Center for Transportation Infrastructure and Safety

Seismic Performance of Square RC Bridge Columns under Combined Loading including Torsion with Low Shear

by

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16. Abstract

During earthquake excitations, reinforced concrete bridge columns can be subjected to a combination of axial load, shear force, flexural moments, and torsional moments. The torsional moment can be much more significant in columns of bridges that are skewed, curved, have unequal spans, or unequal column heights. Combined loading including torsion can result in complex flexural and shear failure of these bridge columns. This paper presents an experimental study on the seismic behavior of square reinforced concrete columns under combined cyclic flexural and torsional moments. The columns in this study were designed with an aspect ratio of six and tested under various loading conditions: cyclic flexural moment and shear force, cyclic pure torsion, and combined cyclic shear force, bending, and torsional moments. Test results reveal that (1) the flexural and torsional capacity is decreased due to the effect of combined loading, (2) the failure modes and deformation characteristics are changed, and (3) the damage zone tends to move upwards from the typical flexural plastic hinge zone due to the effect of additional torsional moment. The effects of combined loading on the hysteretic loading-displacement response, and damage characteristics are discussed.

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Seismic Performance of Square RC Bridge Columns under Combined Loading including Torsion with Low Shear

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ABSTRACT

During earthquake excitations, reinforced concrete bridge columns can be subjected to a combination of axial load, shear force, flexural moments, and torsional moments. The torsional moment can be much more significant in columns of bridges that are skewed, curved, have unequal spans, or unequal column heights. Combined loading including torsion can result in complex flexural and shear failure of these bridge columns. This paper presents an experimental study on the seismic behavior of square reinforced concrete columns under combined cyclic flexural and torsional moments. The columns in this study were designed with an aspect ratio of six and tested under various loading conditions: cyclic flexural moment and shear force, cyclic pure torsion, and combined cyclic shear force, bending, and torsional moments. Test results reveal that (1) the flexural and torsional capacity is decreased due to the effect of combined loading, (2) the failure modes and deformation characteristics are changed, and (3) the damage zone tends to move upwards from the typical flexural plastic hinge zone due to the effect of additional torsional moment. The effects of combined loading on the hysteretic loading-displacement response, and damage characteristics are discussed.

INTRODUCTION

Reinforced Concrete (RC) bridge columns can be subjected to multi-directional ground motions which result in the combination of axial force, shearing force, flexural moments, and torsional moments. The addition of torsional moment is more likely in skewed or horizontally curved bridges, bridges with unequal spans or column heights, and bridges with outrigger bents. In addition, structural constraints due to a rigid decking, movement of joints, abutment restraints, and soil conditions also lead to combined loading. This combination of seismic loading can result in complex flexural and shear failure of these bridge columns. Behavior of columns under flexure is relatively well understood (Priestley et al., 1996 and Lehman et al., 1998). However, very few experimental results are reported in the literature on the behavior of rectangular or square columns under combined loadings. Otsuka et al. (2004) conducted cyclic loading tests on nine rectangular RC columns under pure torsion, flexure, and at different ratios of combined flexural and torsional moments.

The authors found that the torsional hysteresis was significantly affected by the spacing of the transverse tie reinforcement. Tirasit and Kawashima (2005) tested reinforced concrete columns under combined cyclic flexure and torsion with three different rotation-to-drift ratios and formulated a nonlinear torsional hysteretic model. The authors concluded that the flexural capacity of a reinforced concrete column decreases and the damage tends to occur above the flexural plastic hinge region as the rotation-to-drift ratio increases. Belarbi et al. (2008) presented a state of the art report on behavior of RC columns under combined loadings and scope for further research. They found that the effect of degradation on concrete strength in the presence of shear and torsional loads and confinement of core concrete due to transverse reinforcement significantly affected the ultimate strength of concrete sections under combined loading. They also suggested developing simplified constitutive models incorporating softening and confinement effects. Test results on behavior of circular columns under combined loading with different spiral ratio (Belarbi et al., 2009) and shear span ratio (Prakash et al., 2009) is also reported in the literature. This paper presents the results of experimental studies on the performance of RC square columns under a cyclically applied combined loading. Test results of the four columns: one under cyclic flexure, one under pure cyclic torsion, and two others under combined cyclic flexure and torsion are presented in this paper.

EXPERIMENTAL PROGRAM

Specimen Details

Half-scale test specimens were designed to be representative of typical existing RC square bridge columns. The dimension and reinforcement layout of the specimen are shown in Figure 1. The column specimens had a width of 550 mm and concrete clear cover of 38 mm. Four columns had the same aspect ratio (H/D=6) to simulate flexure dominated behavior with low shear force. Typically, the superstructure dead load induces axial loads in bridge columns varying between 5% and 10% of the capacity of the columns. Therefore, the axial load ratio was taken to be 7% of the concrete capacity of the columns. Four No.9 bars (28 mm. diameter) and eight No.8 bars (25 mm. diameter) were employed as the longitudinal reinforcement to obtain the longitudinal reinforcement ratio of 2.1%. To achieve a better confinement of the core concrete, rectangular and octagonal No.3 (9 mm. diameter) rebar was used for transverse reinforcement with spacing of 83 mm. The transverse reinforcement ratio was kept at 1.32% for all the column specimens.

Material Properties

The concrete was supplied by a local Ready Mix Plant with requested 28-day design cylinder compressive strength of 35 MPa. Deformed bars were used in all specimens. Standard tests for concrete compressive strength, modulus of rupture, and tension tests on steel coupons were conducted. The actual concrete and reinforcement properties of the columns on the day of the testing of column specimens are given in Table 1.

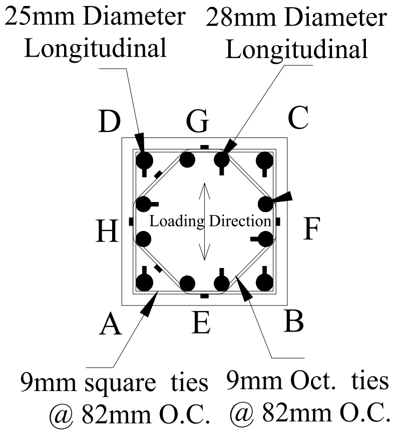


Figure 1 - Cross Sectional Details

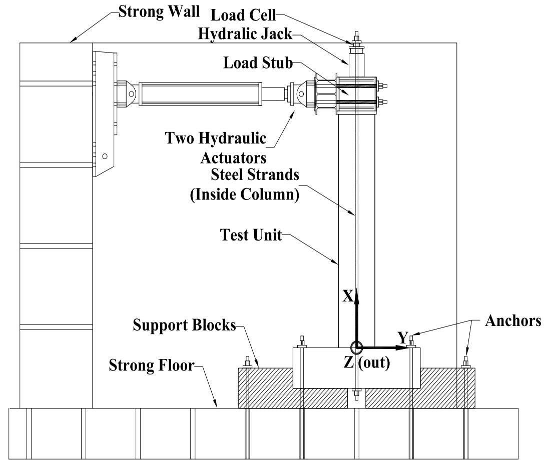


Figure 2 – Elevation of Test Set-up

Table 1. Mechanical Properties of Concrete and Steel used in Columns

PROPERTY	H/B(6)-T/M(0)	H/B(6)-T/M(∞)	H/B(6)-T/M(0.2)	H/B(6)-T/M(0.4)
Compressive Strength (f'_c, MPa)	36.3	34.6	40.5	40.4
Modulus of Rupture (f_{cr}, MPa)	3.73	3.57	3.68	3.64
Transverse Reinforcement Ratio (%)	1.32	1.32	1.32	1.32
Transverse Yield Strength (MPa)	454			
Longitudinal Yield Strength (MPa)	512			

Test Setup and Instrumentation

The axial load was applied by a hydraulic jack on top of the columns to obtain the target 7% axial load ratio. Cyclic pure torsion, flexure, and combined flexure, shear, and torsion were generated by controlling the two horizontal servo-controlled hydraulic actuators. Pure torsional moment was applied through equal but opposite directional forces with the two actuators. Combined cyclic torsional and flexural moments were generated by controlling forces or displacements in each of the actuators. The ratio of the forces or displacements in the two actuators can be maintained to control the desired ratio of the torsion-to-bending moment. The axial load in the un-bonded pre-stressed steel strands was measured by a load cell between the hydraulic jack and the top of the load stub. Load cells within the horizontal hydraulic actuators were used to measure the applied horizontal forces. The columns had a number of strain gages installed at various locations to study the strain variation in longitudinal and transverse reinforcement.

Load Protocol

Tests under flexure, and combined flexure, shear and torsion loading were conducted in load control mode until the first yielding of the longitudinal bars. The loads were applied at intervals of 10% of the lateral load corresponding to the predicted yielding of the first longitudinal bar (F_y) for the columns under flexure and combined flexure, shear, and torsion loading conditions. The horizontal displacement corresponding to yielding of the first longitudinal bar was defined as displacement ductility one (μ_Δ=1). Under pure torsion, the column was tested at 10% intervals of the predicted yielding of the first transverse reinforcement (T_y). The twist corresponding to the first yielding of the transverse reinforcement was defined as twist ductility one (μ_θ=1). After the first yield, the tests were performed in displacement control mode until the failure of the specimens at specific levels of ductility by controlling the desired T/M ratios. Three cycles of loading were applied at each ductility level to provide the indication of strength and stiffness degradation characteristics. Under flexure, the loading along the direction D-A and A-D were defined as positive and negative cycles, respectively (Figure 1). Similarly, the twisting along D-A and A-D were defined as positive and negative cycles, respectively for columns under pure torsion and combined loading.

TEST RESULTS AND DISCUSSIONS

Columns under Cyclic Flexure

The flexural hysteresis of the square column tested under flexure is shown in Figure 3. The column tested under flexure first exhibited horizontal flexural cracking near the bottom 400 mm from the base of the column on side AB and side CD after being cyclically loaded to 40% of F_y. With increasing shear force, these cracks continued to extend and new cracks appeared on each side of the column at higher locations. Subsequently, the concrete cover started to spall at a drift of about 2% when the column was loaded to a displacement ductility of three. Longitudinal bars on sides 'AB' and 'CD' both reached the yield strain at the predicted ductility level one. The square and octagonal transverse reinforcement remained elastic until a ductility level of eight, after which they yielded.

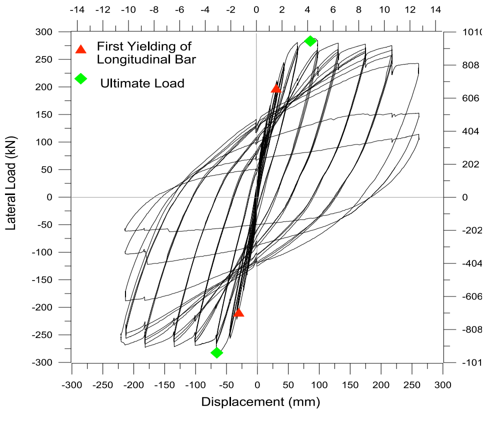


Figure 3 - Hysteresis Curves under Flexure

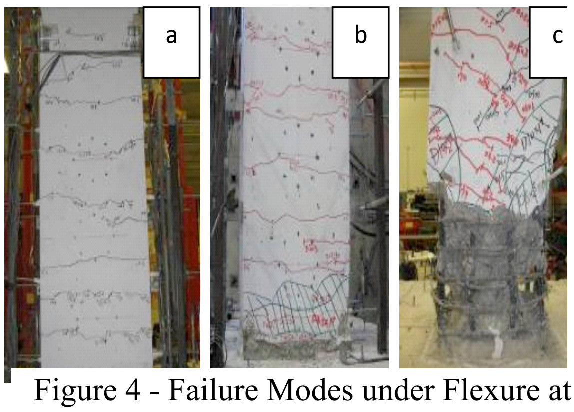


Figure 4 - Failure Modes under Flexure at (a) Longitudinal Bar Yield, (b) Ultimate, and (c) Final failure

The failure mode of the column began with the formation of a flexural plastic hinge with 360 mm height from the base of the column, followed by core concrete degradation due to crushing of concrete. The column failed by the buckling and rupturing of longitudinal bars, followed by rupturing of transverse reinforcement on the compression side at the last cycle of ductility 12. The progressing damage of the square column is shown in Figure 4.

Columns under Cyclic Pure Torsion

Investigating the behavior of members subjected to pure torsion is necessary for generalizing the analysis of a structural member under combined loading. However, only very few studies have been reported on the behavior of RC square sections under pure torsion. Square and octagonal ties were used to obtain better confinement of the core concrete and enhance the strength and ductility characteristics. The torsional moment-twist hysteresis response of the specimen is shown in Figure 5. The torsional moment is approximately linear up to cracking and thereafter becomes nonlinear with a decrease in the torsional stiffness. The post cracking stiffness decreased proportionally with increase in the cycles of loading. Under pure torsional loading, significant shear cracks started developing near mid-height of the column at a lower level of 60% T_y. Typical damage progress of the column under pure torsion is shown in Figure 6. Concrete cover spalling started at mid-height of the column at ductility one and spread to the full height of the column at ductility eight. At higher cycles of loading, a torsional plastic hinge formed near the mid-height of the column due to significant concrete spalling and severe core degradation. Finally, the square and octagonal ties ruptured in the plastic hinge zone leading to the overall failure of the column.

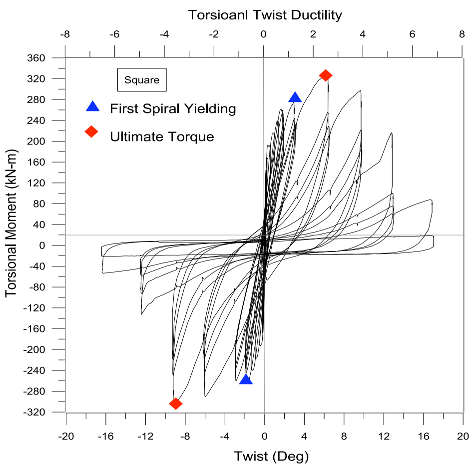


Figure 5 - Hysteresis Curves under Pure Torsion

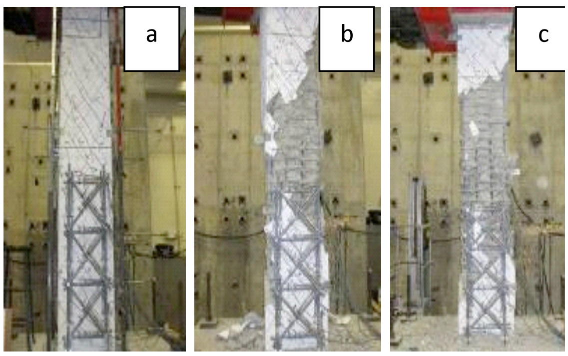
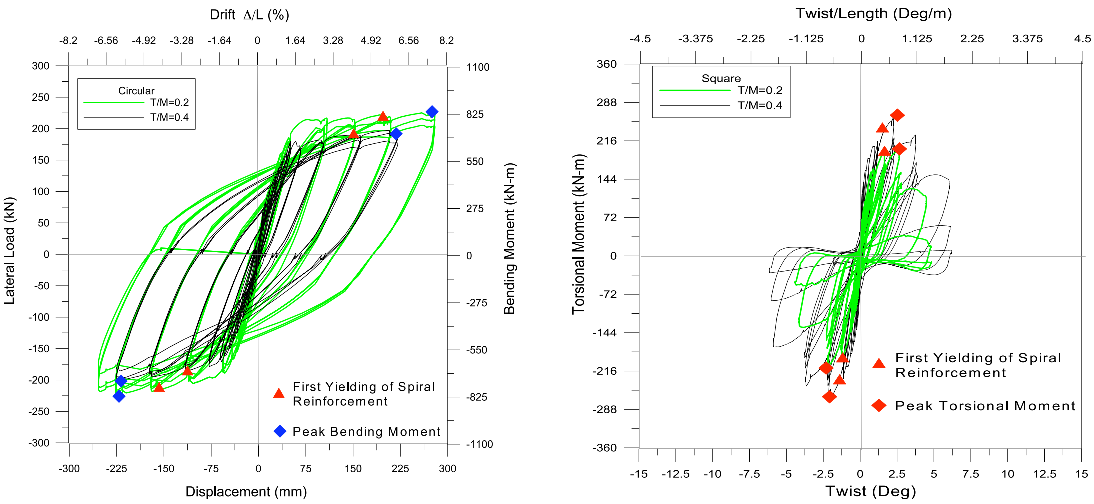


Figure 6 - Failure Modes under Pure Torsion at (a) Transverse Yield, (b) Ultimate, and (c) Final failure

Columns under Cyclic Combined Flexure, Shear and Torsion

To study the interaction of flexure and torsional moments, two square columns were tested at T/M ratios of 0.2 and 0.4. The test results from columns under flexure and pure torsion were used as the benchmarks for analyzing the behavior of specimens under combined loading. For the columns under combined loading, flexural cracks firstly appeared near the base of the column. With increasing levels of torsional and flexural moments, the angle of the cracks became more inclined at increasing heights above the top of the footing due to the effect of torsional moment. The flexural and torsional hysteresis behaviors of the column are shown in Figure 7 (a) and (b). Strength and stiffness degradation were observed with increases in the loading cycles at each ductility level. The flexural and torsional capacities reduced considerately due to the effect of combined loading compared to pure flexure and pure torsion results. Typical damage characteristics and failure sequence of the columns under combined flexure and torsion is shown in Figure 8. Under combined loading, failure of the columns started due to severe combinations of shear and flexural cracks followed by crushing of the concrete core. The column finally failed due to buckling of the longitudinal bars on sides ‘AB’ and ‘CD’.



(a) Flexural Hysteresis (b) Torsional Hysteresis

Figure 7 – Flexural and Torsional Hysteresis Behavior under Combined Loading

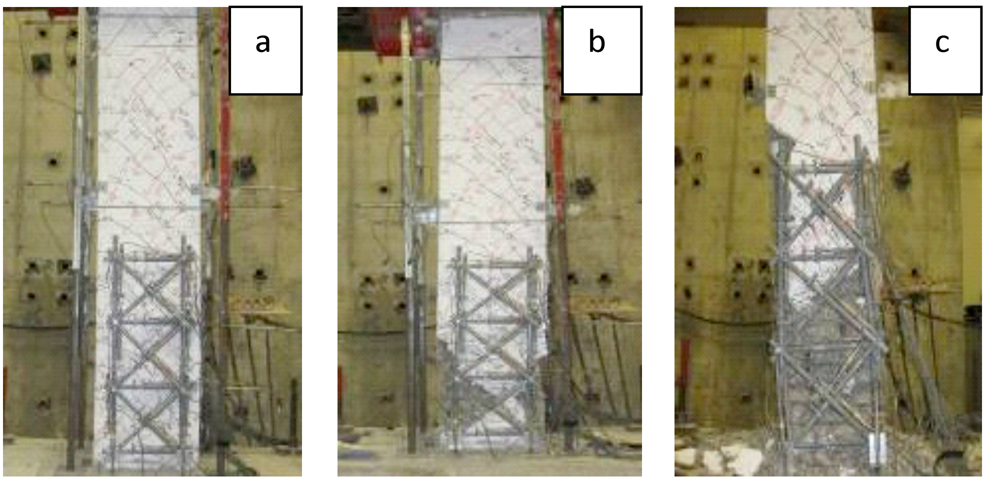


Figure 8 –Failure Mode under Combined Loading at (a) Longitudinal Reinforcement Yield (b) Peak Torsional moment and (c) Overall Failure

EFFECT OF COMBINED FLEXURAL AND TORSIONAL LOADING

The damage distribution for the test specimens under various T/M ratios is shown in Figure 9. The damage zone increased to 560 and 950 mm from the base of the column for the columns tested at T/M ratios of 0.2 and 0.4 respectively compared to 360 mm for the column tested under flexure. This shows that the damage location moves upward due to the effects of the additional torsional moment. However, the specific location of the plastic hinge or damage zone depends on a number of factors, such as the amount of transverse and longitudinal reinforcement, aspect ratio of the section, and concrete strength which all need to be investigated further. Interaction diagrams between torsional and bending moments for the tested specimens are shown in Figure 10. It clearly shows the torsional and flexural strength degradation according to the applied T/M ratio.

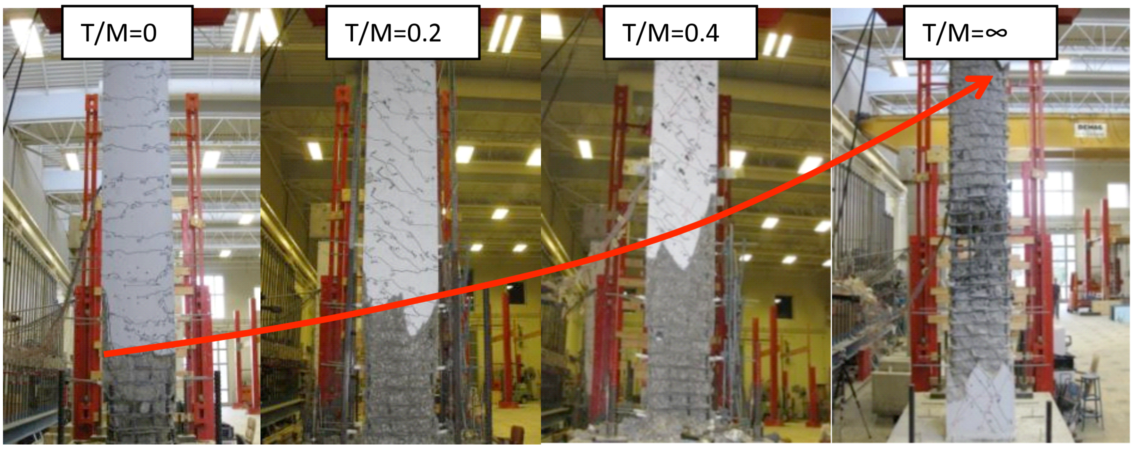


Figure 9 –Effect of Torsion on Damage Distribution of Test Columns under Combined Loading

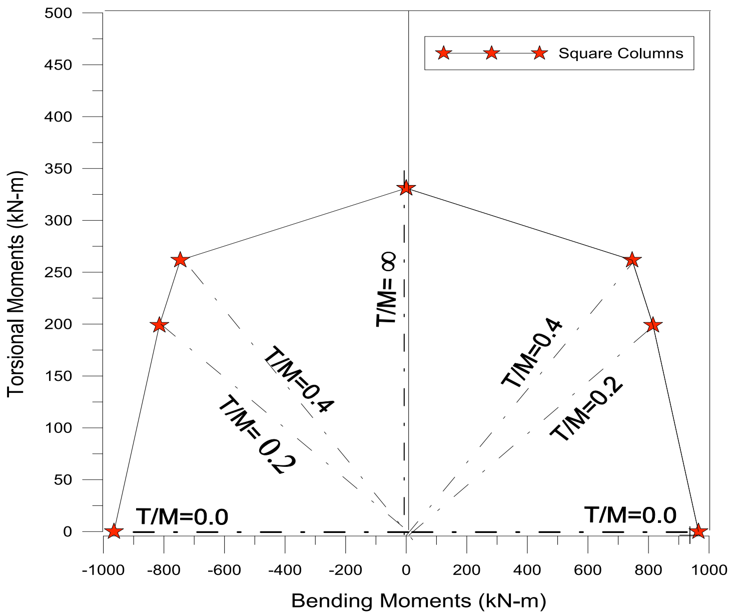


Figure 10 –Interaction of Torsion and Bending Moment at Peak Torque

CONCLUDING REMARKS

An experimental study on the effect of combined cyclic flexure and torsion on the behavior of square reinforced concrete columns was presented. Based on the test results of four specimens presented in this paper, the following conclusions were made:

1) The column tested under flexure and low shear failed in a flexure mode by formation of a plastic hinge at the base of the column, followed by core degradation, and finally by the buckling of longitudinal bars.
2) The failure of columns under pure torsion occurred due to significant diagonal shear cracking followed by significant core damage at mid-height of the column. In addition, the concrete cover spalled along almost the full height of the column.
3) The combined loading including torsion altered the damage patterns of the reinforced concrete columns. The location and length of the damage zone moved upward from the base of the column with increasing level of torsional moment.
4) The ultimate lateral load and displacement capacity of the columns significantly decreased with increasing torsional moment. Similarly, the ultimate torsional moment and the corresponding twist reduced with increasing amount of flexural moment.

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