Shake Table Testing of Bridge Reinforced Concrete Columns under Combined Actions

by

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ABSTRACT

Combined loadings (axial, shear, bending and torsion) can have significant effects on the force and deformation capacity of reinforced concrete bridge columns (RCC); these loads can result in unexpected large deformations and extensive damage. To study the impact of different loadings on both circular and non-circular sections (interlocking spirals), eight large-scale cantilever-type RCC specimens will be tested on the bidirectional shake table facility at University of Nevada, Reno (UNR). As part of the study, an inertial loading system was developed to test on shake table 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.

KEYWORDS: bridge engineering, reinforced concrete columns, combined loadings, shake table test

1.0 INTRODUCTION

During moderate to large earthquakes, reinforced concrete bridge columns are subjected to combinations of actions and deformations, caused by spatially-complex earthquake ground motions, 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 critical components of transportation systems. In addition, current analysis 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 bridge members under combined loadings and its impact on system response, a comprehensive project sponsored by the National Science Foundation was established in 2006. This project includes researchers from six institutions, and the objectives are 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.

The work at UNR focuses on the development of refined analysis and shaking table tests of small-scale models of bridge columns 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, energy dissipation 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 some of the preliminary work underway at UNR.

2.0 SPECIMEN DETAILS

Two sets of specimens of circular and interlocking columns were constructed using current bridge design details typical of bridges in California in accordance with the *Seismic Design Criteria* (CALTRANS, 2006). The structural configuration selected was similar to previous columns tested at UNR (Laplace *et al.*, 1999 and Correal *et al.*, 2004). For circular columns the scaling factor selected was 1/3. The diameter of the specimens was 406 mm (16 in) and the height 1830 mm (72

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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 uniformly 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 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 and the resulting volumetric ratio of the spiral reinforcement was 0.92%. Details of circular specimens are shown in Fig. 1.

For interlocking columns a scale factor of 1/4 was used. Consequently, the height was 1800 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 for each of the circular sections consisted of a continuous spiral made from galvanized 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 specimens are shown in Fig. 2.

The design 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 steel wire. Table 1 shows the real properties of steel and concrete based on coupons and cylinders tests. The superstructure mass was defined as 356 kN (80 kips), which is equivalent to an axial load of 8% of $A_g f'_c$.

3.0 EXPERIMENTAL TEST SETUP

As part of the project a new inertial loading system was developed at UNR to test single cantilever-type columns on shake table under biaxial excitations. The aim of the test setup is to have a supporting structure that carries safely the vertical component of the inertial mass (superstructure weight) but allows transfer the inertial forces from the structure to the specimen. A similar structure that allows dynamic excitation in one direction was developed at UNR ten years ago (Laplace, 1999). The new system is composed by a 3D four columns 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 transfer shear and torsion but not axial load (Fig. 3a). Additional mass is set on the platform to simulate the weight of a portion of the bridge superstructure and this can be distributed in an asymmetric configuration to induce torsion in the system. In addition, a safety system was designed to catch the platform in the event of large displacements or specimen collapse.

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 specimen 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 designed system 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. 3b).

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.

4.0 ANALYTICAL INVESTIGATION

Analytical models were developed to anticipate the seismic performance of the specimens and to determine the appropriate input loadings to be used during the tests. Time history inelastic analysis have been performed using OpenSees (Mazzoni *et al*.,2006). Analytical models of single cantilever-type columns with lumped mass as well 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. Fig.5. shows the analytical models used in this study.

The biaxial flexural behavior of the columns was simulated using a lumped plasticity model throughout uniaxial fiber elements (element beam-with-hinges in OpenSees). The stress-strain properties of the unconfined and confined concrete were simulated using the Mander's model (Mander *et al*., 1988). For that, the actual strength of the concrete measured from cylinders at 28 days was used. Likewise, the longitudinal reinforcing steel was idealized using the uniaxial steel material model developed by Chang and Mander (1994). The actual stress-strain backbone curve measured from coupons was used as the input parameter for the steel material model. 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% the elastic torsional stiffness (GJ) was used to take in account the torsional cracking of the concrete in agreement with the *Seismic Design Criteria* (CALTRANS, 2006).

To estimate the lateral load and displacement capacities of the specimens moment-curvature analysis were performed. Table 2 summarizes the capacities of the circular and interlocking columns. Once the capacity was estimated, a series of nonlinear time history analysis were conducted to select the input motion to be simulated in the shake table test.

As was mentioned before, five cases of mass distribution were studied to determine the largest torsional demand on the specimen. Fig. 4 shows five cases of mass distribution at the top of the inertial frame.

4.1 Ground Motions

The two horizontal components of the 1940 Imperial Valley earthquake (El Centro), the 1994 Northridge earthquake, the 1992 Cape Mendocino earthquake and the 1995 Hyogo-ken Nanbu earthquake (Kobe) were used as the input motions. The earthquake records for Northridge and Cape Mendocino were scaled to have a hazard level of 2% of exceedence in 50 years (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 compressed to account for the specimen scale factor.

From the dynamic analysis, it was found that the record at Cape Mendocino amplified by a factor of 1.4 will induce the maximum displacement ductility demand on the specimens without exceeding the shake table capacity. The maximum accelerations imposed in both horizontal directions were 0.8g and 0.95g, respectively.

5.0 ANALYTICAL RESULTS

Fig. 6 compares the displacement history and hysteresis (base shear-displacement) curves for the models of a single column and the specimen with the inertial load system, without taking in consideration the axial load. From the figure is clear that the inertial loading system does not change the behavior of the specimen.

In terms of the torsion, it was found that the load case 2 induces the largest demand on the circular specimen (64 kN-m), which is in between the values at cracking (26 kN-m) and ultimate (80 kN-m) calculated using the ACI code (ACI, 2008).

6.0 CONCLUDING REMARKS

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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8.0 REFERENCES

ACI Committee 318 (2008), "Building Code Requirements for Structural Concrete (ACI 318-08) and Commentary." American Concrete Institute, Farmington Hills, Michigan, USA, 465 pp.

California Department of Transportation. (2006) "Bridge Design Specifications." Engineering Service Center, Earthquake Engineering Branch, California, USA, 250 pp.

Chang, G. and Mander, J. (1994). "Seismic Energy Based Fatigue Damage Analysis of Bridge Columns: Part I – Evaluation of Seismic capacity." NCEER Technical Report 94-0006.

Correal, J.F., Saiidi, M.S., and Sanders, D.H. (2004). "Seismic Performance of RC Bridge Columns Reinforced with Interlocking Spirals." Report No. CCEER-04-6, Center for Civil Engineering Earthquake Research, Department of Civil Engineering, University of Nevada-Reno, USA, 438 pp.

Zhang, J. and Xu, S.Y. (2008). " Seismic Response Simulations of Bridges Considering Shear-Flexural Interaction of Columns. " Proceedings of the 6th National Seismic Conference on Bridges & Highways, Paper No. P29, Charleston, South Carolina, USA.

Mander J.B., Priestley, M.J.N. and Park, R. (1988). "Theoretical Stress-Strain Model for Confined Concrete." Journal of Structural Eng. 114 (8), pp 1804-1826.

Laplace, P., Sanders, D.H., and Saiidi, M.S. (1999). "Shake Table Testing of Flexure Dominated Reinforced Concrete Bridge Columns." Report No. CCEER-99-13, Center for Civil Engineering Earthquake Research, Department of Civil Engineering, University of Nevada-Reno, USA, 438 pp.

Mazzoni, S., McKenna, F., Scott, M., and Fenves, G.L. "Open System for Earthquake Engineering Simulation (OpenSees), 2006." User manual, version 1.7.3, Pacific Earthquake Engineering Research Center, University of California, Berkeley,California,USA, http://opensees.berkeley.edu/OpenSees/manuals/usermanual/index.html

Mullapudi, T.R., Ayoub, S. and Belarbi, A. (2008). "Effect of Coupled Shear-Bending Deformations on the Behavior of RC Highway Structures Subjected to Extreme Seismic Loading." Proceedings of the 6th National Seismic Conference on Bridges & Highways, Paper No. P19, Charleston, South Carolina, USA.

Sakai, J., Jeong H. and Mahin, S.A. (2006). "Reinforced Concrete Bridge Columns that Re-Center Following Earthquakes." Proceedings of the 8th U.S. National Conference on Earthquake Engineering, Paper No. 1421, San Francisco, California, USA.

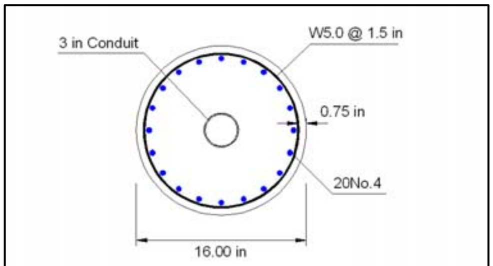
Table 1: Material properties

Days	Concrete Compressive Strength [MPa]			
	Circular		Interlocking	
	Footing	Column	Footing	Column
28	33	28	36	27

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

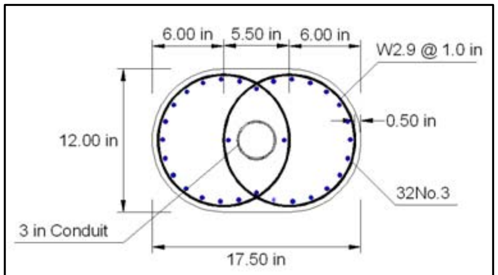
Table 2: Lateral load capacities of the specimens

Circular Columns P=0	
Properties	Radial
ϕy	0.00034
My (kN-m)	177
ϕu	0.00584
Mu (kN-m)	223
$\mu\Delta$	8.29
Vu (kN)	122



1 in = 25.4 mm

Interlocking Columns P=0		
Properties	Short dimension	Long dimension
ϕy	0.0004	0.0003
My (kN-m)	158	229
ϕu	0.00742	0.00431
Mu (kN-m)	177	253
$\mu\Delta$	7.36	7.36
Vu (kN)	98	138



1 in = 25.4 mm

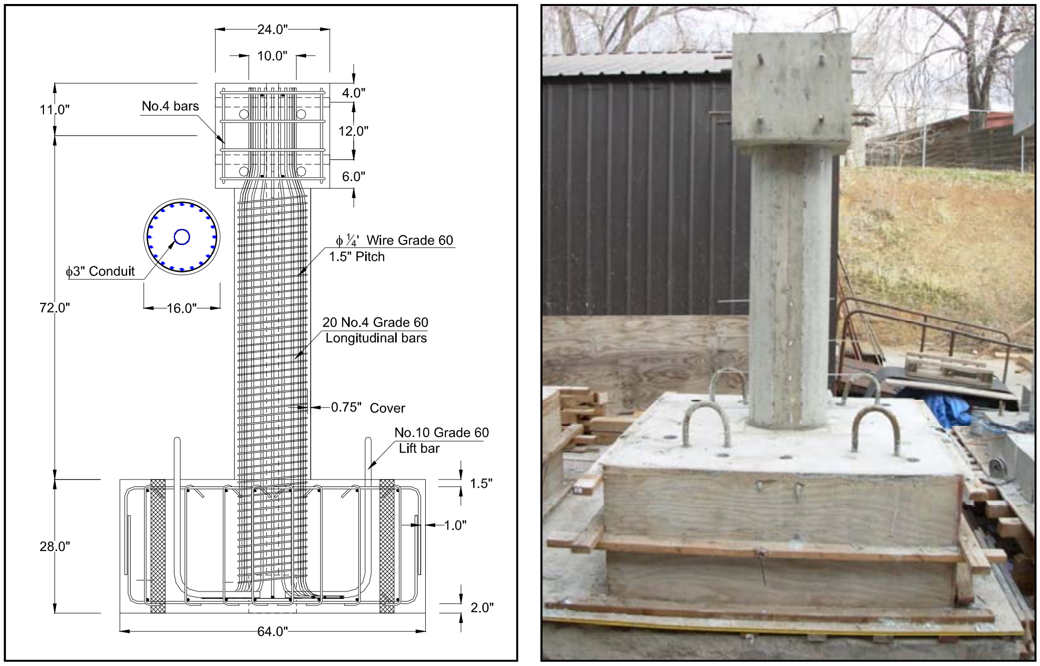


Figure 1: Geometric configuration and reinforcement for circular RCC*.

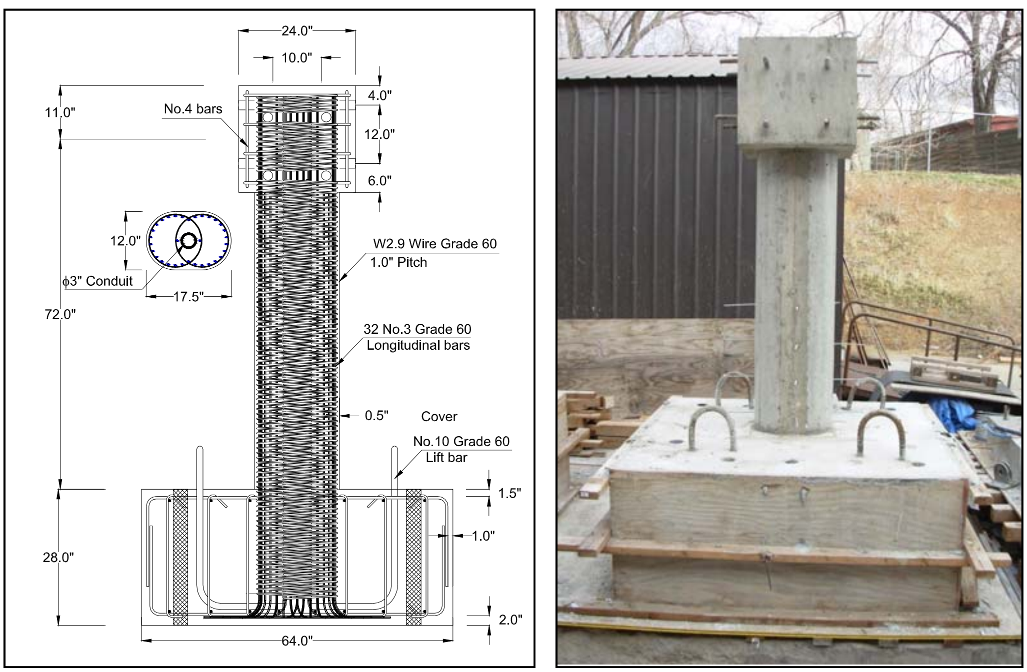
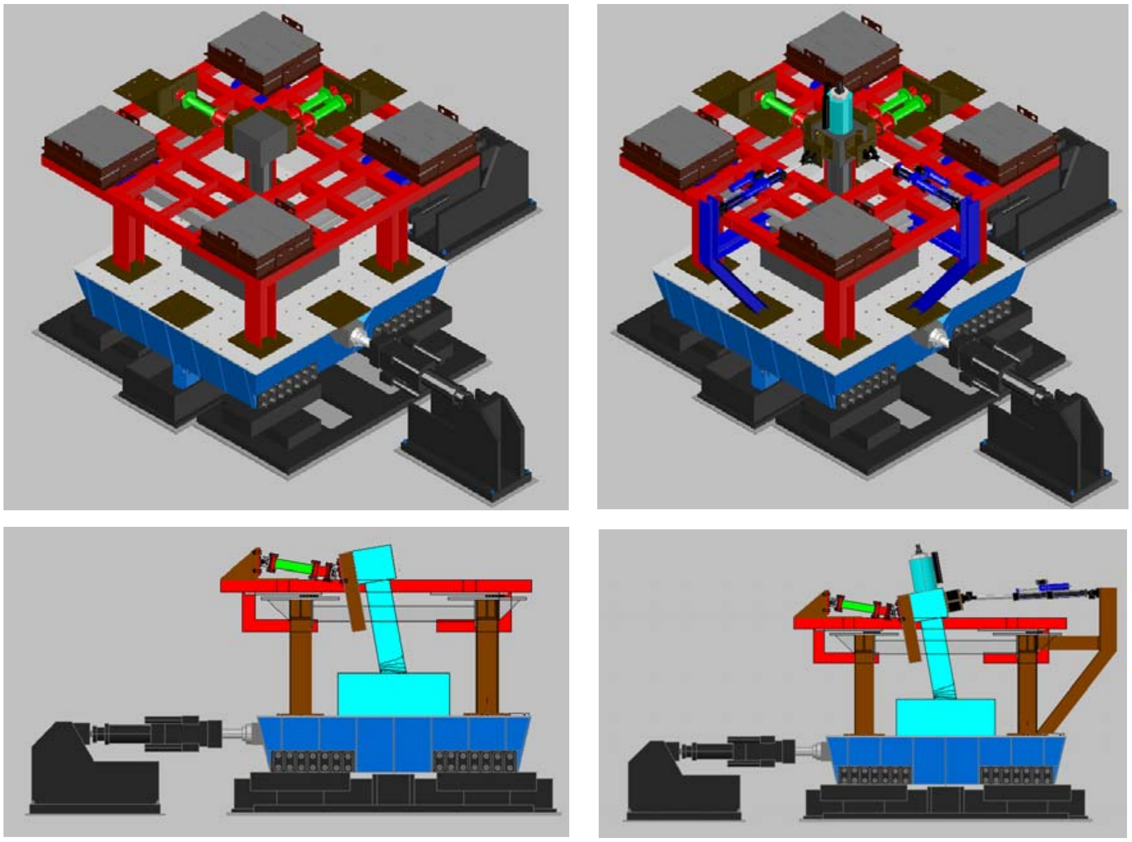


Figure 2: Geometric configuration and reinforcement for interlocking RCC*.

* Unit conversion 1 in = 25.4 mm.



a: Without axial load.   b: With axial load (prestressed bar + actuators)

Figure 3: Inertial loading system.

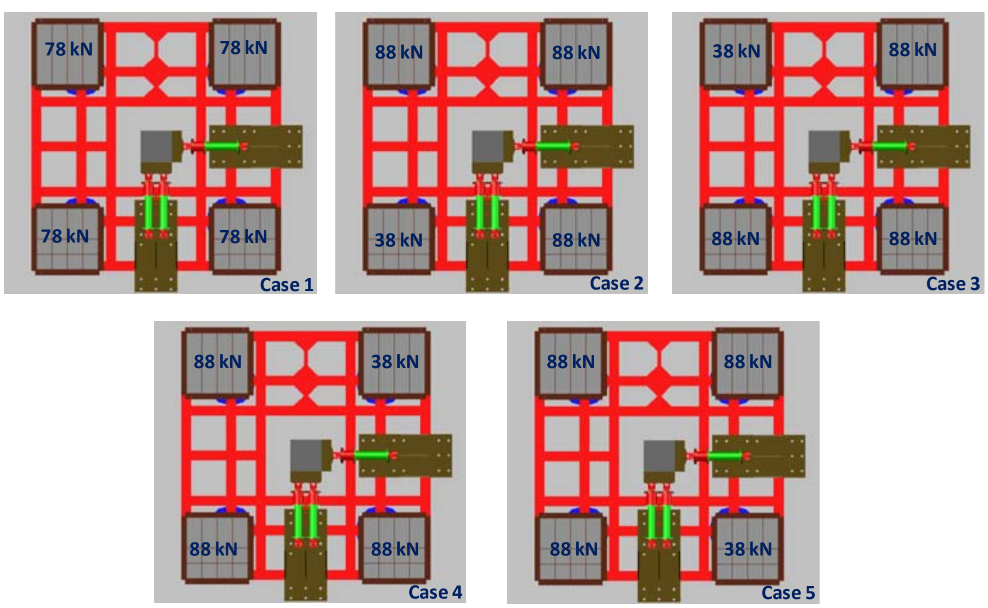
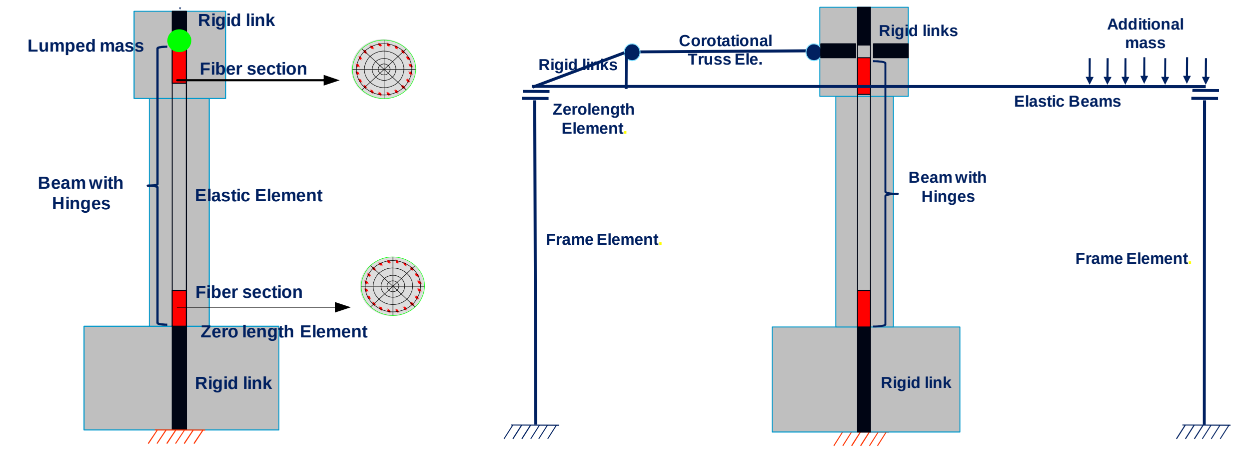


Figure 4: Mass distribution cases studied.



a: Single cantilever-type column.

b: Specimen including test setup

Figure 5: Analytical models.

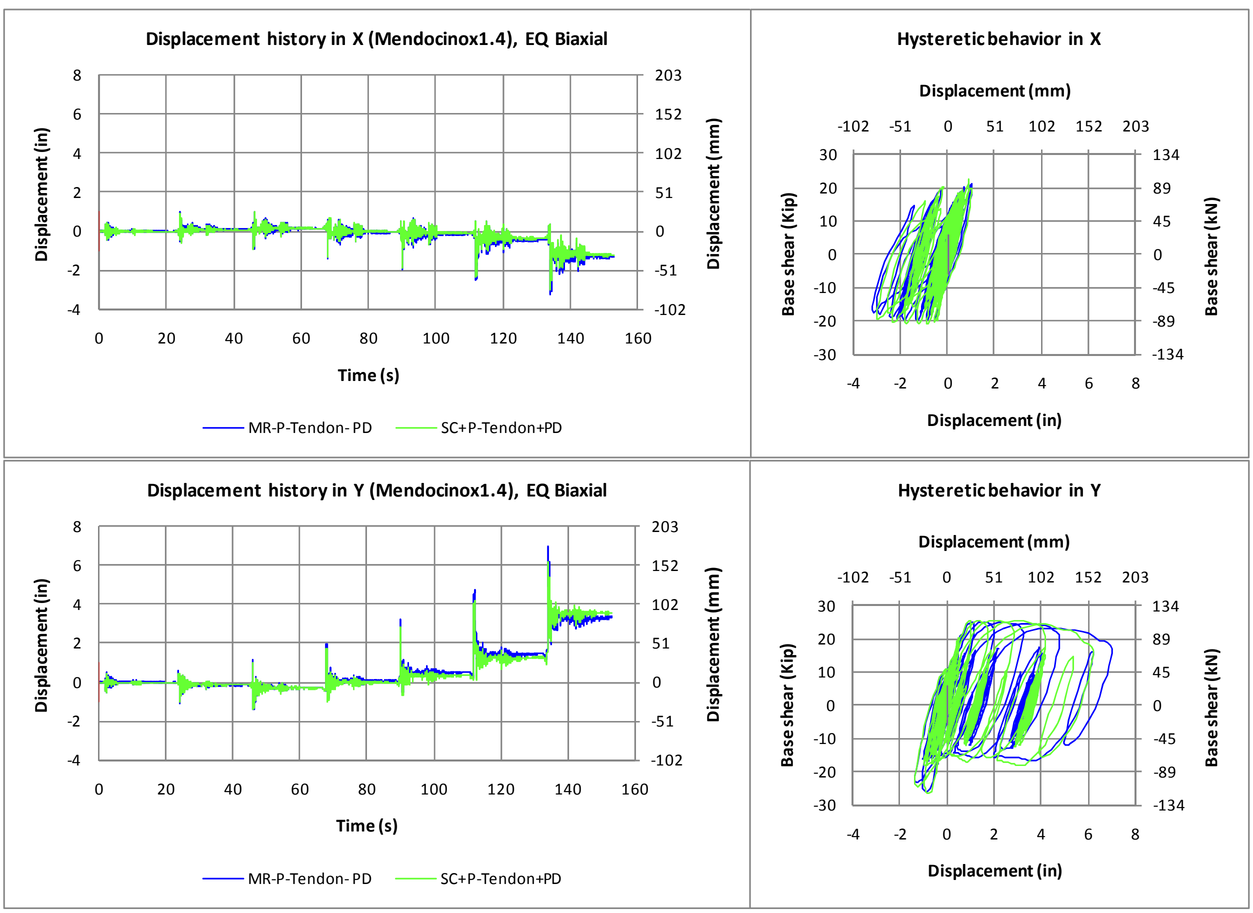


Figure 6: Analytical results, columns without axial load