DAMAGE AND ENERGY DISSIPATION OF RC BRIDGE COLUMNS UNDER
COMBINED LOADINGS INCLUDING TORSION DURING EARTHQUAKES

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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, flexural, shear and torsional loadings during an earthquake. The combination of axial, bending, shear and torsion in RC bridge columns can result in complex failure modes. Under a NSF-NEES funded project, experimental and analytical studies are conducted to investigate the performance of RC columns under combined loadings including torsion. The main variables considered are (i) the ratio of torsion to bending moment, (ii) the ratio of bending moment to shear, and (iii) level of detailing for high and moderate seismicity (low or high spiral ratio). The experimental results are used to develop and calibrate the design interaction equations. Based on the experimental results, damage and ductility models that account for the combined loading effects are also developed from design point of view. This paper presents an overall summary of the major findings and relevant results from both the experimental and analytical studies. In addition, it also provides new directions in the design and detailing of RC bridge columns under seismic loading.

1. INTRODUCTION
During earthquake excitations, reinforced concrete (RC) bridge columns can be subjected to torsional moments in addition to axial, bending and shear forces. 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 cause complex failure modes. Very few experimental results have been reported on the behavior of rectangular columns under combined loadings. 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 various 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 T/M ratios, the energy dissipation capacity decreases.

The behavior of columns under bending with and without axial loadings has been extensively investigated by a number of researchers. There are rational models available for analyzing the interaction between axial and bending loads. Park and Ang (1985), Priestly and Benzoni (1996), Priestly et al. (1996) and Lehman et al. (1998) have 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. 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. Moving toward such a model, 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 development of analytical models, however, has been hindered by the paucity of test results of RC circular columns with different reinforcement ratios under combined bending, shear, and torsion loadings. Therefore, the research work done in this study will be helpful not only for the enhancement of

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knowledge on the behavior of RC circular bridge columns under cyclic combined loadings but also for providing experimental data towards the development of rational analytical models.

2. EXPERIMENTAL PROGRAM
The main variables considered in this study are (1) the ratio of torsion-to-bending moment, (2) column aspect ratio 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 \( \frac{M/V}{H} \) to diameter \( D \). The study consisted of testing circular columns at high aspect ratio \( \frac{H/D}{6} \) with low shear and at low aspect ratio \( \frac{H/D}{3} \) 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.

2.1. 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. 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.

Table 1. Test Matrix

<table>
<thead>
<tr>
<th>Test Columns</th>
<th>Compressive Strength (MPa)</th>
<th>Spiral Ratio (%)</th>
<th>Aspect Ratio (H/D)</th>
<th>Torsion to Bending Ratio (T/M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M/V(12)-T/M(0)</td>
<td>33.4</td>
<td>0.73</td>
<td>6</td>
<td>0.0</td>
</tr>
<tr>
<td>M/V(12)-T/M(0.1)</td>
<td>29.7</td>
<td>0.73</td>
<td>6</td>
<td>0.1</td>
</tr>
<tr>
<td>M/V(12)-T/M(0.2)</td>
<td>26.5</td>
<td>0.73</td>
<td>6</td>
<td>0.2</td>
</tr>
<tr>
<td>M/V(12)-T/M(0.4)</td>
<td>25.7</td>
<td>0.73</td>
<td>6</td>
<td>0.4</td>
</tr>
<tr>
<td>M/V(12)-T/M(∞)</td>
<td>37.9</td>
<td>1.32</td>
<td>3</td>
<td>0.4</td>
</tr>
<tr>
<td>M/V(12)-T/M(0.2)</td>
<td>41.2</td>
<td>1.32</td>
<td>3</td>
<td>0.2</td>
</tr>
<tr>
<td>M/V(12)-T/M(0.4)</td>
<td>41.2</td>
<td>1.32</td>
<td>3</td>
<td>0.4</td>
</tr>
<tr>
<td>M/V(6)-T/M(0)</td>
<td>25.8</td>
<td>1.32</td>
<td>3</td>
<td>0.4</td>
</tr>
<tr>
<td>M/V(0)-T/M(∞)</td>
<td>28.0</td>
<td>1.32</td>
<td>3</td>
<td>0.4</td>
</tr>
<tr>
<td>M/V(6)-T/M(0.2)</td>
<td>28.7</td>
<td>1.32</td>
<td>3</td>
<td>0.4</td>
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<td>0.4</td>
</tr>
</tbody>
</table>

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

The axial load due to the superstructure dead weight was assumed to be 7% of the capacity of the columns. 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%. Detailed information of the material properties of the test specimens can be found elsewhere (Belarbi et al., 2008 and Suriya Prakash et al., 2008).

3. TEST RESULTS AND DISCUSSION
3.1. 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 more or less 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 tested under pure torsion. The angle of diagonal cracks was nearly 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 test.

![Diagram](image)

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

![Diagram](image)

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

![Diagram](image)

**Fig. 4** Torsion-bending moments interaction diagrams

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 flexural cracking, followed by shear cracking, longitudinal bar yielding, spalling, spiral yielding,
and then overall failure by buckling of the longitudinal bars immediately after significant core degradation. Yielding of the longitudinal and spiral reinforcement occurred in quick succession 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 no longer be maintained to complete the test.

3.2. Effect of Shear Span/Aspect Ratio under Combined Loadings

The behavior of RC columns can be classified into flexure or shear dominated or with significant flexure-shear interaction. The aspect ratio of the column determines the level of flexure-shear interaction. 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 like 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 could no longer be 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 due to shear.

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

Fig. 6 Torsion-bending moments interaction diagrams
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 nonlinear fashion after the spiral and longitudinal bar yielding.

3.3 3D Flexure-Shear-Torsion Interaction Diagrams

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 reduced 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. 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 T/M 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.

3.4 Ductility and Energy Dissipation Characteristics

In the recent years, the focus of research has shifted towards performance-based seismic design (Lehman and Moehle 2000) to improve the methods of evaluating the column performance over a range of performance levels. From a performance based-design point of view, the designers are interested in strength, stiffness, deformational capacity, and energy dissipation ability of members under combined loadings. Energy dissipation capacity is a crucial parameter in assessing the seismic performance of the structure.

RC members dissipate energy through the formation of cracks, and internal friction from the plastic deformation of the reinforcement and friction due to sliding of the concrete struts (Greene 2006). 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. Therefore, it is necessary to rationally assess the inelastic response of RC columns under combined loadings.

The effect of increasing the spiral reinforcement ratio on energy dissipation capacity and ductility is shown in Fig. 9. The increase in spiral reinforcement ratio significantly increased the energy dissipation capacity and ductility in bending and torsion. The columns with lower aspect ratio of 3 or shear dominated columns has less energy dissipation capacity in bending as well as torsion when compared to columns with aspect ratio of 6 (Fig. 10). In addition, the torsional rotation and displacement ductility reduced with reduction in aspect ratio. Moreover, the equivalent damping ratio is significantly lesser for torsional hysteresis when compared to bending hysteresis.

Significant improvement in the energy dissipation and increase in equivalent damping ratio is obtained with increase in spiral reinforcement ratio for both bending and torsional hysteresis. Also, the equivalent damping ratio decreased with reduction in aspect ratio or with decrease in moment to shear ratio.
in spiral reinforcement ratio. However, they decreased with increase in T/M ratio and reduction in shear span ratio.

5. ACKNOWLEDGMENTS
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6. REFERENCES