



AN INNOVATIVE SEMI-RIGID SEISMIC-RESISTANT MECHANICAL DEVICE

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Abstract

This paper presents an innovative semi-rigid, high ductility, mechanical aseismic device which simulates a universal pivot joint. This device is manufactured using conventional steel elements that can be installed at the foundation level between pile and pile caps or at the bottom of the superstructure columns to enhance structural ductibility and seismic performance. This device will keep the rigidity of the structure under small or medium level earthquakes however under large earthquakes, it will accommodate the inelastic non-linear behavior of the structures and will behave like as a universal joint which will decrease internal forces and dissipate seismic energy.

Performance of this device was verified through large-scale prototypes tested at various levels of combined axial and lateral cyclic loading using the Multi-Axial Testing System (MATS) at the National Center for Research on Earthquake Engineering (NCREE) in Taiwan in 2014. This paper summarizes the method to get the rotational characteristics of this device based on the conducted testing program and the results obtained from structural analysis.

Keywords: seismic, semi-rigid; mechanical; device; large-scale, testing.

1. Introduction

The response of a structure to earthquake shaking is affected by interactions between three linked systems: the structure, the foundation, and the soil underlying and surrounding the foundation. Some improvements and a better understanding of the seismic response of these three systems may be required in order to appropriately withstand earthquake loading.

Improvements in the structural system may be related to the optimization of structural elements that can enhance ductibility resulting in a better seismic performance of the overall structure. Improvements in the structural system may also involve improvements in the foundation components of the structure. A better understanding of the dynamic response of soils during earthquakes and its interaction with the structure which is supporting is essential to improve the seismic performance of the overall structure. In addition, awareness of potential seismic hazards and the verification for the adequacy of ground motions used as the input loading parameter in seismic design are important factors that can affect the seismic performance of the structures.



Previous research efforts [1,2] showed that coupling devices (High Ductility Aseismatic Joint [HDAJ]) modelled as rotational springs installed in pile foundations close to the interface foundation-superstructure (i.e., devices installed in between and close the pile foundations and pile caps) may serve as energy dissipating devices which can provide additional ductility at the foundation level of the structures.

Based on the results of that previous research which proved the effectiveness of rotational spring models for contributing to the ductility of foundations under large seismic demands, this paper presents the development of an innovative mechanical device that can be installed at the bottom portion of the superstructure to enhance ductility and contribute to the good performance of the structure during seismic events.

2. Device Overview and Characteristics

Following the concept of rotational spring models used for coupling devices such as the HDAJ devices to enhance ductility at foundation level, an attempt was done to verify if mechanical devices modeled as rotational springs installed in the superstructure can also enhance stability at the superstructure level. An innovative mechanical device which resembles the bones articulations was proposed for this purpose and was modeled as a rotational spring to be embedded at the bottom portion of the superstructures.

This device preliminarily called as “RBone” was manufactured using conventional structural steel elements such as plates, c-channels and reinforced steel. Manufacturing process includes welding operations. RBone was designed as a short concrete-steel column and the design also involves the verification of that exerted stress do not exceed the allowable stresses of the material components. RBone has gaps in between its components to allow for rotation to occur (i.e., the allowable initial rotational angle for a structural member of 1 m² structure member is approximate 0.006 rad). Photos and sketches of RBone are show in Figure 1.

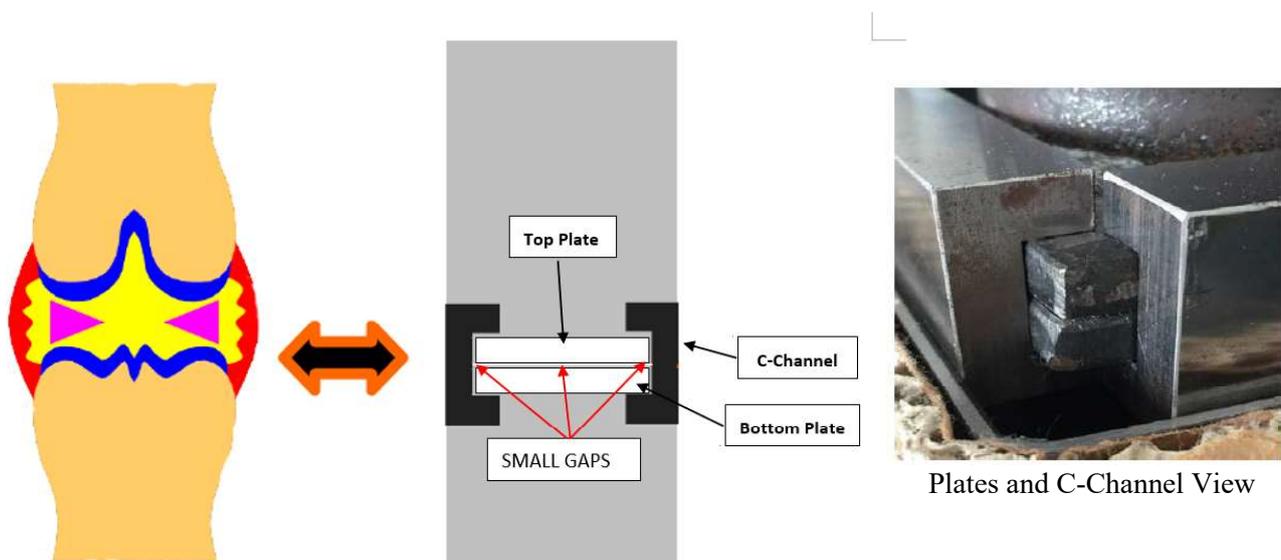


Fig. 1 – RBone concept and actual photos

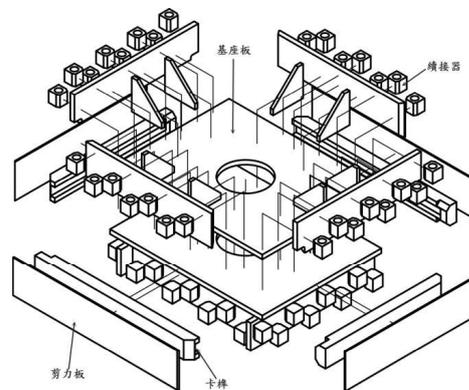
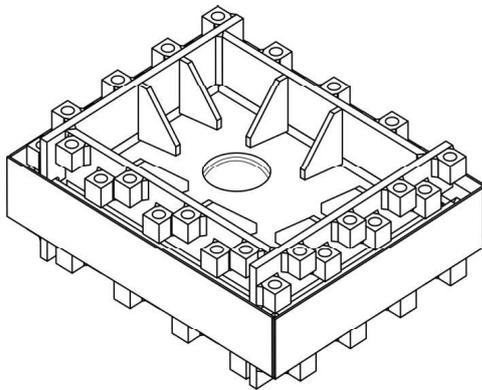


Fig. 2 – RBone concept and actual photos (cont.)

3. Experimental Testing

The performance of this device was investigated by means of large-scale prototypes tested at various levels of combined axial and cyclic loading using the Multi-Axial Testing System (MATS) at the National Center for Research on Earthquake Engineering (NCREE) in Taiwan in 2014 [3]. A sketch and photos of the test set up are shown in Figure 2.

The device was tested in a specimen consisted of a rectangular column of reinforced concrete with a cross section of 1.0 m by 0.8 m (in the X and Y directions, respectively based on the coordinate system shown in Figure 2). The size of the device was such as it covered the entire cross section of the column. Reinforced concrete pedestals of 2.0 m by 1.0m were placed in the top and bottom of the column. The device was installed just above the bottom pedestal. The length of the column was 3.5 m (effective length without considering the length of the pedestals). Thirty rebars of No.11 size (36 mm diameter) were used as vertical reinforcement along the entire length of the column which gives approximately a steel reinforcement to gross concrete area of 3.8%. Typical No. 11 stirrups were also installed along the length. The column was fixed at the top such as rotations and vertical and horizontal displacements were not allowed. The bottom portion of the column was also fixed against rotations and vertical displacements; however, displacements were allowed in the parallel and perpendicular directions of the lateral force actuator (X and Y directions, respectively). The column was instrumented with several strain gauges installed in the concrete surface.



Stain gauges were also installed embedded into the concrete attached to the longitudinal rebars close to where the device was installed. The design capacity of the column was approximately 21 MN.

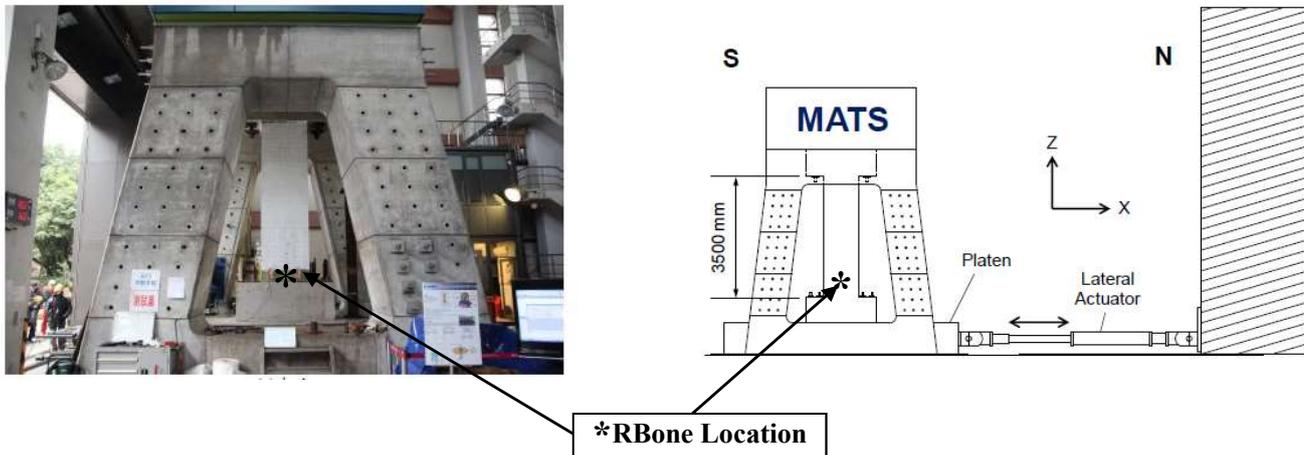


Fig. 3 – Testing Setup at the NCREE Facility

Loading was applied in the axial direction (Z direction) in 7 phases. The lateral actuator applied cyclic loading in the X direction during the 7 phases. Lateral cyclic loading was also applied in the Y direction during the fifth phase only. Lateral loading was applied in rotational strain-controlled cycles which ranged between 0.2 to 2.0 percent and were gradually increased as the phases progressed. Typical rotations were 0.2, 0.4, 0.6 percent for the first to the fifth phases and 1.0, 1.2 and 2.0 percent for the sixth and seventh phases. Figure 3 depicts the loading patterns used during the test.

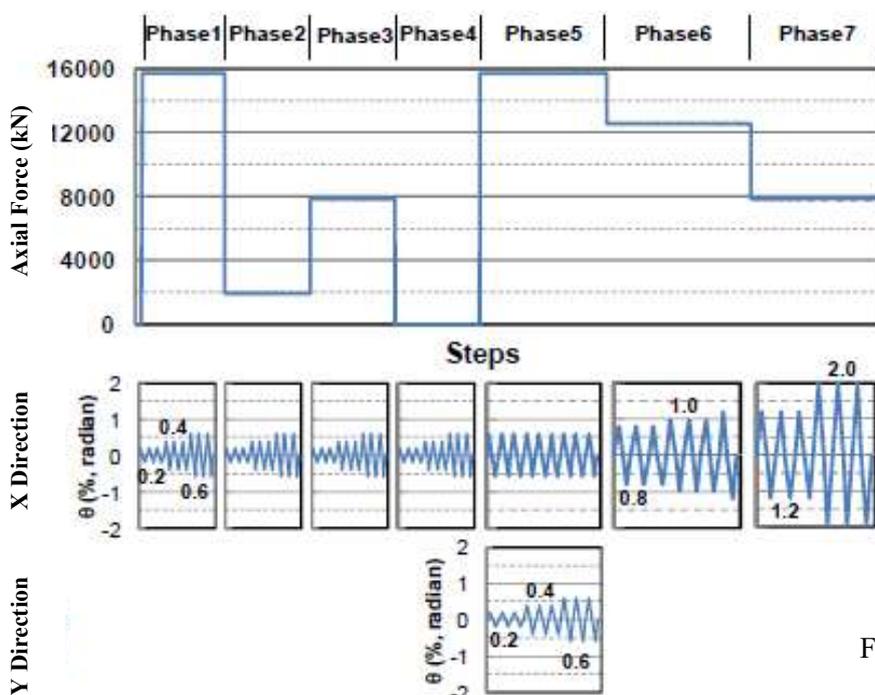


Fig. 4 – Test Loading Pattern



4. Test Results and Observations

Horizontal displacements and shear forces (lateral actuator forces) were measured at each relevant rotational strain levels. Table 1 summarizes the main results for the conducted tests. It can be noted that displacements are independent from the applied axial forces during the test. In addition, rotational strains and horizontal displacements have a linear relationship for all rotational strain levels. This linear relationship can also be observed in the hysteresis cyclic loops shown in Figure 4. These hysteresis cyclic loops also show that the largest shear forces are obtained for the largest axial forces and displacements.

Conventional reinforced concrete analysis to verify the deflections and moments at the bottom of the column assuming the no presence of the device indicates that for the largest axial force of 15,696 kN, the horizontal displacement is about 10 mm for a shear force of 3,000 kN with a bending moment of 5,250 kN-m. For a similar level of lateral displacement and axial force, the bending moments at the bottom of the column when the device is installed, is approximately 600 kN-m.

Table 1 – Summary of Test Results

Phase	Axial Force (kN)	Max. Shear Force (kN)	X Displ. (mm)	X Rotation (%)	Cycles	Y Displ. (mm)	Y Rotation (%)	Cycles
1	15,696	3,047	7	0.2	3			
			14	0.4	3			
			21	0.6	3			
2	1,962	1,409	7	0.2	3			
			14	0.4	3			
			21	0.6	3			
3	7,848	2,263	7	0.2	3			
			14	0.4	3			
			21	0.6	3			
4	0	1,041	7	0.2	3			
			14	0.4	3			
			21	0.6	3			
5	15,696	3,090	21	0.6	3	7	0.2	3
			21	0.6	3	14	0.4	3
			21	0.6	3	21	0.6	3
6	12,557	3,729	28	0.8	3			
			35	1.0	3			
			42	1.2	1			
7	7,848	3,788	42	1.2	3			
			70	2.0	3			

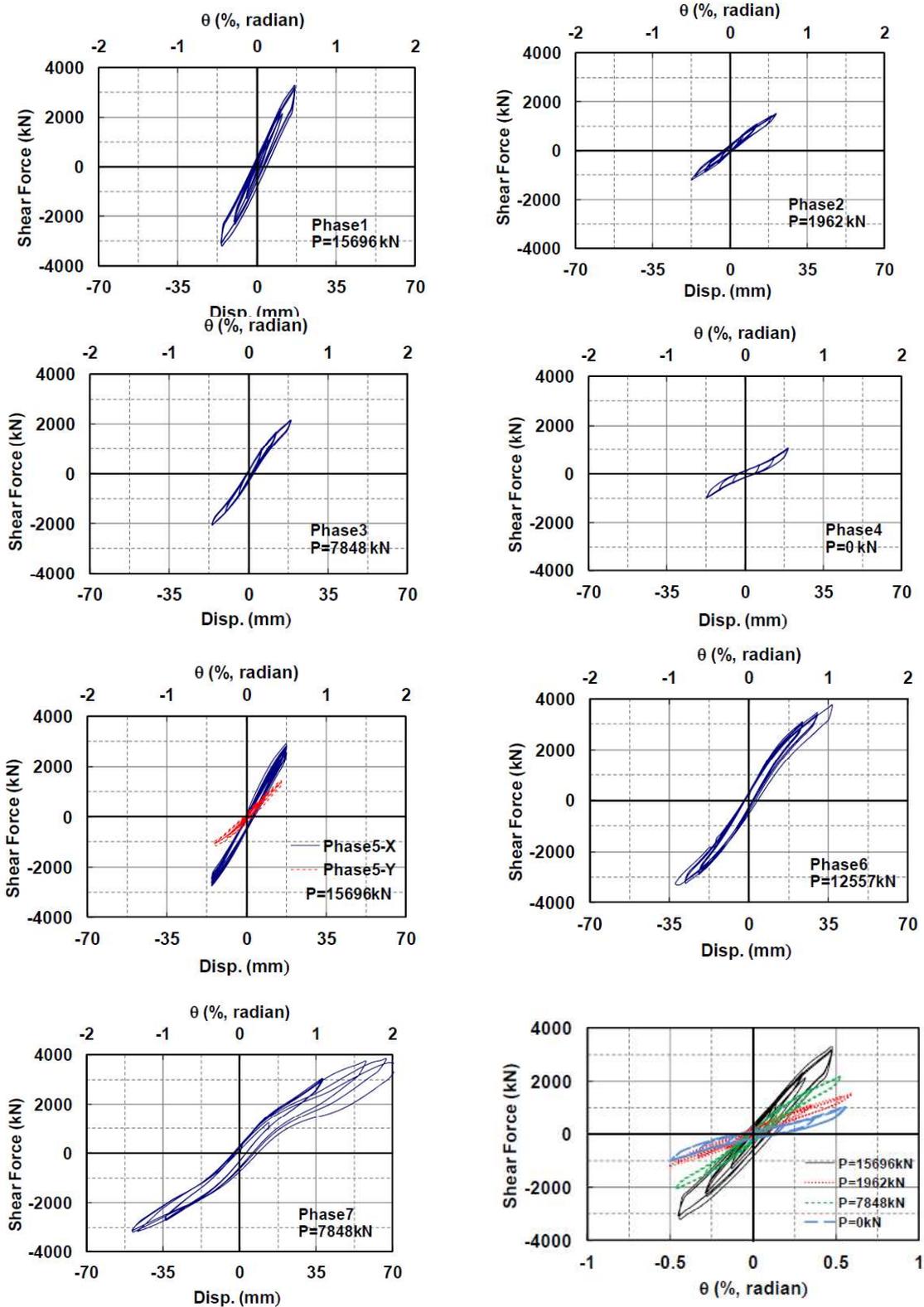


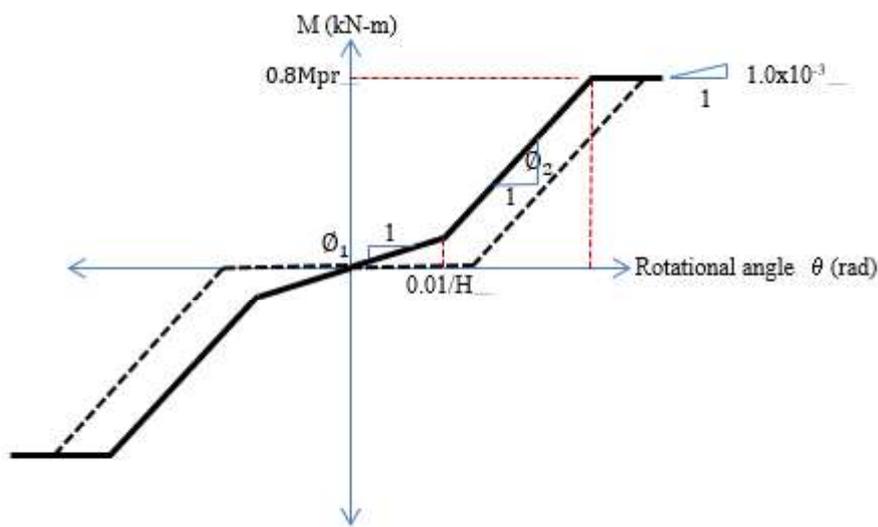
Fig. 5 – Hysteresis Cyclic Loops



In addition, in order to further evaluate the response of the device, an attempt to construct bending moment-rotation curves was conducted.

Based on the experiment results conducted at the NCREE in 2015, bending moment and rotational angle characteristics for structural analysis is recommended to follow a bilinear relationship as indicated in Figure 5.

Fig. 6 – RBone Bending Moment – Rotational Angle Relationship



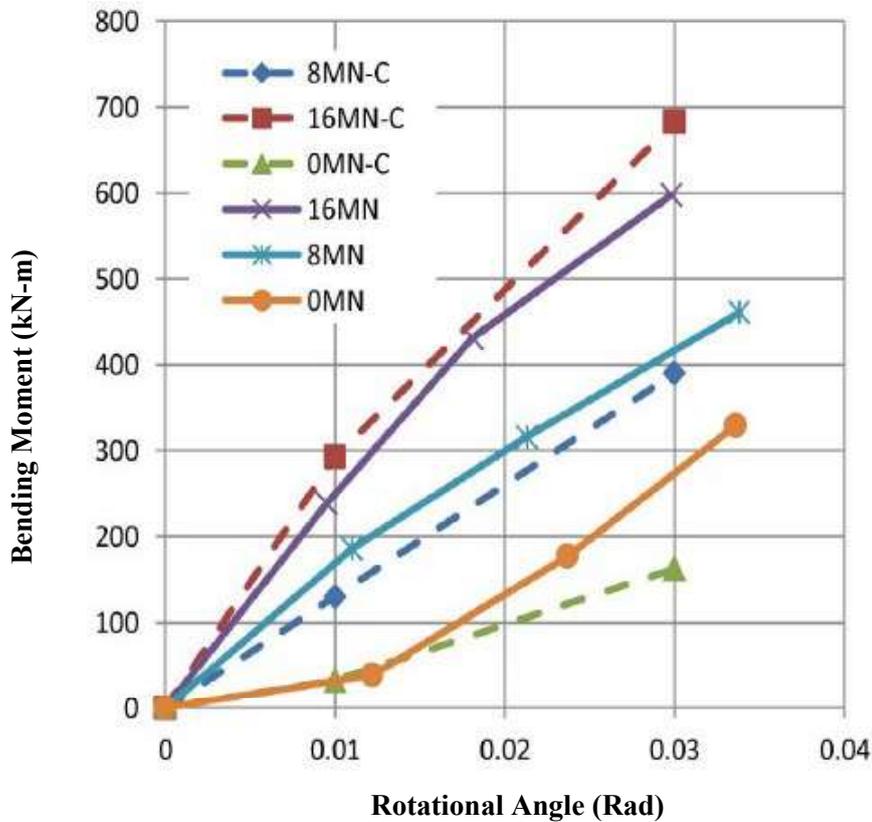
Where:

- ϕ_0 : Nominal Rotational stiffness = 1.3×10^4 kN-m/rad for a 0.8 m x 1.0 m column, determined by inertia moment ratio (I/I_0) for columns with different sizes
- $\phi_2 = \alpha \phi_0$
- $\phi_1 = \alpha \phi_2$
- α : Axial force dependent coefficient, $=0.5 + N/N_s$
- N : applied axial force
- N_s : design axial force
- H : Depth of column (m)

Figure 6 shows the bending moment and rotational angle relationships based on the above approach and test results. Dotted and solid lines indicate the theoretical curves based on the above approach and the calculated curves obtained from the test results.



Fig. 7 – Bending Moment – Rotational Angle Relationship



5. Conclusions

A new device was presented and tested using a large scale column prototype to verify its potential contributions to enhance the seismic behavior of superstructures. This device can be installed at the bottom portion of the structure where important deformations are expected to occur during seismic events. The conducted test provided encouraging results which indicate that the response of structures against lateral loading may be superior in the case when this device is installed. For example, smaller horizontal displacements may be expected due to the allowance of rotational response of the device. RBone is still in its development stage and based on the test results, we would like to keep investigating about the potential benefits of RBone in structural seismic design.

6. References

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