the ductility and energy dissipation capacity of the columns, the selection of suitable and properly detailed plastic hinges is made at the ends of the column where the moments are at a maximum under lateral response. Performance of RC columns dominated in shear or shear-flexure or shear-torsion however cannot be estimated only by assuming section analysis because shear/torsion behavior is not taken into account with this approach. Also, the plastic hinge model assumes that length of plastic zone in a member is proportional to the member's shear span. Accordingly, a member with a shorter shear span has a lower spread of plastic hinge zone. There is no available information in the existing literature to account for the effect of torsion in calculation of the plastic hinge zone. In addition, presence of torsional moments can increase the shear deformation and make the predictions of currently available models unreliable. Ozcebe and Saaticoglu (1989) reported that the contribution of shear to the lateral displacement can be significant even if the behavior of RC member is not governed by shear. They also indicated that RC members with higher shear strength than flexural strength do not guarantee an elastic behavior due to shear. Also, research has shown that relatively stiffer or short columns dominated by shear behavior in bridges will introduce a higher level of asymmetry into the system and thereby resulting in higher torsional-to-bending moment (T/M) ratios (Zhang and Xu, 2008). They also reported that the shear-flexural interaction generally results in larger displacement demand in both transverse and longitudinal directions. Other researchers have studied the behavior of RC rectangular sections under combined loadings based on strain (displacement) and stress (force) field theories. However, there have been no analytical models developed including the effect of flexure-shear-torsion interaction for assessment of seismic performance of RC circular bridge columns. In this direction, You and Belarbi (2008) developed a model for RC circular bridge columns under pure torsion with or without axial loading effect based on the softened truss model. The paucity of test results of RC circular columns with different reinforcement ratios under combined bending, shear and torsion loadings has hinder the development of analytical models. Therefore, the research work done in this study will be helpful not only for the enhancement of knowledge on the behavior of RC circular bridge columns under cyclic combined loadings but also for providing experimental data towards the further development of rational analytical models. Research is currently underway at Missouri S&T to improve and develop rational analytical models that can lead to simplified design methods for RC circular columns under combined cyclic loadings.

Experimental Program

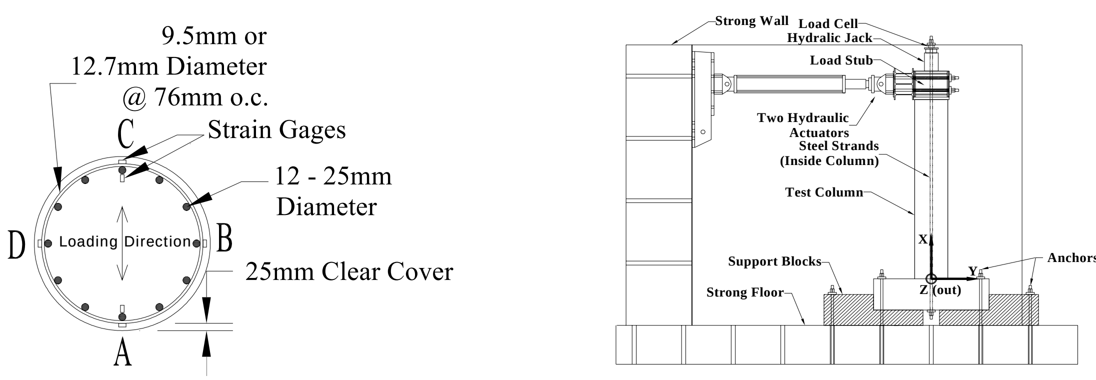
The main variables considered in this study are (1) the ratio of torsion-to-bending moment, (2) column aspect ratio (H/D) to simulate a flexural or shear dominant response, and (3) level of detailing for high and moderate seismicity. The aspect ratio plays an important role in determining the behavior of columns dominated by flexure or by shear. For the columns tested in single curvature, the aspect ratio is defined as the ratio of height (M/V=H) to diameter (D). Columns with higher aspect ratio are long and flexible and attract lesser seismic load where as, shorter and stiff columns attract much greater portion of the seismic input. The study consisted of testing circular columns at high aspect ratio (H/D=6) with low shear and at low aspect ratio (H/D=3) with moderate shear at different levels of torsion-to-bending moment ratios with two different spiral reinforcement ratios as shown in Table 1. The hysteretic lateral load-displacement response, torsional moment-twist response, reinforcement stress variations, and plastic hinge characteristics for the individual tested columns can be found elsewhere (Belarbi et al., 2008; Suriya Prakash et al., 2008). In particular, the effect of spiral reinforcement ratio and aspect ratio on behavior of RC circular columns under combined loadings is focused in this paper.

Test Specimen Details

The half-scale test specimens were designed to be representative of typical existing bridge columns. The column dimensions and reinforcement layout are shown in Fig. 1. These RC columns had a diameter of 610 mm and clear concrete cover of 25 mm and were fabricated in the High Bay Structures Laboratory at Missouri University of Science and Technology (Missouri S&T). The total height of the column for columns with aspect ratio of 6 was 4,550 mm and the effective height was 3,650 mm from the top of the footing to the centerline of the applied forces. Similarly, total height for columns with aspect ratio of 3 was 2,750 mm and the effective height was 1,850 mm from the top of the footing to the centerline of the applied loads The axial load due to the superstructure dead weight was assumed to be 7% of the capacity of the columns. Twelve 25.4 mm diameter deformed bars were employed as the longitudinal reinforcement. The spiral reinforcement was 9.5 mm diameter spaced at 70 mm center-to-center for columns with low spiral reinforcement ratio. The longitudinal and spiral reinforcement ratios were 2.1% and 0.73%, respectively. In order to investigate the effectiveness of spiral reinforcement ratio under combined torsion and bending moments, spiral reinforcement ratio was increased from 0.73% to 1.32% by increasing the spiral size from 9.5 mm to 12.7 mm diameter. Detailed information of the material properties of the test specimens can be found elsewhere (Belarbi et al., 2008 and Suriya Prakash et al., 2008).

Table 1. Test Matrix

Test Columns	Compressive Strength (MPa)	Spiral Ratio (%)	Longitudinal Ratio (%)	Aspect Ratio (H/D)	Torsion to Bending Ratio (T/M)
M/V(12)-T/M(0	33.4	0.73	2.10	6	0.0
M/V(12)-T/M(0.1)	29.7	0.73	2.10	6	0.1
M/V(12)-T/M(0.2)	26.5	0.73	2.10	6	0.2
M/V(12)-T/M(0.4)	25.7	0.73	2.10	6	0.4
M/V(12)-T/M(∞)	37.9	0.73	2.10	6	∞
M/V(12)-T/M(0.2)	41.2	1.32	2.10	6	0.2
M/V(12)-T/M(0.4	41.2	1.32	2.10	6	0.4
M/V(6)-T/M(0)	25.8	1.32	2.10	3	0.0
M/V(0)-T/M(∞)	28.0	1.32	2.10	3	∞
M/V(6)-T/M(0.2)	28.7	1.32	2.10	3	0.2
M/V(6)-T/M(0.4)	26.8	1.32	2.10	3	0.4



(a) (b)

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

Effect of Transverse Spiral Reinforcement Ratio

Increase in spiral reinforcement ratio improves the shear strength and confinement of the concrete core for the columns tested under combined bending-shear. However, there is only marginal strength increase due to an increase in the spiral reinforcement ratio for the flexure dominated columns with low longitudinal reinforcement ratio and adequate confinement. Significant improvement in performance with increase in spiral reinforcement ratio can be achieved for cases under pure torsional loading. The hysteresis curves of columns with spiral reinforcement ratio of 0.73% and 1.32% are presented in the Fig. 2. Soon after cracking, the yielding of spirals was observed in the subsequent loading cycle of the column with spiral reinforcement ratio of 0.73%. This implies that the spiral ratio of 0.73% is in the neighborhood of the minimum design requirement for a torsional design. It is worth mentioning that 1% spiral ratio is a more practical value in the design of bridge columns in USA. To offset the cracking level from yielding level, the spiral ratio was increased to 1.32% and again tested under pure torsion. The angle of diagonal cracks was nealry 39 to 42 degrees relative to the cross section (horizontal) of the column. The spalled region occurred near the top of the column at the completion of the test.

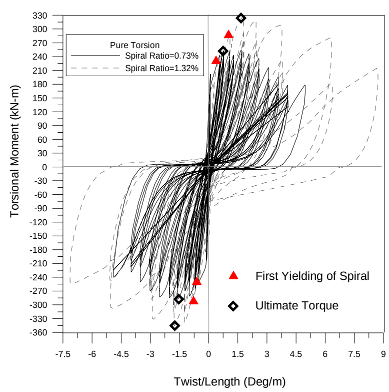


Fig. 2 Torsional hysteresis curves under pure torsion with different spiral reinforcement ratios

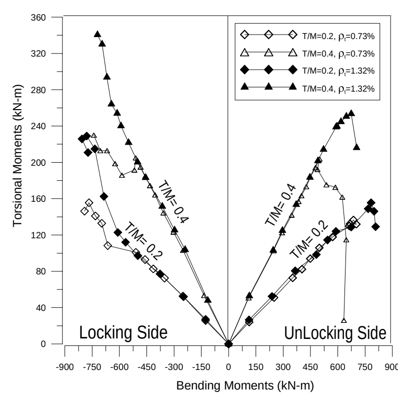
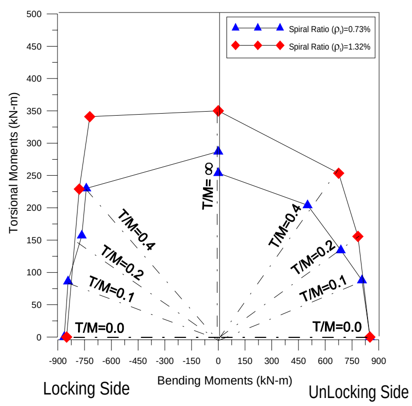
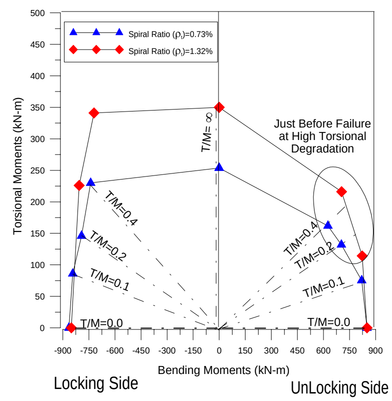


Fig. 3 Comparison of torsion-bending moments curves for various combined loading ratios

The torsional moment versus twist curves are approximately linear up to cracking and thereafter become nonlinear with a decrease in the torsional stiffness. The column with a spiral reinforcement ratio of 1.32% had a higher post-cracking stiffness. The yielding strength increased by 20% and the ultimate strength by 30% due to increase in spiral reinforcement ratio from 0.73% to 1.32%. More importantly, significant increase in rotational ductility was achieved due to increase in spiral reinforcement ratio. Torsion-bending moment loading curves for the columns tested under combined bending and torsional moments are shown in Fig. 3. As shown in the curves, all specimens reached their torsional capacity prior to reaching their flexural capacity. However, the longitudinal rebars yielded before the spirals. Hence, the failure sequence in all the specimens were in the order of flexural cracking, followed by shear cracking, longitudinal bar yielding, spalling, spiral yielding, and then overall failure by buckling of the longitudinal bars right after significant core degradation. Yielding of the longitudinal and spiral reinforcement occurred relatively close to each other for the columns reinforced with a spiral reinforcement ratio of 0.73%. By increasing the spiral reinforcement ratio, significant improvement in torsional and bending strengths was achieved. Torsion-bending moment interaction diagrams were determined at peak torsional moment (Fig. 4a) and peak shear (Fig. 4b) for all columns. It should be noted that the T/M ratio was maintained closely to the desired loading ratio in all columns until the peak torsional moment was attained in the unlocking direction. Soon after reaching the peak torsional strength, it was impossible to maintain the desired loading ratio as the torsional stiffness was degrading much faster in both the unlocking and locking directions. However, the bending strength was degrading faster than the torsional strength in the locking direction for the columns with a spiral reinforcement ratio of 1.32% and hence the load ratio could not be maintained to complete the test.



(a) Peak shear



(b) Peak torsion

Fig. 4 Torsion-bending moments interaction diagrams

Effect of Shear Span/Aspect Ratio under Combined Loadings

The behavior of RC columns can be classified into flexure dominated or shear dominated or with significant flexure-shear interaction. The aspect ratio of the column determines the level of flexure-shear interaction. There are few studies in this area of bending-shear interaction though the full understanding is yet lacking (Ang et al., 1989; and Kowalsky and Priestley, 2000). In order to adopt the plastic analysis methods in the design of RC members by assigning the plastic hinges at the weak regions, inelastic response at these regions must be assessed in the presence of combined loadings including torsion. Specifically, designers would prefer to quantify flexural response such that the dependability of flexural plastic hinges can be assessed under dominant shear/torsional loads.

Test results of the six columns: one tested under cyclic pure bending (H/D=3), one column tested under cyclic pure torsion (H/D=3), and four columns tested under combined cyclic bending and torsion with different ratios of T/M such as 0.2 and 0.4 but with different shear spans (H/D=6 and 3) were used to investigate the effect of shear span under combined loadings including torsion. Analytical models were used to predict the behavior of column with aspect ratio of 6 under bending-shear and pure torsion respectively. All the columns had a spiral reinforcement ratio of 1.32%.Torsion-bending moment loading curves for the columns tested under combined bending and torsional moments but with two different aspect ratios are shown in Fig. 5. As shown in these curves, the columns with low and high aspect ratio reached their torsional and bending moment capacity almost simultaneously in the unlocking direction. However, it is somewhat different in the locking direction. After yielding of the spiral and longitudinal reinforcement, the bending and torsional strength increased in a non-linear fashion due to the locking effect of spiral which resulted in better confinement of concrete core. Hence, the ratios were not closely maintained in the locking direction. No significant change in the torsional and bending strengths was observed with change in the aspect ratio. This is mainly due to the flexural failure mode in the columns with high and low aspect ratio. However, the effect of aspect ratio would have been more pronounced if the failure modes were in shear. Torsion-bending moment interaction diagrams were determined at peak torsional moment (Fig. 6a) and peak shear (Fig. 6b) for tested columns. It should be noted that the T/M ratio was not maintained closely to the desired loading ratio in the locking direction due to highly nonlinear behavior due to locking effect of spiral reinforcement. This resulted in variation of bending and torsional stiffness in a non-linear fashion after the spiral and longitudinal bar yielding.

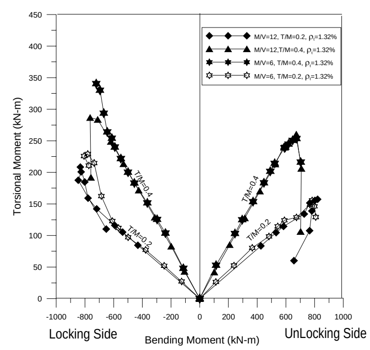
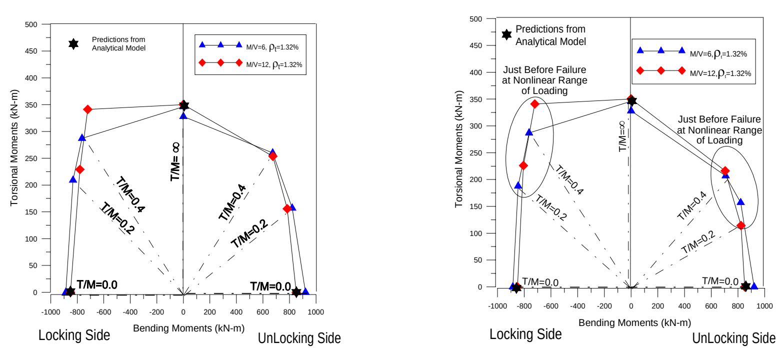


Fig. 5 Comparison of torsion-bending loading curves for two different aspect ratios



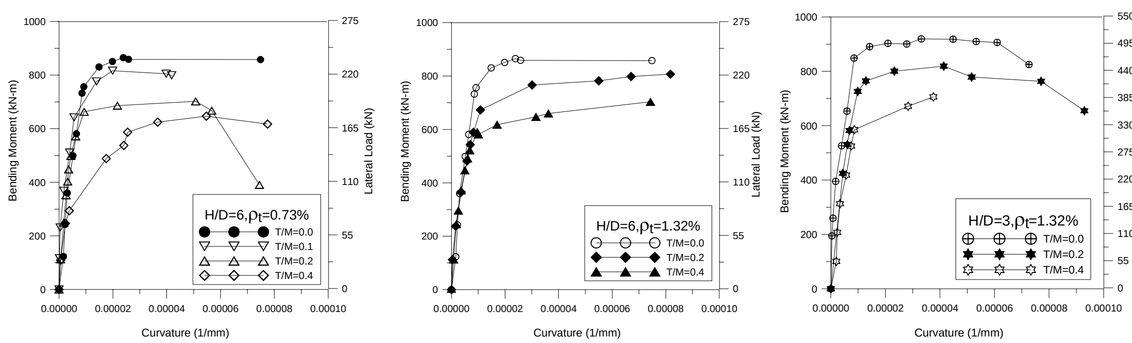
(a) Peak torque (b) Peak shear

Fig. 6 Torsion-bending moments interaction diagrams

Effect of Torsion on Bending Moment-Curvature Behavior

Bending moment curvature analyses are widely used as the basis for assessing the overall force displacement response of RC members that is also subjected to inelastic deformation demands under seismic loads. The evaluation of the bending moment-curvature at different heights along the column was carried out. An average curvature of a segment of the column is obtained using the longitudinal deformations measured by a pair of linear variable displacement transducers (LVDT). The average curvature can be expressed as shown in Eqn (1). In Eqn (1), Φ_{ave} is the average curvature over the specified length, Δ_1 and Δ_2 are the measured longitudinal deformations on two sides, *D'* and l_1 are the distance of the linear potentiometers and the length of the segment, respectively. The corresponding moment is calculated at the mid-height of the segment, using the recorded values for the horizontal force, and the relative horizontal deflection at the corresponding step. The moment curvature behavior was calculated at 240 mm from the top of foundation and presented in Fig. 7.

$$\phi_{ave} = \frac{\Delta_1 - \Delta_2}{D'l_1} \qquad (1)$$



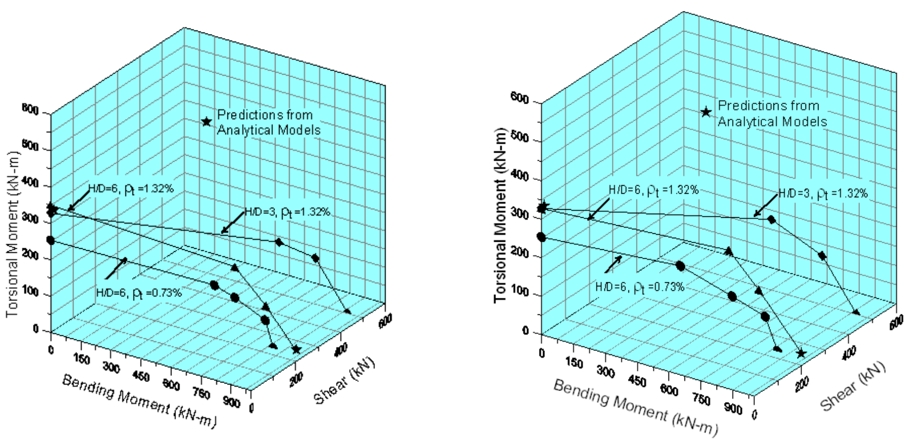
(a) H/D=6 and ρ_t = 0.73% (b) H/D=6 and ρ_t = 1.32% (c) H/D=3 and ρ_t = 1.32%

Fig. 7. Bending moment curvature behavior under combined torsion and bending

It is shown that the yield curvature increases with respect to an increase in the applied torsion-to-bending moment (T/M) ratio. A reduction in flexural stiffness was observed for the column that was tested under T/M=0.4, though flexural strength was reached later than torsional strength. This resulted in increased curvature due to the simultaneous application of higher level of torsion (Fig. 7a). It is also shown that the yield moment increased and yield curvature reduced considerably with increase in spiral reinforcement ratio (Fig. 7b). Bending moment curvature curves are shown in Fig. 7c for the columns tested at low aspect ratio. As expected, and as shown in Fig. 7c the bending moment curvature behavior of columns with aspect ratio of '3' was stiffer compared to columns with aspect ratio of '6'. Available methods in the literature by Priestley et al. (1996) were used to calculate the plastic hinge lengths. As the torsional loading changes the damage location of the column, this also leads to change in the plastic hinge formation under combined loadings. The calculation of plastic hinge lengths was not feasible in the presence of torsional loadings and it did not yield practical results.

Flexure-Shear-Torsion Interaction Diagrams

The test results were subsequently used to create a 3-dimensional interaction diagrams as shown in Fig. 8. Interaction curves for columns with spiral reinforcement ratios of 0.73% and 1.32% and with aspect ratio of 3 and 6 are shown in Fig. 8. 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 large number of factors, such as the amount of transverse and longitudinal reinforcement, aspect ratio of the section, and concrete strength. As explained in the previous sections, increase in the spiral reinforcement ratio resulted in a better performance. It is to be noted that there was no degradation in strength due to change in aspect ratio or moment to shear ratio as the columns failed predominantly in flexure. For the columns with low transverse reinforcement ratio of 0.73%, degradation in strength and stiffness increased with increase in torsion-to-bending moment ratios. This show that transverse reinforcement ratio of 0.73% which may be adequate from flexural design point of view may not satisfy the expected design performance in the presence of torsional loadings.



(a) Peak torque (b) Peak shear

Fig. 8 3-Dimensional bending-shear-torsion interaction diagrams

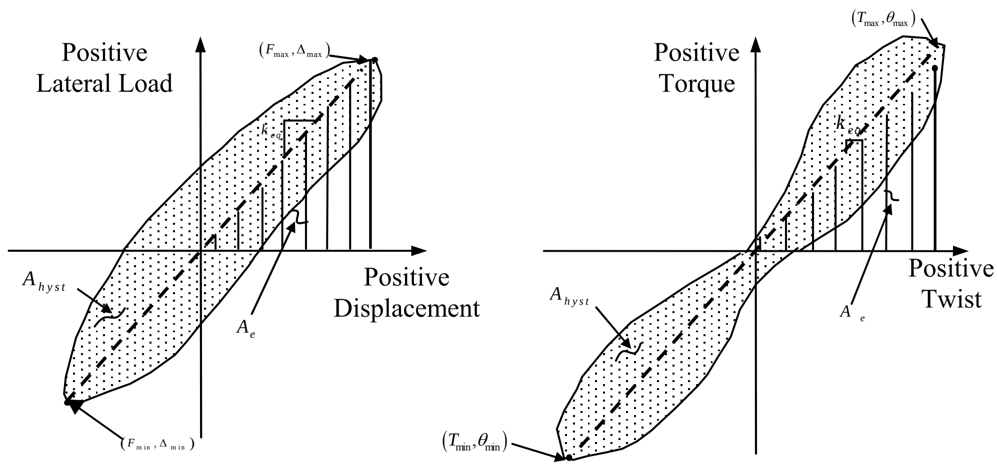
Ductility and Energy Dissipation Characteristics

In the recent years, the research focus has shifted towards performance oriented seismic design (Lehman and Moehle 2000). This shift in research focus was mainly to improve the methods for evaluating the performance of bridge columns over the range of performance levels. From a performance based design point of view, designers are interested in strength, stiffness, deformation capacity, and energy dissipation ability of members under combined loadings. Energy dissipation capacity can be a very important parameter in assessing the seismic performance of the structure. RC members dissipate energy through formation of cracks, internal friction from the plastic deformation of the reinforcement and friction due to sliding of the concrete struts. The strength and stability of bridge columns and the superstructures supported by them depend on the capacity of these columns capable of sustaining a large number of inelastic deformation reversals without significant strength decay. The parameters that are needed to define the energy dissipation and equivalent damping ratios of the RC columns in bending and torsion are defined in Table 2. The energy dissipated in one cycle is the area under that cycle of loading in bending and torsion as shown in Figs. 9a and 9b respectively. The average peak torque and twist in one cycle is T_m and θ_m as shown in Eqns. 4 and 6. Similarly, the average peak lateral load and displacement in one cycle is F_m and Δ_m as shown in Eqns. 5 and 7. The effective stiffness under torsion ($k_{eff,torsion}$) and bending ($k_{eff,bending}$) are given by Eqns. 8 and 9 respectively. The elastic strain energy in bending and torsion stored in an equivalent linear system is proportional to the area $A_{e,torsion}$ and $A_{e,torsion}$ as shown in Eqns. 10 and 11 respectively. The equivalent viscous damping ratio in bending and torsion are given in Eqns. 12 and 13, respectively. Energy dissipated by the columns in the form of bending ($E_{D,bending}$) and torsion ($E_{D,torsion}$) is compared in Figs. 10a and 10b, respectively, for the columns with spiral reinforcement ratio of 0.73% and aspect ratio of 6. The effect of increasing spiral reinforcement ratio on energy dissipation capacity and ductility is shown in Fig. 11.

Table 2. Definition of Parameters for Energy Dissipation and Equivalent Damping Ratio

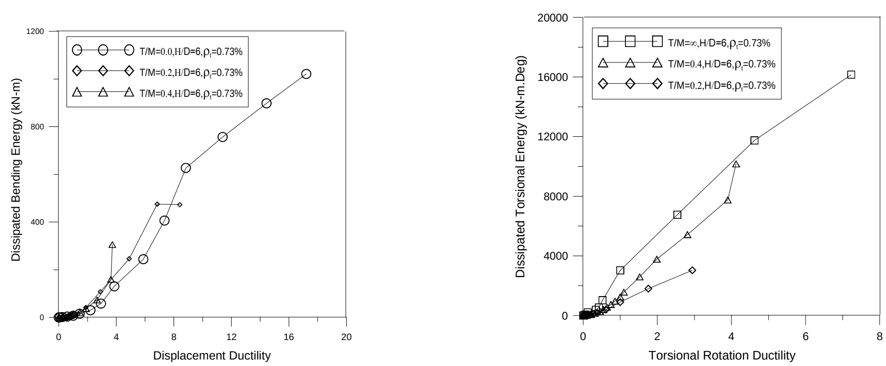
Parameters	Torsional Hysteresis (Eqn)	Bending Hysteresis (Eqn)
Energy Dissipation	$E_{D,torsion} = A_{hyst,torsion}$ (2)	$E_{D,flexure} = A_{hyst,flexure}$ (3)
Average Peak Moment/Force	$T_m = \frac{1}{2}(T_{max} - T_{min})$ (4)	$F_m = \frac{1}{2}(F_{max} - F_{min})$ (5)
Average Peak Twist/Displacement	$\theta_m = \frac{1}{2}(\theta_{max} - \theta_{min})$ (6)	$\Delta_m = \frac{1}{2}(\Delta_{max} - \Delta_{min})$ (7)
Effective Stiffness	$k_{eff,torsion} = \frac{T_m}{\theta_m}$ (8)	$k_{eff,flexure} = \frac{F_m}{\Delta_m}$ (9)
Strain Energy in Equivalent System	$A_{e,torsion} = \frac{k_{eff,torsion}}{2}(\theta_m)^2$ (10)	$A_{e,flexure} = \frac{k_{eff,flexure}}{2}(\Delta_m)^2$ (11)
Equivalent Damping System	$\xi_{eq,torsion} = \frac{A_{hyst,torsion}}{4\pi A_{e,torsion}}$ (12)	$\xi_{eq,flexure} = \frac{A_{hyst,flexure}}{4\pi A_{e,flexure}}$ (13)

It is shown that increasing the spiral reinforcement ratio significantly increased the energy dissipation capacity and ductility in bending and torsion. Columns with lower aspect ratio of 3 or shear dominated columns have less energy dissipation capacity in bending as well as torsion when compared to columns with aspect ratio of 6 (Fig. 12). It is also shown that torsional rotation and displacement ductility reduces with a reduction in the aspect ratio. Similarly the variation of equivalent damping ratio with respect to an increase in torsion-to-bending moment ratios, spiral reinforcement ratio and shear span under combined bending and torsional moments are shown in Figs. 13, 14 and 15 respectively. It is shown that the equivalent damping ratio is significantly less for torsional hysteresis when compared to bending hysteresis (Fig. 13). Significant improvement in the energy dissipation increase in equivalent damping ratio is obtained with increase in spiral reinforcement ratio for both the bending and torsional hysteresis (Fig. 14). Also, the equivalent damping ratio is found to decrease with reduction in aspect ratio or with decrease in moment to shear ratio (Fig. 15).



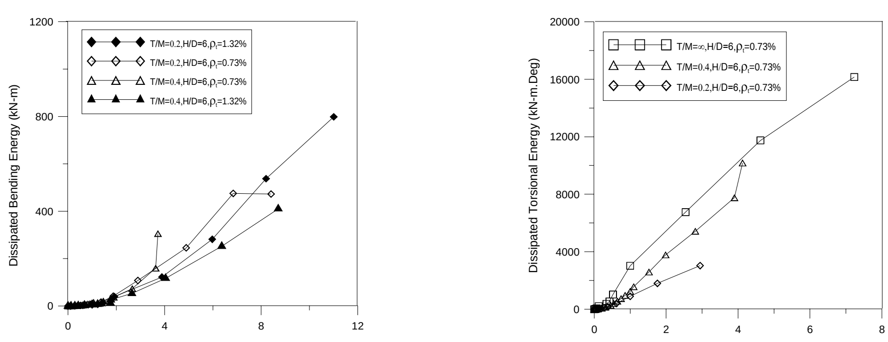
(a) Bending hysteresis (b) Torsional hysteresis

Fig. 9 Energy dissipation and equivalent definition of parameters



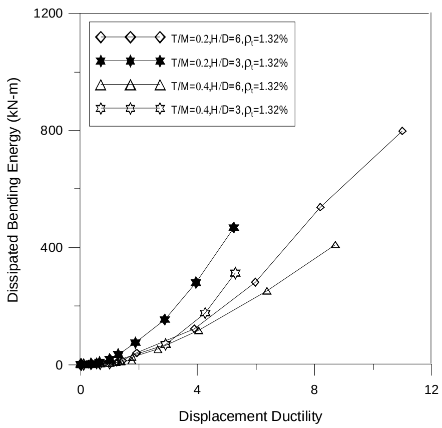
(a) Bending hysteresis (b) Torsional hysteresis

Fig. 10 Cumulative energy dissipation

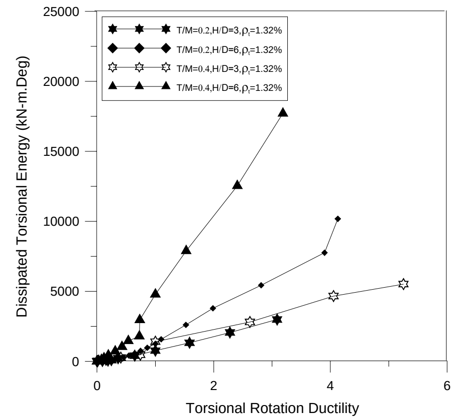


(a) Bending energy (b) Torsional energy

Fig. 11 Effect of spiral reinforcement ratio on energy dissipation

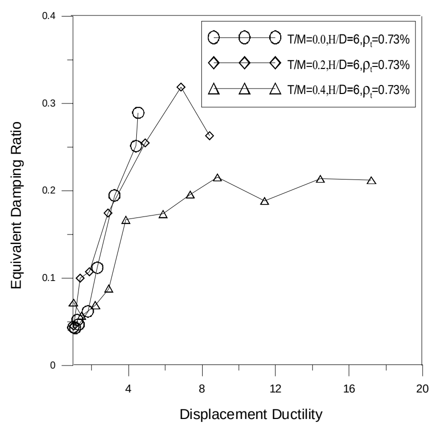


(a) Bending energy

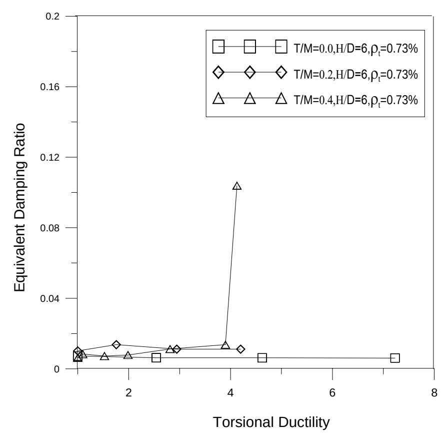


(b) Torsional energy

Fig. 12 Effect of shear span on energy dissipation

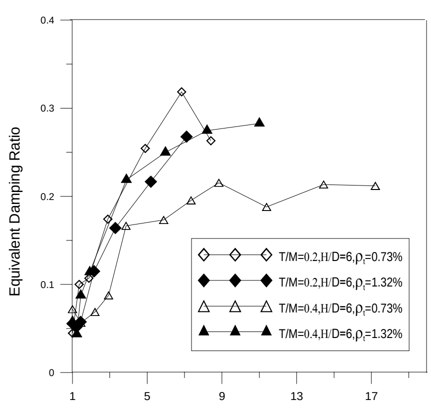


(a) Bending hysteresis

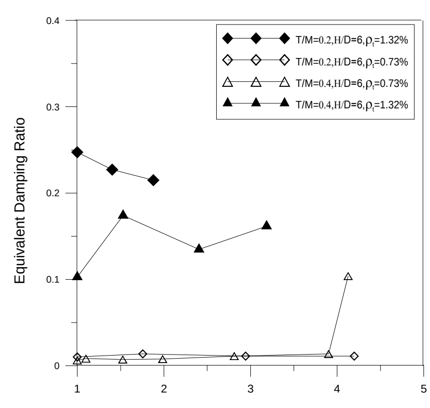


(b) Torsional hysteresis

Fig. 13 Effect of torsion on equivalent damping ratio

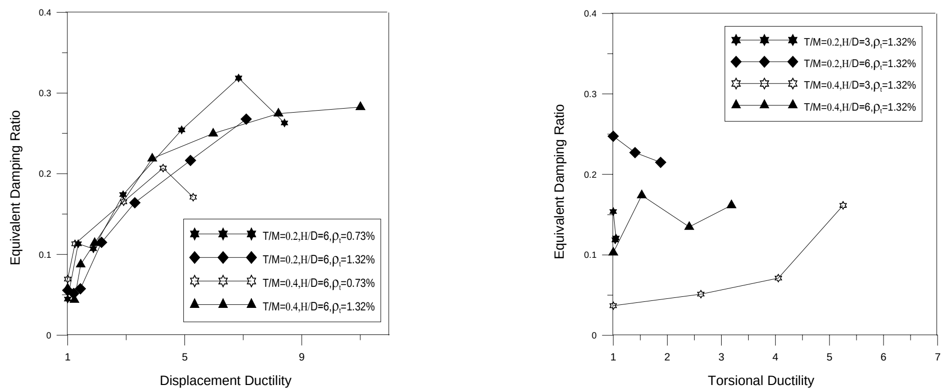


(a) Bending hysteresis



(b) Torsional hysteresis

Fig. 14 Effect of spiral reinforcement ratio on equivalent damping ratio



(a) Bending hysteresis (b) Torsional hysteresis

Fig. 15 Effect of shear span on equivalent damping ratio

Concluding Remarks

Based on this experimental and analytical investigation, the following major concluding remarks can be drawn:

- The combination of bending and torsion had the effect of reducing the torque required to cause yielding of the transverse reinforcement and the peak torsional component.
- Similarly, the combination of bending and torsion had the effect of reducing the bending moment required to cause yielding of the longitudinal reinforcement and the peak component of bending moment.
- Under combined torsion and bending, the torsional stiffness degraded more rapidly than the bending stiffness under increasing increments of displacement/rotation.
- The degradation in strength of the column under pure torsion was contained by increasing the spiral ratio. Increasing the spiral reinforcement ratio helped to increase the torsional strength and rotational ductility by increasing deformational capacity after yielding.
- Increase in the spiral reinforcement ratio resulted in more confinement and thereby helped reducing the degradation of bending as well as torsional strength under combined bending moments and torsion.
- There was no reduction in bending and torsional strength with reduction in shear span. This was mainly due to predominant flexural failure mode because of low longitudinal reinforcement ratio considered in this study. However, the energy dissipation under bending and torsion reduced considerably with reduction in shear span ratio.
- Energy dissipation capacity and equivalent damping ratio under combined bending and torsion increased with increase in spiral reinforcement ratio. However, they decreased with increase in torsion to bending moment ratio and reduction in shear span ratio.

Acknowledgements

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

References

Ang, B.G., Priestley, M.J.N. and Paulay, T. (1989). Seismic shear strength of circular reinforced concrete columns. *ACI Structural Journal,* V. 86, No. 1, pp. 45-59.

Belarbi, A., Suriya Prakash, S. and You, Y.M. (2008). Effect of spiral ratio on behavior of reinforced concrete bridge columns under combined loadings including torsion. *Proceedings of the 4th International Conference on Advances in Structural Engineering and Mechanics,* Jeju, Korea. May 26-28, pp. 1190-1205.

Hsu, H.L. and Wang, C.L. (2000). Flexural-torsional behavior of steel reinforced concrete members subjected to repeated loading. *Earthquake Engineering and Structural Dynamics,*V. 29, pp. 667-682

Kowalsky, M.J. and Priestley, M.J.N. (2000). Improved analytical model for shear strength of circular reinforced concrete columns in seismic regions. *ACI Structural Journal,* V. 97, No. 3, pp. 388-396.

Lehman, D.E., Calderone, A.J. and Moehle, J.P. (1998). Behavior and design of slender columns subjected to lateral loading. *Proceedings of Sixth U.S. National Conference on Earthquake Engineering,* EERI, Oakland, California. May 31-June 4, Paper No. 87.

Otsuka, H., Takeshita, E., Yabuki, W., Wang, Y., Yoshimura, T. and Tsunomoto, M. (2004). Study on the seismic performance of reinforced concrete columns subjected to torsional moment, bending moment and axial force. *13th World Conference on Earthquake Engineering*, Vancouver, Canada. August 1-6. Paper No. 393.

Ozcebe, G. and Saatcioglu, M. (1989). Hysteretic shear model for reinforced concrete members. *Journal of Structural Engineering, ASCE,* V. 115, No.1, pp. 132-148.

Park, Y.J. and Ang, A.H.S. (1985). Mechanistic seismic damage model for reinforced concrete. *Journal of Structural Engineering, ASCE*, V. 111, No.4, pp. 722-739.

Priestly, M.J.N and Benzoni, G. (1996). Seismic performance of circular columns with low longitudinal reinforcement ratios. *ACI Structural Journal,* V. 93, No. 4, pp. 474-485.

Priestly, M.J.N, Seible, F. and Calvi, G.M. (1996). Seismic design and retrofit of bridges. *John Wiley and Sons, Inc.,* New York, 686 pp.

Suriya Prakash, S., Belarbi, A. and Ayoub, A. (2008). Cyclic behavior of RC bridge columns under combined loadings including torsion. *Sixth Seismic National Conference on Highways and Bridges*, Charleston, South Carolina. July 27-30.

Tirasit, P., Kawashima, K. and Watanabe, G. (2005). An experimental study on the performance of RC columns subjected to cyclic flexural torsional loading. *Second International Conference on Urban Earthquake Engineering,* Tokyo, Japan. pp. 357-364.

You, Y.M. and Belarbi, A. (2008). An analytical model to predict the behavior of circular reinforced concrete columns subjected to combined loadings including torsion. October 11-14. 14th World Conference on Earthquake Engineering, Beijing, China.

Zhang, J. and Xu, S.Y. (2008). Seismic response of simulations of bridges considering shear-flexural interaction of columns. *Proceedings of the 4th International Conference on Advances in Structural Engineering and Mechanics*, May 26-28, Jeju, Korea, pp. 1167-1179.