

# **EVALUATION OF THE SEISMIC PERFORMANCE OF BRIDGE REINFORCED CONCRETE COLUMNS UNDER COMBINED ACTIONS USING SHAKE TABLE**

Juan G. Arias-Acosta<sup>1</sup> and David H. Sanders<sup>2</sup>

## **Abstract**

Combined actions (axial, shear, bending and torsion) can have significant effects on the force and deformation capacity of reinforced concrete bridge columns (RCC); 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 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 named 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.

## **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 essential 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 cantilever-type 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.

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<sup>1</sup> Graduate Student, Dept. of Civil & Environmental Engineering, Univ. of Nevada, Reno, NV89557, USA

<sup>2</sup> Professor, Dept. of Civil & Environmental Engineering, Univ. of Nevada, Reno, NV89557, USA

## **Specimen Details**

Two sets of specimens of circular and double 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 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 (0.75 in) and the resulting volumetric ratio of the spiral reinforcement was 0.92%. Details of circular specimens are shown in Fig. 1.

For double interlocking columns a scale factor of 1/4 was used. Consequently, 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 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  $A_g f'_c$ .

## **Experimental Test Setup**

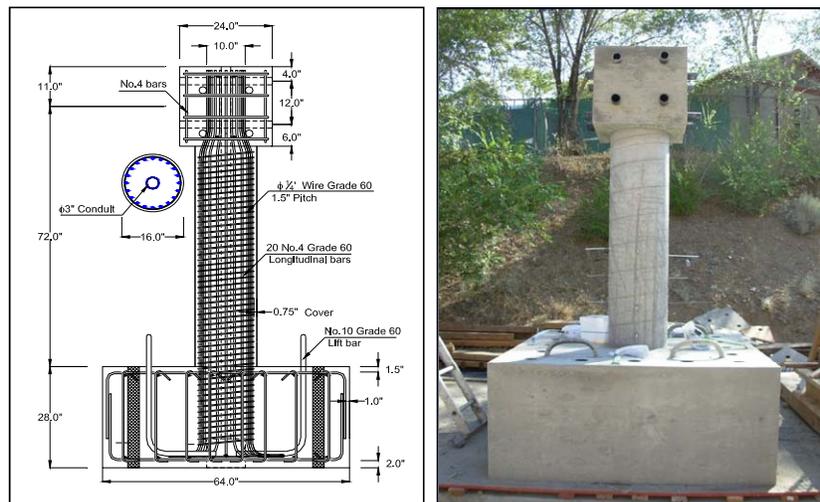
As part of the project a new inertial loading system was developed at UNR to test single cantilever-type columns on shake table under biaxial excitations. The aim of the test setup is to have a supporting structure that carries safely the vertical component of the inertial mass (superstructure weight) 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.

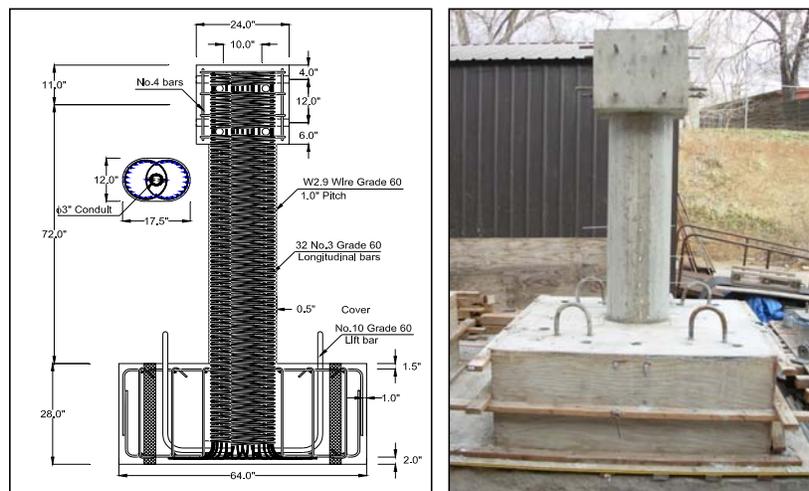
**Table 1: Material properties**

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



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



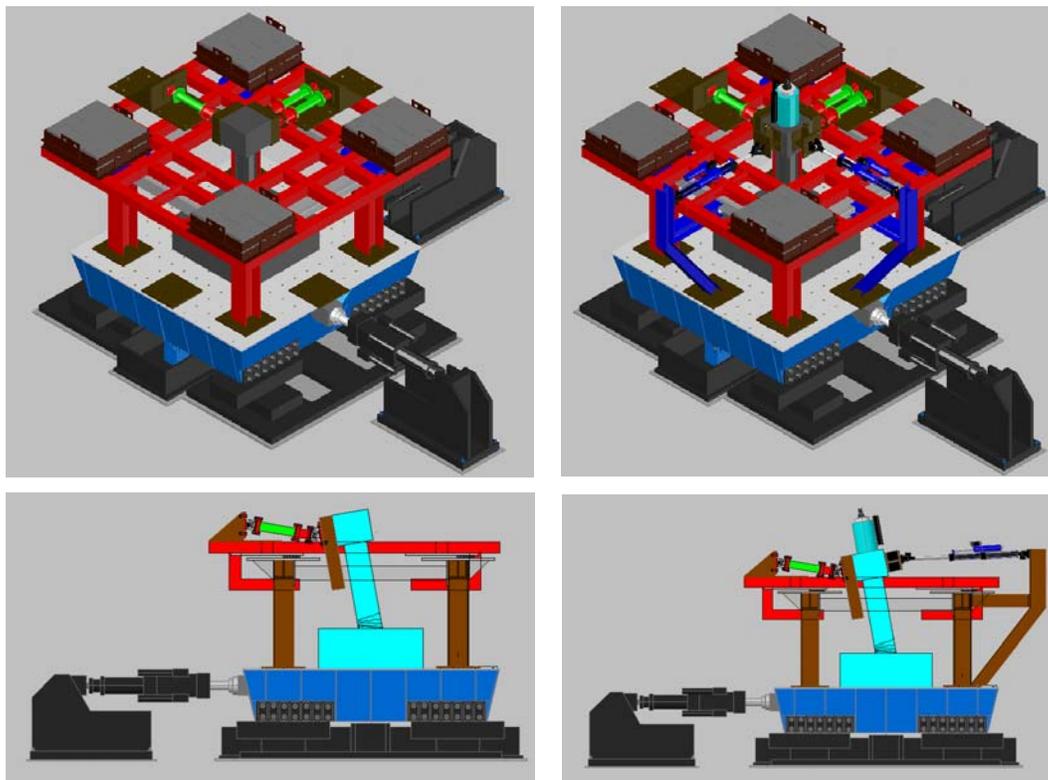
**Figure 2: Geometric configuration and reinforcement for double interlocking RCC\*.**

\* Unit conversion 1 in = 25.4 mm.

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.



a: Without axial load.

b: With axial load (prestressed bar + actuators)

**Figure 3 - Inertial loading system (Bidirectional Mass Rig).**

### **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 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.

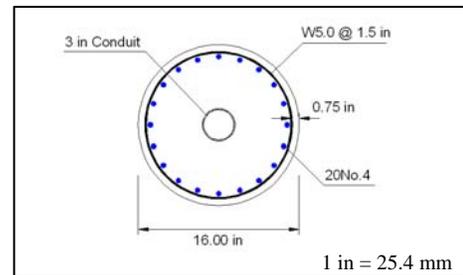
The biaxial flexural behavior of the columns was simulated using a distributed plasticity model throughout uniaxial fiber elements (element inelastic beam-column in OpenSees). The stress-strain properties of the unconfined and confined concrete were simulated using the Mander’s model (Mander *et al.*, 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).

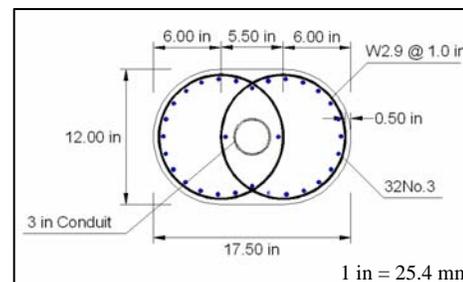
To estimate the lateral load and displacement capacities of the specimens moment-curvature analysis were performed. Table 2 summarizes the capacities of the circular and interlocking columns. Once the capacity was estimated, a series of nonlinear time history analysis were conducted to select the input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

**Table 2: Lateral load capacities of the specimens**

Circular Columns P=0	
Properties	Radial
$\phi_y$	0.00034
$M_y$ (kN-m)	177
$\phi_u$	0.00584
$M_u$ (kN-m)	223
$\mu\Delta$	8.29
$V_u$ (kN)	122



Interlocking Columns P=0		
Properties	Short dimension	Long dimension
$\phi_y$	0.0004	0.0003
$M_y$ (kN-m)	158	229
$\phi_u$	0.00742	0.00431
$M_u$ (kN-m)	177	253
$\mu\Delta$	11.5	9.3
$V_u$ (kN)	98	138



## **Ground motions**

The two horizontal components of the 1940 Imperial Valley earthquake (El Centro), the 1994 Northridge earthquake, the 1992 Petrolia at Mendocino earthquake and the 1995 Hyogo-ken Nanbu earthquake (Kobe) were used as the input motions. The earthquake records for Northridge and Petrolia 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. Factors of 0.58 and 0.5 were used for circular and interlocking specimens, respectively.

From the dynamic analysis, it was found that the record Petrolia at Mendocino and Sylmar at Northridge amplified by factors of 2.0 and 1.8, will induce the maximum displacement ductility demand on the circular and double interlocking specimens without exceeding the shake table capacity. The maximum accelerations imposed in both horizontal directions were 0.9g and 1.2g, for Petrolia and 1.1g and 1.5g for Sylmar ground motion.

## **Column C1 – Experimental Results**

The first circular specimen (C1) was tested under the two components of the Petrolia earthquake. For this test no axial load was applied, and also the distribution of the mass was symmetric to induce low torsion. The column was subjected to multiple motions, increasing the amplitude in subsequent runs. Small increments (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 model to measure the change in period and damping ratio between runs. Table 3 summarizes the measured response of the column during the test.

**Table 3: Measured Response of Specimen C1**

Earthquake		Accel. in X (g)	Accel. in Y (g)	Rel. disp. in X (mm)	Rel disp. in Y (mm)	Force in X (kN)	Force in Y (kN)
0.1xPET	MAX	0.105	0.050	10.83	6.26	42.43	24.72
	MIN	-0.086	-0.049	-10.33	-6.86	-52.18	-25.93
0.2xPET	MAX	0.191	0.106	13.55	22.46	68.83	45.57
	MIN	-0.185	-0.104	-18.15	-23.27	-95.58	-40.65
0.4xPET	MAX	0.363	0.255	-20.33	-11.67	99.45	56.01
	MIN	-0.444	-0.238	24.98	9.81	-115.69	-57.96
0.6xPET	MAX	0.455	0.337	-20.64	-12.81	93.34	50.33
	MIN	-0.588	-0.381	24.97	9.32	-103.29	-49.70
0.8xPET	MAX	0.590	0.466	36.25	12.91	111.65	49.23
	MIN	-0.667	-0.456	-29.43	-17.67	-82.56	-58.14
1.0xPET	MAX	0.692	0.607	38.39	48.38	121.39	48.41
	MIN	-0.737	-0.570	-97.04	-15.73	-65.64	-66.46
1.2xPET	MAX	0.806	0.752	61.38	21.40	123.72	44.27
	MIN	-0.808	-0.656	-47.59	-28.66	-67.80	-70.47
1.4xPET	MAX	0.887	0.863	74.08	25.83	125.73	45.71
	MIN	-0.868	-0.762	-56.22	-34.41	-66.53	-73.43
1.6xPET	MAX	0.981	1.039	86.97	30.17	127.03	45.14
	MIN	-0.939	-0.876	-65.48	-40.09	-67.50	-73.95
1.8xPET	MAX	1.098	1.175	-59.48	156.00	124.16	49.24
	MIN	-0.993	-0.965	-316.66	32.81	-71.81	-74.40

The behavior of the specimen was controlled by the biaxial effect of bending, with horizontal cracks distributed on the height of the specimen, as well as some inclined cracks at the plastic hinge zone.

The first yielding was observed during 0.2xPET, after this motion, horizontal cracks spreaded out from the bottom of the column until the motion 1.0xPET, where the concrete cover at the south side spalled out. The maximum force was recorded at 1.6xPET, at this stage most of the transverse reinforcement was exposed. Finally the failure of the column was observed at 1.8xPET, at this stage some of the longitudinal bars undergone buckling and large degradation of the concrete core was observed. Figure 4 shows the final damage state of the column, while figure 5 shows the displacement history and the hysteretic behavior of the specimen in longitudinal direction (X). On the same plot is shown the predicted behavior using the analytical model.

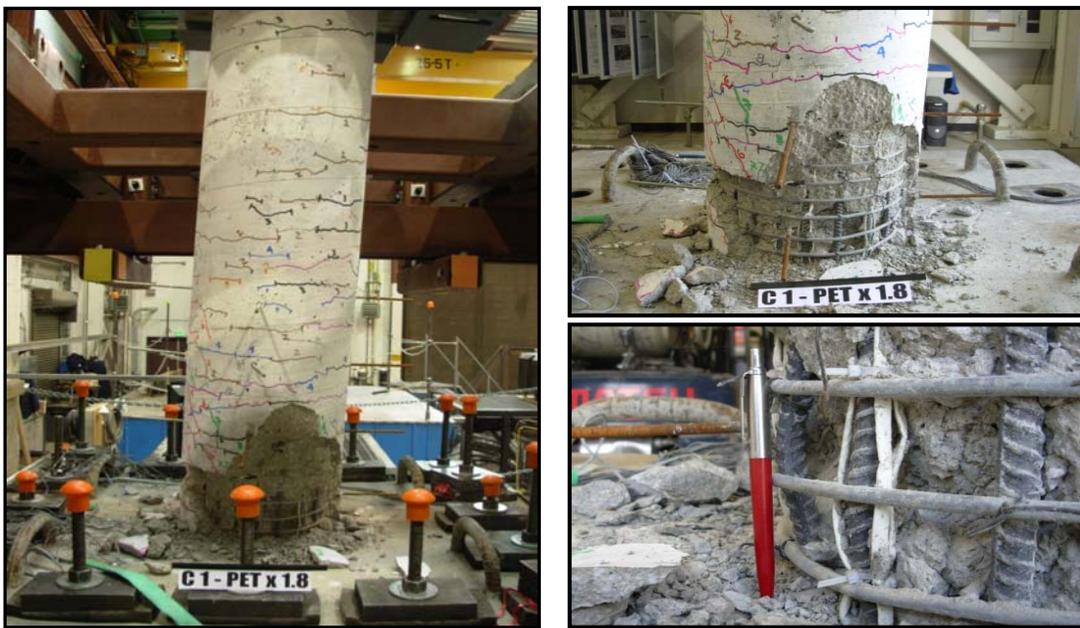


Figure 4 – Specimen C1 after failure

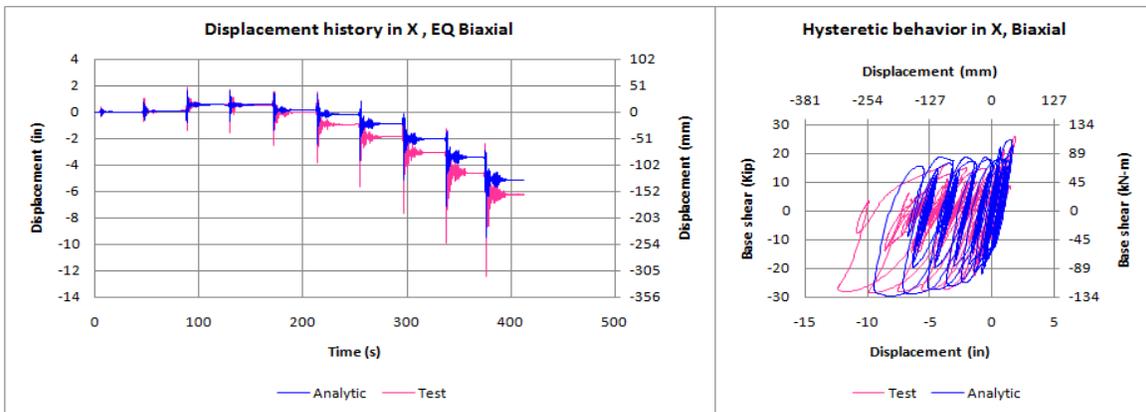


Figure 5– Displacement history and hysteresis for specimen C1

## **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.

The analytical model used to simulate the seismic performance of the specimen and the inertial mass system as shown in Fig.4 predicted the answer reasonably well in terms of relative displacement and hysteretic behavior.

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.

## **Acknowledgements**

The research presented in this paper was founded by The National Science Foundation under Grant No.EMS – 0530737. The assistance of Ian Buckle, Patrick Laplace, Chad Lyttle and the staff of the Large Scale Structural Laboratory at University of Nevada Reno is gratefully acknowledged.

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