



PERFORMANCE OF BRIDGE REINFORCED CONCRETE COLUMNS UNDER COMBINED ACTIONS THROUGHOUT SHAKE TABLE TESTING

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ABSTRACT

Evidence found after significant earthquakes have shown that the force and deformation capacity of reinforced concrete bridge columns (RCC) can be significantly affected by the combined effect of dynamic loads (axial, shear, bending and torsion); these load combinations can result in unexpected large deformations and extensive damage that can seriously affect the seismic performance of bridges. To study the impact of different loadings combinations on both circular and non-circular sections (double interlocking spirals), eight scaled cantilever-type RCC specimens will be tested on the bidirectional shake table facility at the University of Nevada, Reno (UNR). As part of the study, a unique inertial loading system named the Bidirectional Mass Rig was developed to allow shake table testing of single RCC under biaxial ground motions. Two sets of circular and interlocking RCC will be subjected to different levels of biaxial, torsion and vertical loads through real time earthquake motions. The performance of the specimens will be assessed in terms of strength, deformation, and failure mode. Four of the eight specimens are reported in this paper

Introduction

Under seismic excitations reinforced concrete bridge columns (RCC) are subjected to combinations of forces and deformations; these are caused by, among other reasons, spatially-complex variation of earthquake ground motions, the bridge structural configurations and the interaction between input and response characteristics. As a result, the seismic behavior of RCC will be seriously affected, and that in turn influences the performance of bridges as essential components of transportation systems. In addition, current analytical methods, behavior theories and design practices do not take into consideration the full range of interactions, due to the scarcity of experimental data and a lack of behavioral understanding.

In order to address the complex behavior of RCC under combined loadings and to develop a fundamental knowledge of the impact of combined actions on column performance and their implications on system response through analytical and experimental research, a comprehensive project sponsored by the National Science Foundation was established in 2006. This project includes researchers from six institutions.

The work at UNR focuses on the development of refined analysis and shaking table tests of cantilever-type large scale models of RCC subjected to different levels of biaxial, torsion and vertical loads through real time earthquake motions. The study was divided into two stages, first

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RCC will be tested without axial load and subsequently, other set of RCC will be tested including axial load and Pdelta effects. The seismic performance of the specimens will be assessed in terms of strength, deformation, and failure mode. These results will be used to validate analytical tools, developing new inelastic models for RCC under combined loadings and to propose new design methodologies. This paper highlights the first stage of the study.

Specimen Details

Four circular and four double interlocking specimens were designed and constructed using current details typical of bridges in California in accordance with the Seismic Design Criteria (CALTRANS, 2006). The structural configurations were similar to previous columns tested at UNR (Laplace et al., 1999 and Correal et al., 2004). For circular columns the scaling factor was 1/3. The diameter of the specimens was 406 mm (16 in) and the height 1830 mm (72 in), thus the aspect ratio was 4.5, which allows for flexural dominated behavior. The columns were reinforced with 20 No.4 (D13) deformed longitudinal bars, distributed evenly around the perimeter and fully developed with 90 degree hooks in the footing. This resulted in a longitudinal reinforcement ratio of 2%. The confinement consisted of a continuous spiral made from galvanized smooth steel wire with a diameter of 6.25 mm (0.25 in) and a pitch of 38 mm (1.5 in). The clear cover was set to 19 mm (0.75 in) and the resulting volumetric ratio of the spiral reinforcement was 0.92%. Details of circular columns are shown in Fig. 1.

For double interlocking columns a scale factor of 1/4 was used. The height was 1830 mm (72 in) and the width in the short side was 305 mm (12 in), while that in the long dimension was 445 mm (17.5 in). The longitudinal reinforcement consisted of 32 No. 3 (D10) deformed bars, spaced evenly in two circular patterns and fully developed in the footing. The resulting reinforcement ratio was 2%, while the volumetric ratio of the spiral reinforcement was 1.0%. The confinement consisted of two continuous spirals made from galvanized smooth steel wire with a diameter of 4.9 mm (0.192 in) and a pitch of 25 mm (1.0 in). The clear cover was set to 13 mm (0.5 in). Details of the interlocking columns are shown in Fig. 1.

The compressive strength of the concrete was set as 30 MPa (4.5 ksi), while the nominal yielding strength of the steel was 447 MPa (64 ksi) for deformed bars and 420 MPa (60 ksi) for wire. Table 1 shows the real properties of steel and concrete based on coupons and cylinders.

Experimental Test Setup

As part of the study, a inertial loading system named the Bidirectional Mass Rig (BMR) was developed to enable the shake table test of single RCC under biaxial motions. The purpose of the setup is to have a supporting structure that carries safely the vertical component of the inertial mass (superstructure weight) but allows transfer of the inertial forces from the structure to the specimen, when the shake table and specimen move together. A similar structure that allows unidirectional testing was developed before at UNR (Laplace, 1999).

The new system is composed by a 3D four columns steel frame and a platform that sets on ball bearings located at the top of the columns. The platform is connected to the RCC specimen through links in two perpendicular directions, which allow transferring shear and torsion but not axial load (Fig. 2a). Additional mass is set on the platform to simulate a portion of the bridge superstructure the weight, and this can be placed in a symmetric or asymmetric configuration to induce different levels of torsion. The superstructure mass was set as 356 kN (80 kips), which is $0.08A_g f'_c$, where f'_c is the compressive concrete strength, and A_g the gross section of the column.

Table 1. Material Properties

| Test day | Concrete Compressive Strength [MPa] | | | |
|----------|-------------------------------------|--------|--------------|--------|
| | Circular | | Interlocking | |
| Column | Footing | Column | Footing | Column |
| 1 | 39 | 32 | 42 | 39 |
| 2 | 41 | 32 | 43 | 31 |

| Steel Properties | No.3 | No.4 | W2.9 | W5.0 |
|-----------------------|--------|--------|--------|--------|
| Yield stress [MPa] | 423 | 448 | 400 | 400 |
| Yield strain | 0.0022 | 0.0023 | 0.0024 | 0.0024 |
| Strain at hardening | 0.012 | 0.0075 | N.A | N.A |
| Peak stress [MPa] | 653 | 712 | 541 | 541 |
| Strain at peak | 0.124 | 0.115 | 0.115 | 0.126 |
| Fracture stress [MPa] | 561 | 687 | 537 | 484 |
| Fracture strain | 0.195 | 0.151 | 0.154 | 0.138 |

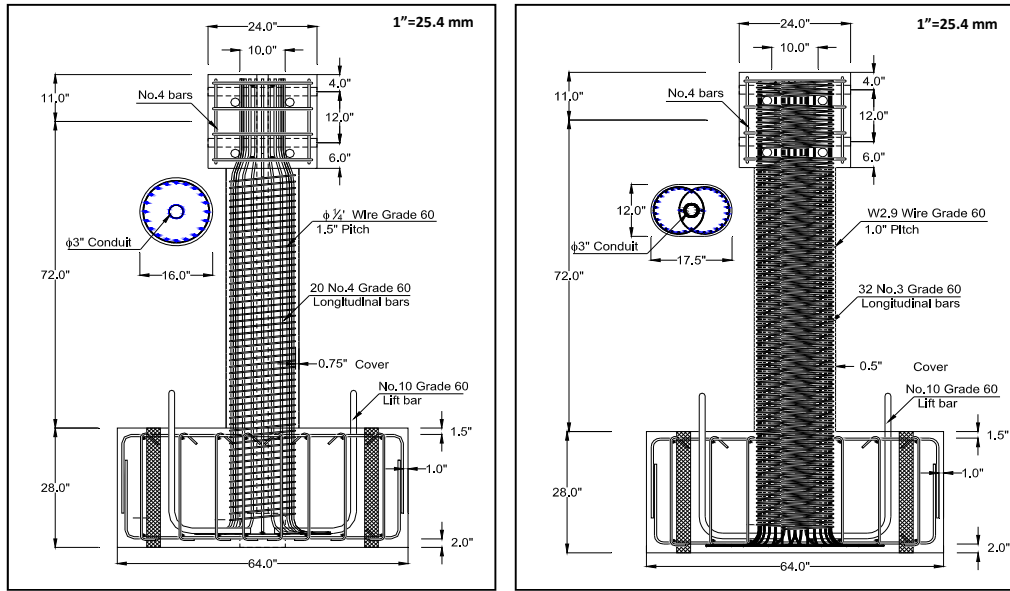


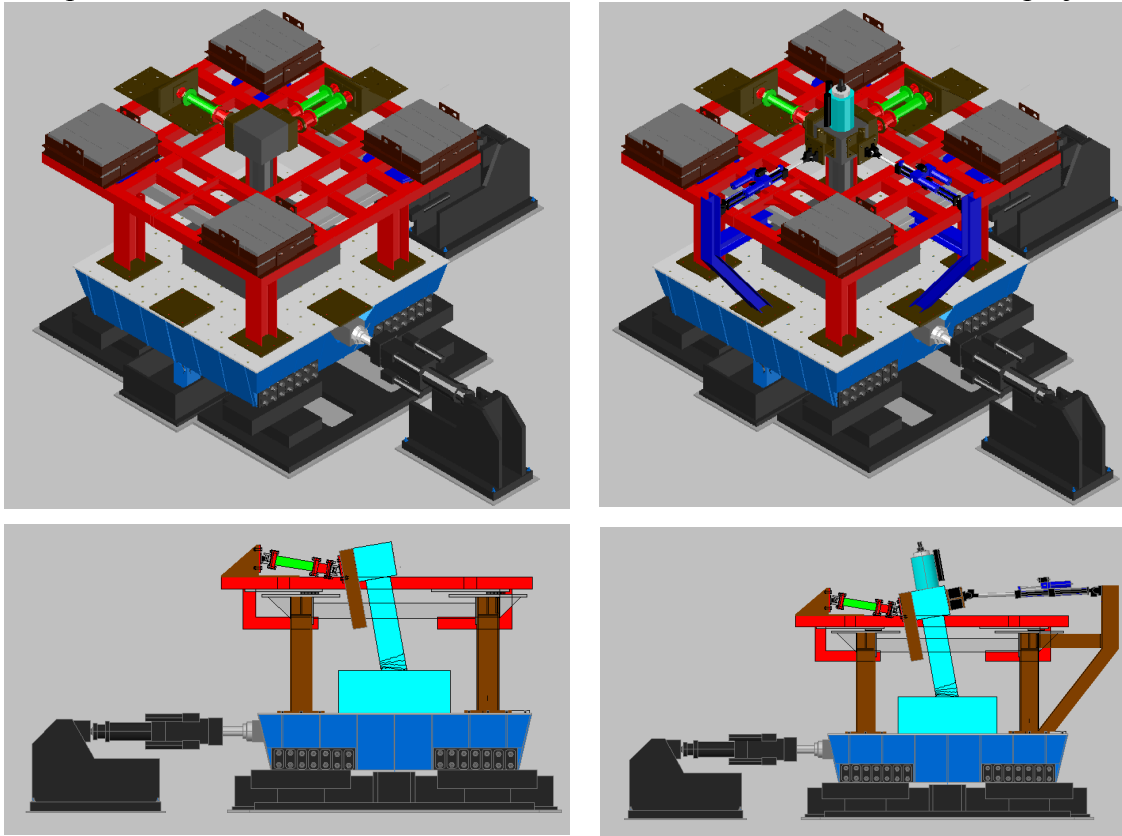
Figure 1. Geometric configuration and reinforcement for the RCC specimens

The axial load is applied directly to the specimen through a center-hole ram equipped with a servo-valve. The ram is connected to the specimens throughout an unbonded prestressed bar placed in an ungrouted conduit at the middle of the column and anchored at the footing. It is important to note that the main purpose of the prestressed bar is to induce the required level of axial load in the columns rather than increases its displacement capacity as has been found in other studies (Sakai *et al.*, 2006).

Since the BMR does not induce secondary moments (PD-effects) in the specimen and the unbonded prestressed bar inside the column would generate restoring lateral forces, additional dynamic actuators will be located at the top of the specimen to induce the equivalent force to have PD effects and to compensate the restoring force throughout hybrid simulation (Fig. 2b).

In view of the complexity of the system in terms of the active control of dynamic actuators, the test program was divided in two phases. At the beginning a set of two circular and two interlocking columns will be tested without any axial load or PD effects. A second phase

will incorporate all the effects. Table 2 outline the test matrix for the entire research project.



a: Without axial load.

b: With axial load (prestressed bar + actuators)

Figure 2. Inertial loading system (Bidirectional Mass Rig)

Table 2. Experimental test matrix

| Test | Shape | Diameter (mm) | Scale | Ht (mm) | Biaxial Bending | Torsion | Axial & PD-effect |
|----------|-------|---------------|-------|---------|-----------------|----------|-------------------|
| Phase I | ● | 406 | 1:3 | 1830 | ✓ | Low | ✗ |
| | ● | 406 | 1:3 | 1830 | ✓ | Moderate | ✗ |
| | ● | 305x445 | 1:4 | 1830 | ✓ | Low | ✗ |
| | ● | 305x445 | 1:4 | 1830 | ✓ | Moderate | ✗ |
| Phase II | ● | 406 | 1:3 | 1830 | ✓ | Low | ✓ |
| | ● | 406 | 1:3 | 1830 | ✓ | Moderate | ✓ |
| | ● | 305x445 | 1:4 | 1830 | ✓ | Low | ✓ |
| | ● | 305x445 | 1:4 | 1830 | ✓ | Moderate | ✓ |

Preliminary Analysis and Ground Motion Selection

To determine the appropriate input loadings to be used during the tests and to anticipate the seismic performance of the specimens and test setup analytical models were performed using

OpenSees (Mazzoni et al., 2006). Analytical models of single cantilever-type columns with lumped mass as well as models of the specimens including the inertial loading system were studied under different levels of earthquake excitations and mass distribution to determine limit states in the behavior of the columns during the tests.

Uniaxial fiber elements with distributed plasticity were used to simulate the biaxial flexural behavior of the columns. The stress-strain properties of the unconfined and confined concrete were simulated using Mander's model (Mander et al., 1988). Similarly, the longitudinal reinforcing steel was idealized using the uniaxial steel material model developed by Chang and Mander (1994). The actual strength of the concrete measured from cylinders and the stress-strain backbone curve measured from coupons were used as the input parameters for the steel and concrete models. Also, the reinforcement slippage was included in the models in the form of additional rotation at the plastic hinge location. Since inelastic fiber models for torsion are still under development (Mullapudi et al., 2008), a reduction factor of 20% of the elastic torsional stiffness (GJ) was used to take in account the torsional degradation of the concrete in agreement with the Seismic Design Criteria (CALTRANS, 2006). Results of single cantilever columns tested under uniaxial ground motion at UNR (Laplace et al., 1999 and Correal et al., 2004), were used to calibrate the analytical model.

To estimate the lateral load-displacement capacities and the deformation characteristics of the specimens, moment-curvature and pushover analysis were performed. Table 2 summarizes the capacities of the circular and double interlocking columns for each direction of analysis, under biaxial behavior. Once the capacities were estimated, a series of nonlinear time history analysis were conducted. For that, different cases of mass distribution were studied to determine the largest bending and torsional demands on the specimens.

Ground Motions

For the preliminary analysis the two horizontal components of the 1940 Imperial Valley earthquake (El Centro), the 1994 Northridge earthquake, and the 1992 Petrolia at Mendocino earthquake were used as the input motions. The earthquake records for Petrolia were scaled to have a hazard level of 2% of exceedence in 50 years for a bridge with period of 0.5 sec located in Cape Mendocino, CA. (Zhang and Xu, 2008).

The amplitude of the records was increased until the maximum capacity of the analytical model was achieved. Also, the time axis of the input motions was scaled using the square root of the scale, then, factors of 0.58 and 0.5 were used for circular and double interlocking specimens, respectively. From the preliminary dynamic analysis, it was found that the record Petrolia at Mendocino (PET) and Sylmar at Northridge (SYL) amplified by a factors of 1.8 will induce the maximum displacement ductility demand on the circular and double interlocking specimens without exceeding the shake table capacity.

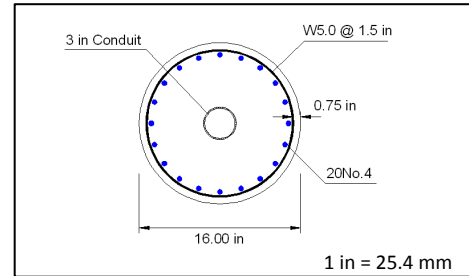
Test Procedure

Two identical circular (C1, C2) and two identical interlocking columns (I1, I2) were tested under the same records. The only difference between specimens was the way in which the mass was distributed on the BMR; for columns C1 and I1 a symmetric distribution of masses was used, while it

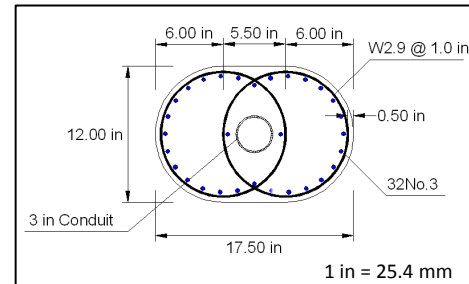
was asymmetric for C2 and I2. Hence, more torsion was expected for C2 and I2.

Table 3: Lateral load capacities of the specimens (Phase I)

| Circular Columns P=0, biaxial @ 45° | |
|-------------------------------------|---------|
| Properties | Radial |
| ϕ_y | 0.00034 |
| My (kN-m) | 177 |
| ϕ_u | 0.00584 |
| Mu (kN-m) | 223 |
| $\mu\Delta$ | 8.29 |
| Vu (kN) | 122 |



| Interlocking Columns P=0, biaxial @ 45° | | |
|---|-----------------|----------------|
| Properties | Short dimension | Long dimension |
| ϕ_y | 0.0004 | 0.0003 |
| My (kN-m) | 158 | 229 |
| ϕ_u | 0.00742 | 0.00431 |
| Mu (kN-m) | 177 | 253 |
| $\mu\Delta$ | 11.5 | 9.3 |
| Vu (kN) | 98 | 138 |



Each column was subjected to the two horizontal components of the selected earthquakes, increasing the amplitude in successive runs and without applying any axial load. Small intensities (10% to 20% of the real earthquake) were initially applied to determine elastic properties and the effective yielding, after that, the amplitude of the records was successively increased until failure. Signals of white noise were applied to the models to measure the change in period and damping ratio between runs. The maximum accelerations imposed in both horizontal directions to the shake table were 0.9g and 1.2g, for Petrolia and 1.1g and 1.5g for Sylmar ground motion. These accelerations corresponded to an amplification factor of 1.8 times the considered earthquakes.

The specimens were extensively instrumented to monitor the local and global response. Transducers were used at selected locations to measure acceleration, lateral force and displacement, torsion, and curvature. Furthermore, strain gages were attached to the longitudinal and transverse steel to measure local deformations. Also, a series of sensors were placed inside the concrete to measure the variation in strains at different locations by a team from the University of Houston lead by Dr. Y.L Mo.

Experimental Results

Observed Behavior

The behavior of the specimens was controlled by the biaxial effect of bending, with horizontal cracks distributed over the specimen height, as well as some inclined cracks at the plastic hinge region near the column base. For small amplitude runs some horizontal flexural cracks were seen on the lower half of the columns and were distributed around the perimeter of the

specimens. The first bar yielding was observed after 0.6xPET for circular columns and after 0.4xSYL for interlocking columns. The damage at this stage was characterized both by the increase in horizontal and the presence of inclined cracks. The first concrete spalling was observed after 0.8xPET, 1.0xPET, 1.0xSYL and 0.8xSYL for specimens C1, C2, I1 and I2, respectively. At this point a large number of horizontal and inclined cracks were observed on the specimens. The spirals and longitudinal bars were visible after 1.6xPET and 1.4xPET for circular columns C1 and C2, whereas in double interlocking specimens I1 and I2, it was observed during 1.6xSYL and 1.4xSYL. The failure for C1 was observed during 1.8xPET, at this stage some of the longitudinal bars buckled and some degradation of the concrete core was observed. In column C2 the failure occurred during 2.0xPET, and was due to torsional buckling and rupture of the longitudinal bars and spirals fracture at the plastic hinge zone. For the double interlocking specimens, since minor steel rupture was observed after 1.8xSYL, the specimens were subjected to an additional run using factors of 1.4 and 1.8 for I1 and I2, respectively. The failure mode in both columns was similar and was due to the torsional buckling and rupture of the outermost longitudinal bars on the long side of the column. Column I2 showed more severe damage in the concrete core than I1. In addition for specimen I2, spiral rupture was observed in the plastic hinge zone. Fig. 3 shows the final damage state for all the columns.

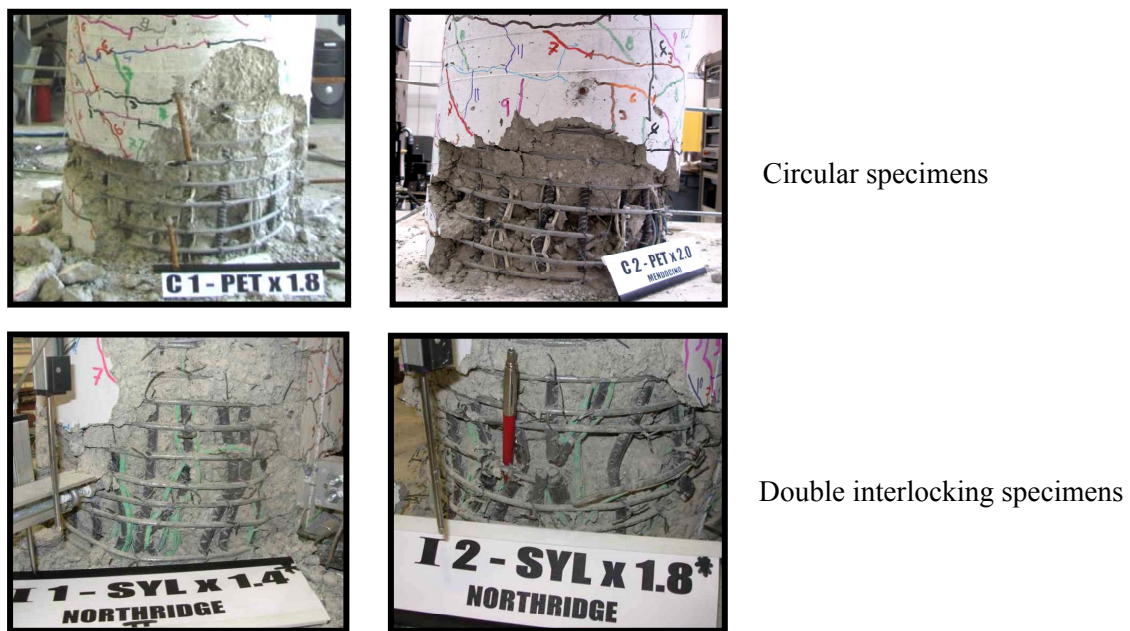


Figure 3. Damage on the specimens after failure

Force-Displacement Hysteresis

The cumulative force-displacement hysteresis curves and the displacement orbits for the specimens are shown in Figs. 4 and 5. The displacements in each direction were calculated by subtracting the table displacement from column displacement, whereas the force was recorded from the load cell placed in the links. The hysteresis response were typical of columns with flexure dominate behavior in which stable loops and progressive reduction in lateral stiffness is observed up to the maximum force is reached. After that point a sudden change in the specimen occurred

due to the longitudinal bars buckling and rupture.

From Fig. 4 It is clear that the hysteresis for the circular specimens shows a biased motion in one direction and becomes more significant after subsequent runs. This effect is due to the ground motion, which is considered as a near fault record with asymmetric peak velocity pulses. As a consequence of this effect, large residual displacements were observed during the test. On the other hand, from the displacement orbits it is evident that the displacement component followed a line with an inclination of 25°.

For the double interlocking specimens the hysteresis in the long direction showed a symmetric pattern with almost the same maximum displacement in each direction. Similarly, that for the short direction was symmetric but just until the maximum force was observed, after that the behavior was influenced by residual displacements (Fig. 5). The displacement orbits showed that the displacement trajectories of the specimens were highly dominated by displacements on the long side of the columns

Fig.6 shows the force-displacements envelopes for the specimens tested. As it can be seen the behavior of specimens sets is almost the same, nevertheless a slightly less capacity is observed for specimens with torsion (C2 and I2) after the first yielding. This behavior is explained because less concrete is effective to resist the tensile stresses in the longitudinal bars induced by the combination of torsion and bending deformations. This effect was more important at high intensity runs and played a significant role in the failure mechanism of the specimens as in Fig. 3.

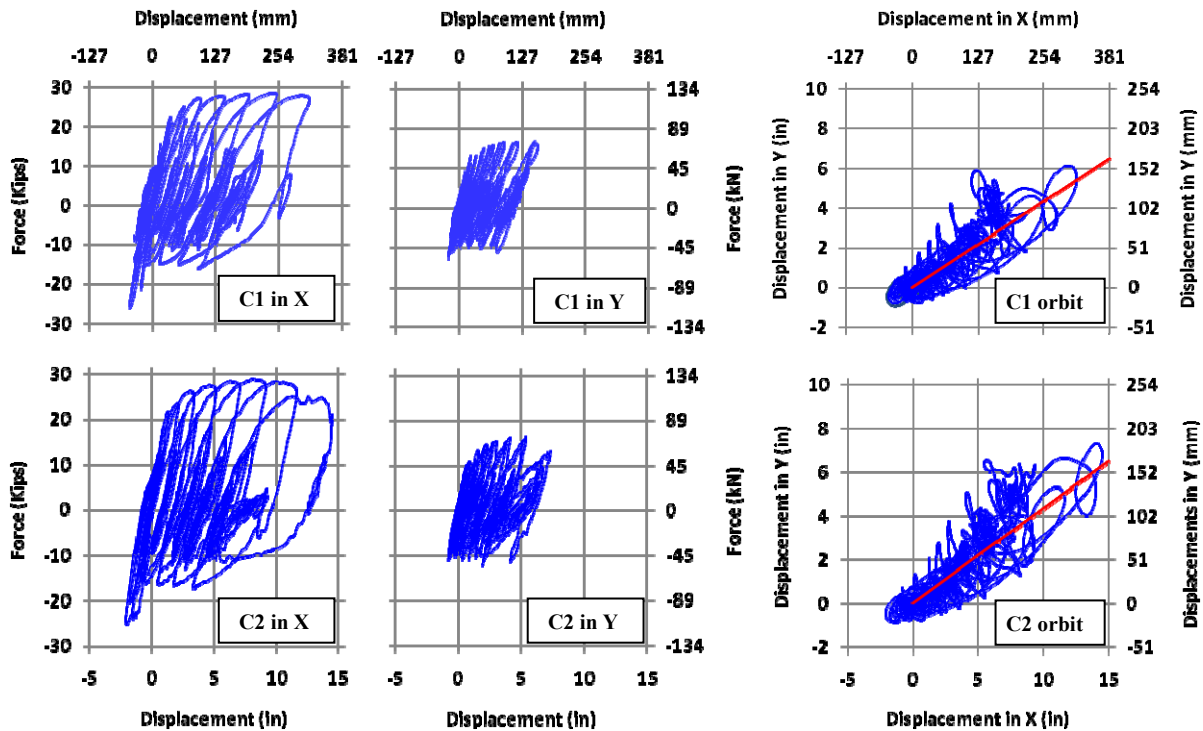


Figure 4. Force-displacement hysteresis for circular columns

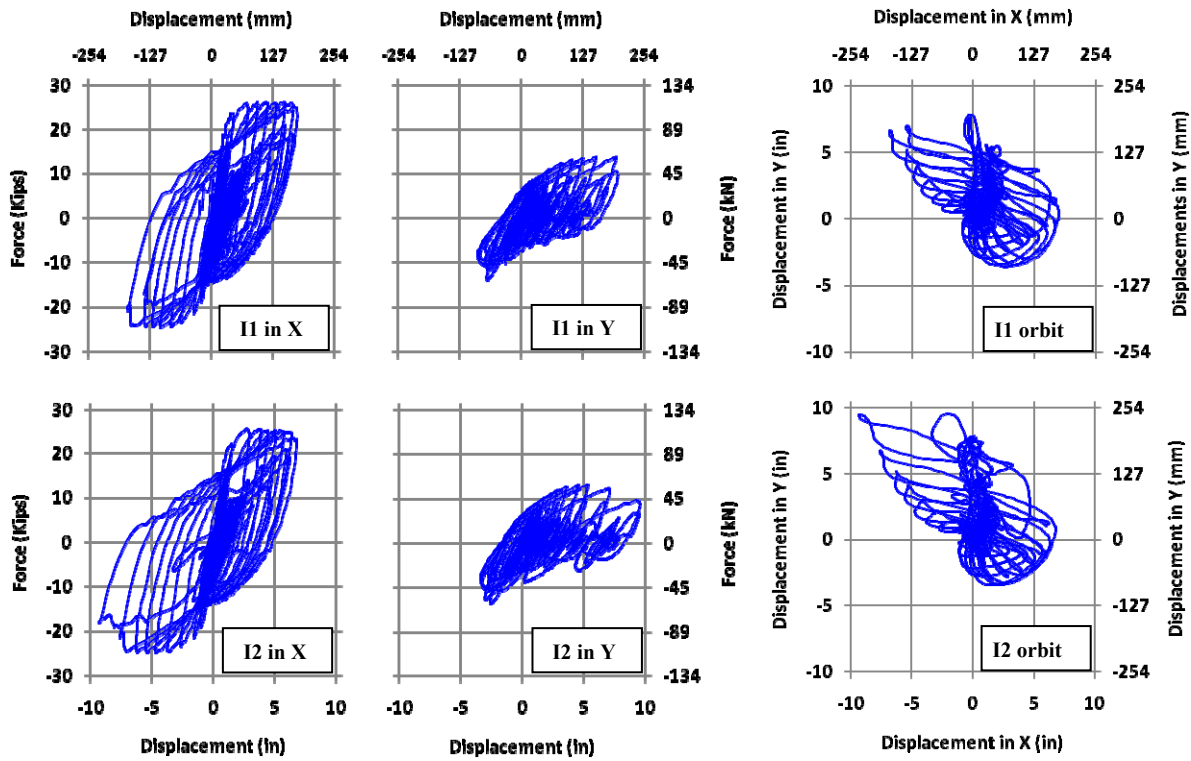


Figure 5. Force-displacement hysteresis for interlocking columns

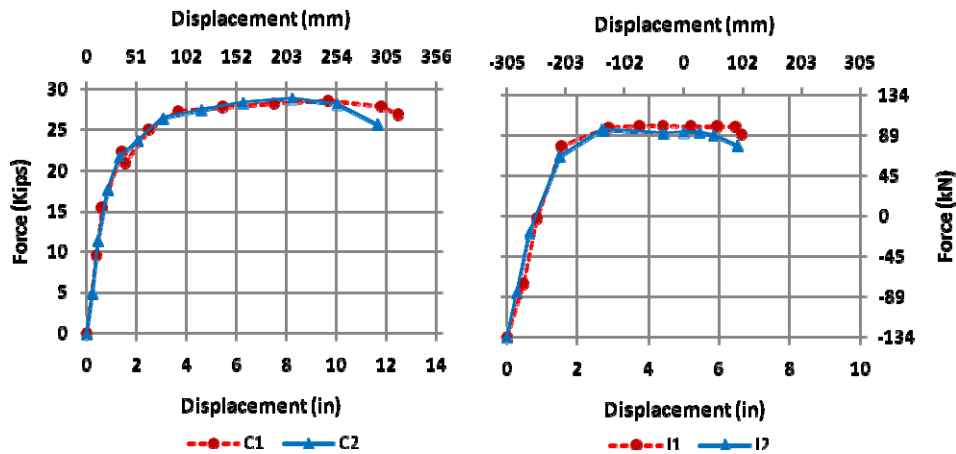


Figure 6. Force-displacement envelopes

Conclusions

The new inertial mass system to be used on bidirectional shake table tests at UNR represent a significant advance in the simulation of single RCC under simultaneous loads induced by real time earthquake motions. One of the most important characteristics of this

system is that it allows the interaction between bending and torsion with or without axial load.

Preliminary analytical and experimental results found at UNR and by researchers from other institutions involved in the project have shown that the interaction between loads have a significant effect in the capacity of reinforced concrete bridge columns under seismic loads. These results are being used to develop analytical tools and new inelastic models for reinforced concrete columns that in turn will assist in the development of new design methodologies.

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