

# Analytical study of a 4-Span Bridge with Advanced Materials

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**Abstract:** As part of a major study on the seismic response of bridge systems with conventional and advanced details, a large-scale specimen of a four-span bridge incorporating several innovative plastic hinges was recently studied on the shake tables at the University of Nevada, Reno. The bridge model included six columns, each pair of which utilized a different unconventional detail at bottom plastic hinges: superelastic shape memory alloys combined with polyvinyl fiber concrete, post-tensioned columns, and columns with built-in rubber pads as base isolators. The upper plastic hinges were of conventional reinforced concrete (RC) construction. Experimental results showed a superior performance of the innovative details compared with conventional RC in terms of damage and residual displacements. Aiming for a widespread implementation of the innovative details in the engineering practice, a comprehensive understanding of the mechanics involved in the innovative details implemented in the bridge is crucial. Therefore, an analytical model of the bridge was developed on OpenSees to study the performance of the bridge specimen. Several elements and solution algorithms from the OpenSees library were attempted and incorporated in the model of the bridge to replicate the response of different plastic hinges. Diverse formulations such as gap and contact elements were implemented to simulate the bridge-abutment interaction. Prior to finalizing the design, the OpenSees model was used to select the location of different piers and the shake table testing program. Post-experimental analyses showed good agreement between the measured and calculated results overall. This article presents the modeling process and the correlation between the calculated and measured results.

**Keywords:** analytical model; bridge; plastic hinges; innovative materials

## 1. Introduction

The extensive damage to bridges during recent earthquakes and the tremendous human and economic losses associated with the disruption of lifeline in urban areas have led to a world wide effort toward improving the seismic performance of the bridges. Innovative, advanced materials and details offer great potential in reducing the vulnerability of bridge structures to earthquake damage. Simulation and analytical modeling are crucial factors that enable design engineers and researchers to accurately estimate the system response performance.

This study focused on the development of a 4-span bridge analytical model using a finite element analysis program, OpenSees (Fenves et al. 2004) and the evaluation of the performance of the model by comparing the calculated response with experimental results. Innovative materials and details, such as superelastic shape memory alloys, fiber-reinforced concrete, post-tensioned columns and built-in

elastomeric pads, were incorporated in the bridge to enhance its seismic performance with respect to damage and residual displacements. Suitable OpenSees material models were used to represent the key features of the innovative materials. The main objective of the pre-test analytical studies was to assess the capacity of the bridge and to predict the seismic response of the specimen under different levels of excitation, thus allowing the determination of an appropriate shake table testing program. The computer model was also used to determine the location of the three bents of the bridge. Specifically, analyses were done to ensure that the lateral displacement demand for different piers were comparable, thereby allowing for a direct comparison of the performance of different advanced plastic hinges. Once the experimental testing concluded, a detailed investigation followed to determine the accuracy of the computer models in terms of displacement and force distribution in the bridge.

## 2. 4-Span bridge model and input motions

### 2.1. MODEL GEOMETRY

The test bridge is a quarter-scale geometric model of the prototype highway bridge discussed in Nelson et al. (2006), except that the bottom plastic hinge zones in the columns of two of the bents were made with innovative materials. The quarter-scale bridge model is 107ft (32.6m) long and 7.5ft (2.30m) wide. The two-column bents have the same dimensions. The geometric configuration of the bridge is shown in Figure 1.

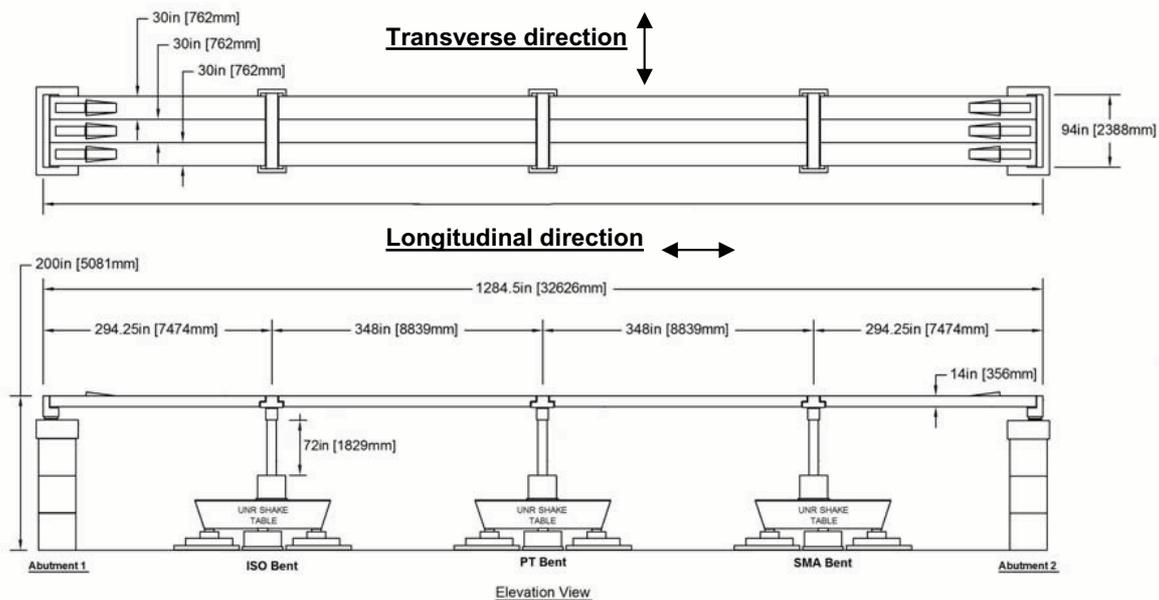


Figure 1. Bridge geometric details

### 2.2 BENT DETAILS

Unique materials were used in the three bents of the bridge. In SMA bent, plastic hinge zones at the bottom of the columns were detailed with superelastic shape memory Nickel-Titanium alloys and polyvinyl fibers mixed with a cement mortar (also called ECC, Engineered Cementitious Composite). In the PT bent, a post-tensioned system was implemented to enhance the recentering capability of the columns. For ISO bent, increased resilience was achieved with a built-in elastomeric rubber pad. The upper column plastic hinges were made with conventional concrete and steel. Detailed information for the bent design can be found in Hillis and Saiidi (2009). Essential details of the columns used in SMA, PT and ISO bents are shown in Figure 2.

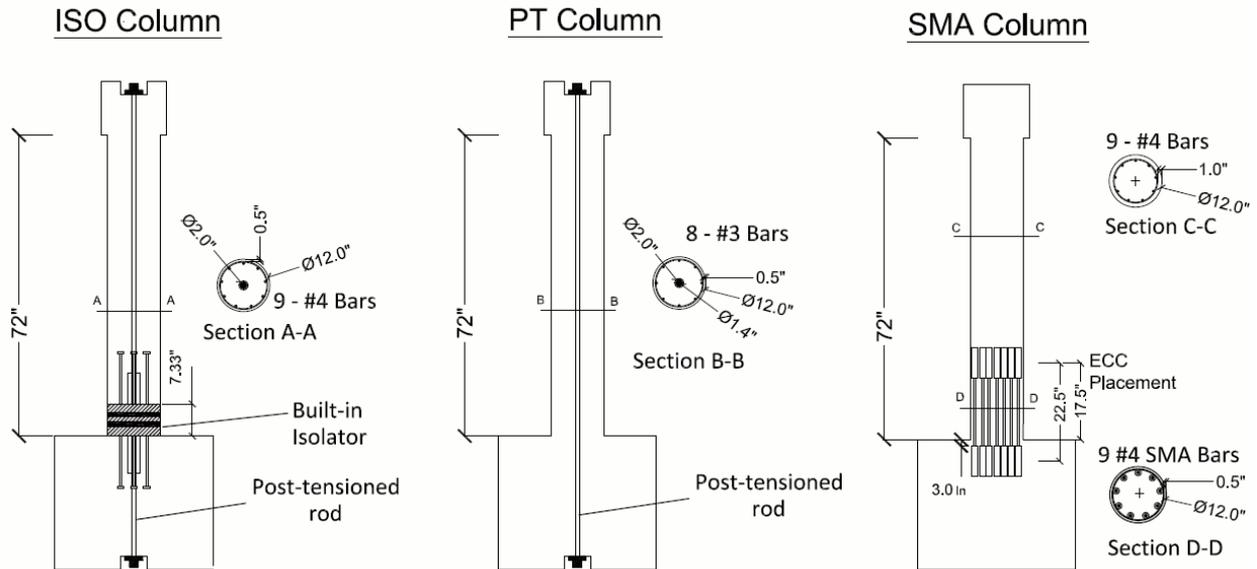


Figure 2. Side-view column basic details

### 2.3 ABUTMENT INTERACTION

The bridge model setup included abutment-superstructure interaction at the ends of the bridge. Displacement histories at the top of the abutments due to the ground motion were used as input by actuators that are connected to the abutment seats at both bridge ends.

### 2.4 INPUT MOTIONS

The motions used in the shake table tests are based on the 1994 Northridge earthquake. The time axis of the prototype motions were compressed by a factor of 2 to account for the scale effect.

## 3. Analytical modeling

The analytical simulations described in this study were conducted using the Open System for Earthquake Engineering Simulation (OpenSees) program (OpenSees 2002). This program is an object-oriented software framework for simulation applications in earthquake engineering using finite element methods (McKenna

and Fenves 2000). Previous experience (Zadeh and Saiidi 2007; Nelson et al. 2007) has shown that OpenSees program is capable of predicting the seismic response of the highly nonlinear structural systems with reasonable accuracy.

### 3.1 MODEL DESCRIPTION

The OpenSees model was composed of linear beam-column elements combined with nonlinear column fiber elements connected in a three-dimensional assemblage of nodes. All elements, except columns, were assumed to behave linearly. Classical damping was assumed with 0.02 damping ratio in the first and third modes. P-delta effects were included in the analysis. The nodal layout for the OpenSees model is shown in Figure 3.

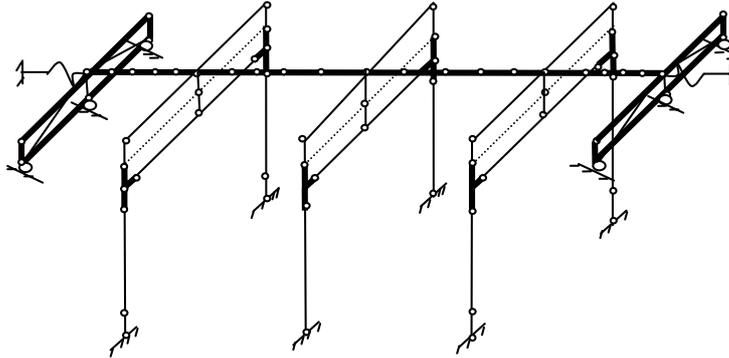


Figure 3. Nodal layout of the OpenSees model for the 4-span bridge

### 3.2 MATERIAL MODELS

Expected compressive strength of concrete and ECC were used. OpenSees “Concrete01” uniaxial material was used for both confined and unconfined concrete. Mander’s model (Mander 1998) was used to calculate confined concrete properties. To represent ECC material properties “Concrete02” uniaxial material model was used as suggested by O’Brien et al. (2007). This model allows for specifying tensile strength and linear tension softening. Reinforcing steel was represented using “Steel02” material model, with symmetric bi-linear stress-strain relationship and strain hardening capability. Steel modulus of elasticity was assumed as 29000 ksi (199810 MPa) and based on previous experience (Nelson et al. 2006) the yield stress was assumed as 68 ksi (469 MPa). To model SMA reinforcing material, OpenSees “Pinching4” material was used, as suggested by O’Brien et al. (2007). Rubber material in the built-in elastomeric pad (ISO bent) was modeled as an elastic uniaxial material. Design was based on the compressive stiffness  $E_{Rubber}$  of the elastomer.

### 3.3 ELEMENT CONFIGURATION

The bridge columns were modeled as non-linear elements. Lumped plasticity element “BeamWithHinges” was used in PT columns. For SMA and ISO bents, due to the fact that the columns are composed by several

different sections, uncertainty about the overall behavior arose. Thus, distributed plasticity was considered for both SMA and ISO bent columns, by using “nonlinearBeamColumn” elements.

### 3.4 BRIDGE-ABUTMENT INTERACTION

The abutment soil was represented by a nonlinear spring based on the force-deformation curve proposed by Shamsabadi et al. (2005) for the backfill soil reaction. The spring stiffness was assigned to a zero length element that connected the abutment to a fixed point. A uniaxial elastic gap element was placed between the deck and the seat spring to model the gap between them.

### 3.5 DYNAMIC ANALYSIS

The OpenSees “Multiple support excitation” option was used. The transverse record was scaled by its peak acceleration and applied in sequential runs of increasing amplitudes with peak ground acceleration (PGA) varying from 0.075 to 1.32g. The same scale factors were used for the longitudinal motion, resulting in PGA values ranging from 0.10 to 1.77g. A total of seven runs were defined, as shown in Table I.

Motion	Unscaled Motion PGA (g)	Scaled PGA (g)						
		Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7
Transverse	0.47	0.075	0.150	0.250	0.500	0.750	1.000	1.320
Longitudinal	0.63	0.100	0.200	0.330	0.660	1.000	1.340	1.770

### 3.6 PUSH-OVER ANALYSIS

One of the main objectives of this study was to determine the bridge model response during shake table testing. Transverse direction was considered to be the most critical since an idealized double-curvature behavior was assumed for the columns. Push-over analyses were conducted to determine the ultimate displacement capacity for each bent in the transverse direction. As suggested by Zadeh and Saiidi (2007), the ultimate displacement was defined as the point where the confined concrete at the core crushes.

## 4. Analytical results

### 4.1 POSITION OF BENTS

During pretest analyses, the location of the three bents was determined by analyzing the model for all possible different configurations of the bents in the bridge and comparing their transverse displacements. The objective of this part of the study was to place comparable displacement demands in the three bents (Hillis and Saiidi 2009). A total of six cases were analyzed. The level of motion for the analysis was selected such the PGA in the transverse direction was 1.00g (Run 6). The standard deviation (SD) of the calculated bent displacement values was taken as a reference to determine the optimum configuration. The

configuration defined by South Abutment, ISO bent, PT bent, SMA bent and North Abutment presented the lower variability for both the maximum and minimum displacements among the bents, with a maximum SD of 0.08 in (2 mm). Therefore, this configuration defined the final arrangement of the bents in the bridge.

#### 4.2 PUSH-OVER ANALYSIS

The push-over analysis results are shown in Figure 4. Bi-linear force-displacement response is observed for all three bents. The bents had approximately the same initial stiffness and for the nonlinear part of the curve, ISO bent presented the highest strength and SMA bent had the lowest.

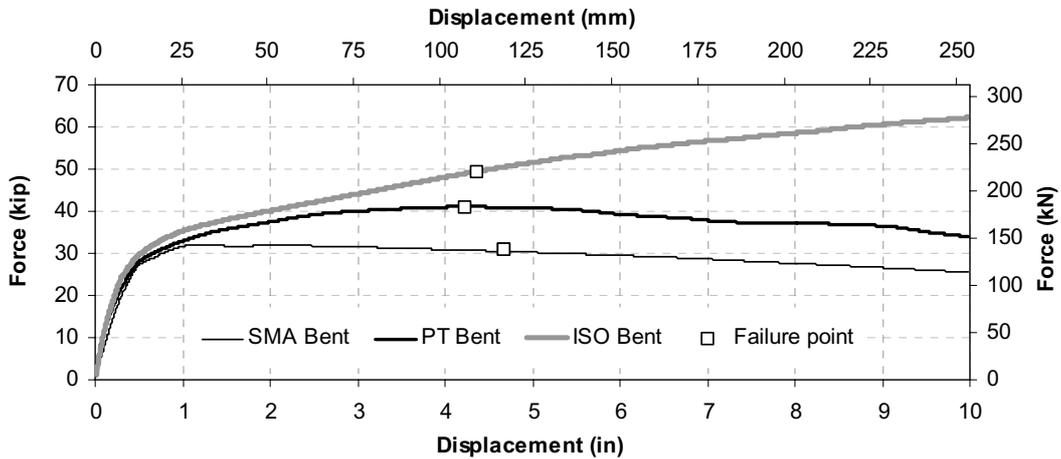


Figure 4. Push-over analyses in the transverse direction for all bents

Elasto-plastic idealizations of pushover curves were assessed from the push-over curves. ISO bent exhibited a post-yielding modulus of elasticity of about one-tenth of the initial stiffness, 3.31 kip/in (14.72 kN/mm). Yield strength of ISO Bent was 35 kip (155.7 kN), while plastic strengths of SMA and PT bents were 29.5 kip (126.8 kN) and 37.7 kip (165.9 kN), respectively. Therefore, the capacity of the bents can be expressed in terms of ductility ratios, as shown in Table II.

Bent	Yield Displacement		Ultimate Displacement		Displacement Ductility
	in	mm	in	mm	
ISO	0.40	10.16	4.36	110.74	10.9
PT	0.61	15.49	4.23	107.44	6.9
SMA	0.53	13.46	4.67	118.62	8.8

As shown in Table II, ductility values of the columns for all bents are comparable to but exceed those of conventional concrete piers meeting current bridge seismic design codes. If ultimate displacements are taken as a reference, columns in PT bent are the most critical columns in the bridge, as they can sustain the smallest displacement, followed by columns of ISO bent. Columns of SMA bent, in contrast, are able to withstand the largest displacement values.

#### 4.3 BENT DISPLACEMENTS

In order to capture the bridge response from the initial yielding of reinforcement through column failure, the motions were sequentially applied to the bridge from Run1 to Run 7. Displacement histories for the ISO bent in the longitudinal and transverse directions are plotted in Figure 5.

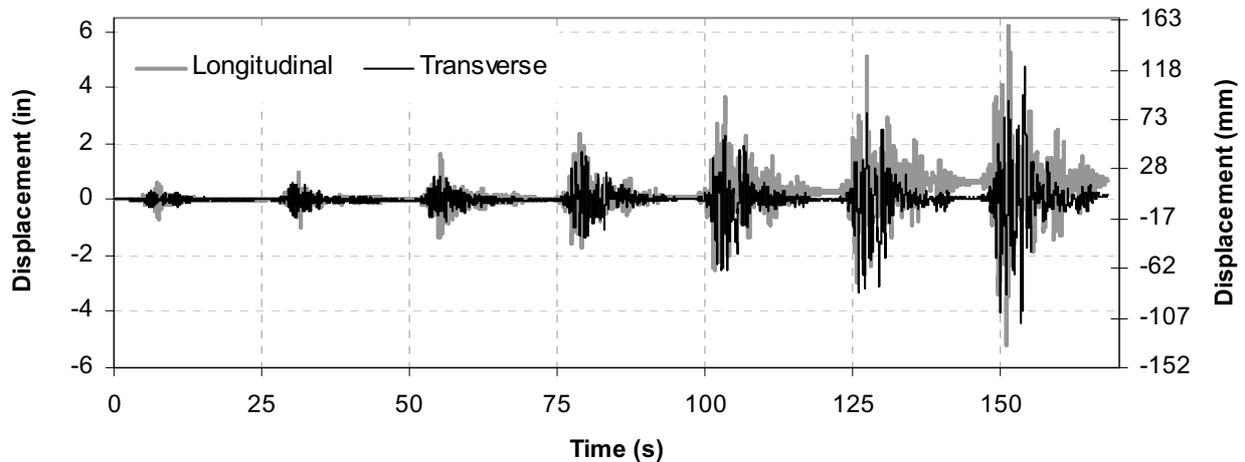


Figure 5. Calculated displacement history for ISO bent

It can be seen that the longitudinal displacements were consistently higher than the transverse displacements for all runs. In the longitudinal direction, all bents exhibited nearly the same displacement because of the large axial stiffness of the superstructure. The average longitudinal displacement for Run 7 was 6.20 in (157.5 mm) while in the transverse direction ISO bent exhibited the largest displacement, 4.78 in (121.4 mm), and PT bent had the smallest with 4.16 in (105.7 mm). To identify the maximum bent displacement demand, resultants of longitudinal and transverse displacement histories were calculated. Then, the ductility demand  $\mu_{\Delta}$  was estimated by dividing the resultant displacements to the bent yield displacements obtained from the idealized pushover curves (Table III). Crushing in the confined core of the bents was expected to occur during Run 5 in ISO and PT bents where the ductility demand was practically the same as the estimated ductility capacity. For Runs 6 and 7, resultant displacements led to ductility demands that surpassed the ductility capacity for all bents. If only the transverse component of the motion were applied to the bridge after Run 5, the bridge could withstand levels of motion similar to those of Run 6 because the calculated displacement demands in the transverse direction are smaller than the ultimate displacements from push-over analyses.

Event No.	ISO Bent Disp.			PT Bent Disp.			SMA Bent Disp.		
	Displacement in	mm	$\mu_D$	Displacement in	mm	$\mu_D$	Displacement in	mm	$\mu_D$
1	0.66	17	1.3	0.66	17	1.1	0.66	17	1.7
2	1.04	26	2.0	1.02	26	1.7	1.03	26	2.6
3	1.69	43	3.2	1.68	43	2.7	1.67	42	4.2
4	2.60	66	4.9	2.61	66	4.3	2.66	68	6.6
5	4.30	109	8.1	4.19	106	6.9	4.16	106	10.4
6	5.90	150	11.1	5.80	147	9.5	5.76	146	14.4
7	7.10	180	13.4	7.01	178	11.5	6.96	177	17.4

Regarding the displacement performance of the bridge, the design objective was to achieve similar transverse displacements in the bents. Figure 6 shows the displacements for ISO, PT and SMA bents during Run 7. It can be seen that all three bents exhibit nearly the same displacement demands, with maximum and minimum values being synchronized. Therefore, the in-plane rotation effect in the bridge superstructure is small.

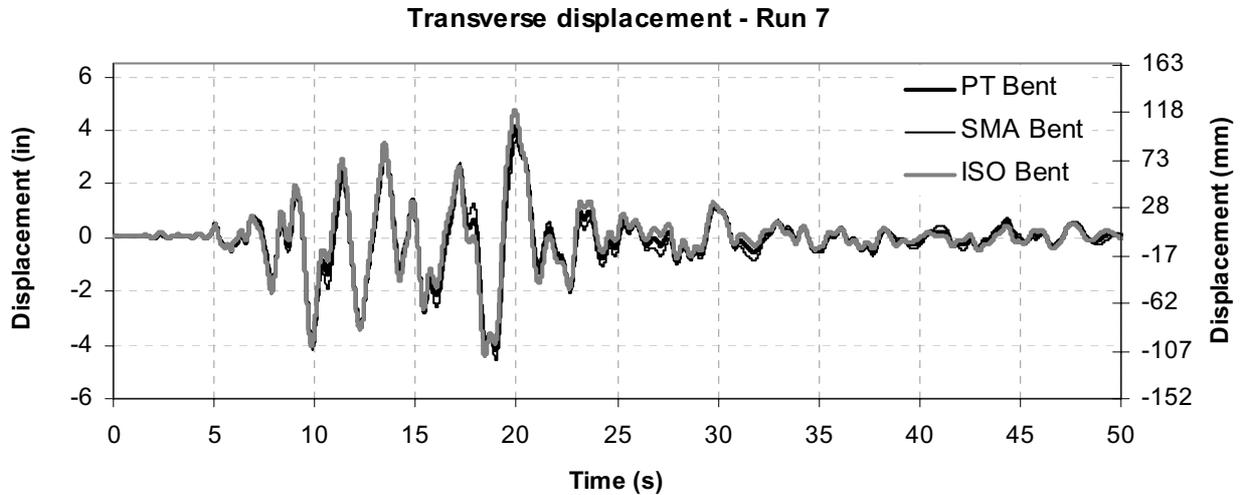


Figure 6. Transverse displacements of ISO, PT and SMA bents for Run7

## 5. Analytical Model Performance and Experimental Results

### 5.1 SHAKE TABLE TESTS

The dynamic tests conducted on the 4-span bridge specimen were carried out from Dec. 4 to Dec. 12, 2008 at the UNR Large Scale Structures Laboratory. To avoid overloading of the abutment actuators, the abutment motions could only be applied in the first two runs. For Runs 3 to 7, the seats were moved away from the bridge ends by a distance of 3 in (76.2 mm) to prevent the engaging of the abutments. The original loading protocol had to be modified as well due to the extensive damage observed at the conventional reinforced concrete plastic hinge zones in ISO columns after Run 5. Because of safety concerns, it was decided to conduct Runs 6 and 7 with only the transverse component of the input motion, keeping the same amplitude for both runs (1.00g) while the longitudinal motions were set to zero.

### 5.2 OPENSEES MODELING OF THE 4-SPAN BRIDGE

The analytical model was used to estimate the response of the bridge model using the measured properties of concrete and ECC obtained from tests conducted on the last day of experiments. The steel properties were also updated based on tests results before the experiment. The achieved displacements recorded at the UNR shake tables and the abutments were used as input motions for the model.

### 5.3 BENT DISPLACEMENTS

The relative displacements of the bents with respect to the shake tables are compared with the corresponding calculated values from the analytical model in each bent for Runs 1 to 7 in Table 4. Figure 7 shows the displacement history of the ISO bent for Run 2 and 7 in the transverse direction.

Event No.	Earthquake Level (g)		ISO Bent Disp. in (mm)				PT Bent Disp. in (mm)				SMA Bent Disp. in (mm)			
			Measured		Calculated		Measured		Calculated		Measured		Calculated	
	Trans. Dir.	Long. Dir.	Max. Trans.	Max. Long.	Max. Trans.	Max. Long.	Max. Trans.	Max. Long.	Max. Trans.	Max. Long.	Max. Trans.	Max. Long.	Max. Trans.	Max. Long.
			(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm)
1	0.075	0.100	0.108 (2.75)	0.235 (5.98)	0.260 (6.6)	0.289 (7.34)	0.096 (2.43)	0.235 (5.98)	0.167 (4.24)	0.247 (6.27)	0.110 (2.8)	0.235 (5.98)	0.350 (8.89)	0.247 (6.28)
2	0.150	0.200	0.266 (6.75)	0.803 (20.39)	0.555 (14.09)	0.572 (14.54)	0.188 (4.78)	0.719 (18.25)	0.343 (8.72)	0.571 (14.49)	0.337 (8.55)	0.739 (18.76)	0.622 (15.8)	0.594 (15.1)
3	0.250	0.330	0.806 (20.47)	1.799 (45.69)	0.975 (24.77)	1.548 (39.32)	0.540 (13.73)	1.688 (42.87)	0.725 (18.42)	1.488 (37.8)	0.744 (18.9)	1.693 (43)	0.729 (18.52)	1.425 (36.2)
4	0.500	0.660	2.020 (51.3)	2.349 (59.67)	1.938 (49.23)	2.239 (56.88)	1.661 (42.2)	2.238 (56.84)	1.856 (47.13)	2.143 (54.44)	1.702 (43.23)	2.212 (56.18)	1.843 (46.82)	2.075 (52.7)
5	0.750	1.000	2.384 (60.55)	3.865 (98.18)	2.915 (74.04)	4.314 (109.57)	2.409 (61.19)	3.716 (94.38)	2.429 (61.7)	3.786 (96.16)	2.517 (63.93)	3.566 (90.58)	2.179 (55.34)	3.765 (95.64)
6	1.000	0.000	4.173 (105.98)	0.048 (1.22)	3.663 (93.04)	0.207 (5.27)	3.587 (91.12)	0.048 (1.21)	3.138 (79.7)	0.258 (6.57)	3.542 (89.96)	0.047 (1.21)	2.960 (75.18)	0.163 (4.14)
7	1.000	0.000	4.220 (107.19)	0.041 (1.04)	3.655 (92.84)	0.221 (5.62)	3.642 (92.5)	0.037 (0.94)	2.997 (76.12)	0.296 (7.51)	3.568 (90.62)	0.039 (0.99)	2.851 (72.42)	0.190 (4.84)

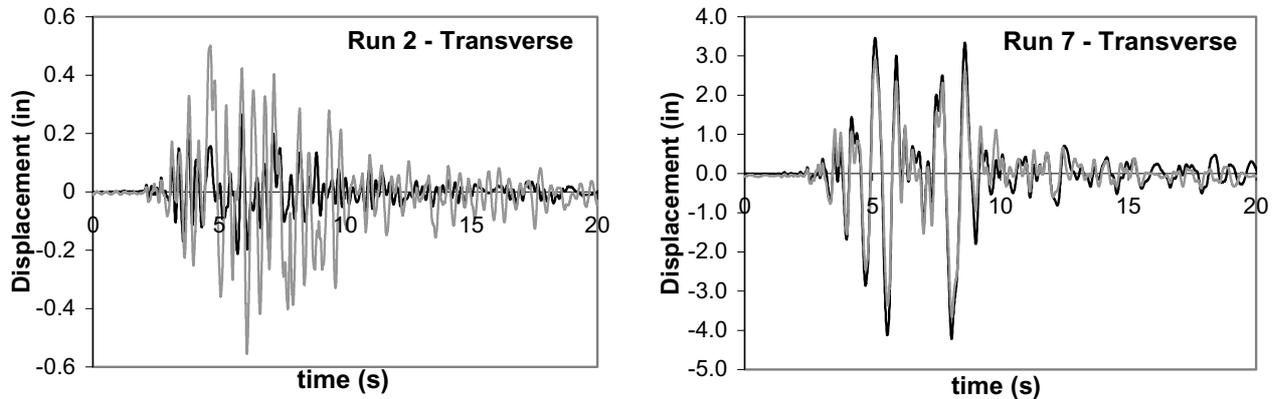


Figure 7. ISO bent displacements. Bold line: measured, gray line: calculated

From Table IV, it is possible to notice that the largest differences in displacement appear in Runs 1 and 2, in which the abutments were active. These differences are attributed to the inability of the OpenSees model to capture the bridge-abutment interaction mechanism. The maximum percentage error during Runs 1 and 2 (340%) occurred for the transverse displacement of the ISO bent with the model greatly

overestimating the displacement. The agreement between the calculated and measured displacements is satisfactory with reasonable accuracy for Runs 3 to 7, with the maximum calculated results being within 1 to 34% of the measured displacements. Regarding the objective of having comparable displacement demands among all three bents, ISO bent presented larger peak displacements (about 16%), when compared with SMA and PT bents which had practically the same peak displacements. These results can be attributed to the increased flexibility in the ISO bent caused by the low stiffness of the elastomeric pad at the bottom plastic hinge zones.

#### 5.4 FORCE-DISPLACEMENT RELATIONSHIPS

The lateral forces in each bent were calculated from the pressure of the dynamic fluid in the shake table actuators, as suggested by Johnson (2007). Figure 8 shows the calculated and measured base shears for the PT bent for Runs 6 and 7 in the transverse direction.

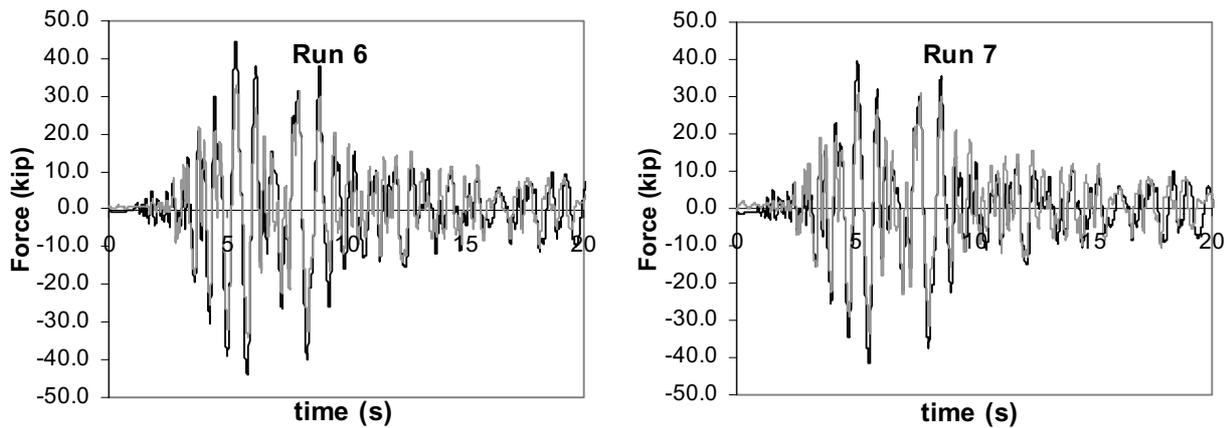


Figure 8. PT bent transverse shear force. Bold line: measured, gray line: calculated

It can be seen from Figure 8 that the overall estimate of the shear force at the PT bent is satisfactory. The quality of these results are typical for other bents during Runs 3 to 7, while for Runs 1 and 2 more dispersion exists as a direct consequence of the bridge-abutment interaction.

#### 5.5 DUCTILITY VERIFICATION

The ductility capacities for the bridge bents were recalculated taking into account the measured test-day material properties using push over analysis. The calculated displacements were 4.22 in (107.2 mm), 3.60 in (91.4 mm) and 3.41 in (86.6 mm) for the SMA, PT and ISO bents, respectively. This led to ductility capacities of 6.93, 7.49 and 5.26 for the bents, respectively. In terms of ultimate displacements, the SMA bent exhibits more capacity than the others (in about 20%). As before, the ISO bent appears to be the most critical component of the bridge, with the lowest ductility. The measured demands observed in the bridge, in terms of ultimate displacement, are presented in Table V.

It is possible to notice that for both the ISO and PT bents, the calculated capacity of the bridge was exceeded by the actual displacement by 29 and 23% during Run 7, respectively. The maximum measured resultant displacement of the SMA bent was lower than the displacement capacity for all runs. For Runs 6

and 7, the resultant displacements experienced by the ISO bent are larger than the calculated displacement capacity.

Run	ISO bent		PT bent		SMA bent	
	(in)	(mm)	(in)	(mm)	(in)	(mm)
1	0.220	5.6	0.219	5.6	0.212	5.4
2	0.803	20.4	0.719	18.3	0.744	18.9
3	1.845	46.9	1.720	43.7	1.746	44.4
4	2.477	62.9	2.273	57.7	2.374	60.3
5	4.405	111.9	4.428	112.5	4.286	108.9
6	4.173	106.0	3.587	91.1	3.542	90.0
7	4.220	107.2	3.642	92.5	3.568	90.6

## 5.6 OBSERVED TEST RESULTS

The observed performance of the bridge model agrees with the analytical results to a large extent. After Run 5, severe concrete spalling and flexural cracks appeared at the top plastic hinges in the ISO bent columns. After Run 6, it was clear that the ISO bent was the most critical component of the system, as the damage extended to the confined core at the top of the columns. The other bents experienced also concrete spalling and cracking, but the column damage seemed to be located only at the concrete cover. After Run 7, extensive damage and sudden loss of load capacity occurred at ISO bent. One of the bars fractured in the east column while several other bars buckled. The bottom plastic hinge zone performance of both the ISO and the SMA bents was remarkable, with no visible residual deformation in the case of the elastomeric pad at the ISO bent and no significant concrete spalling at the bottom plastic hinge zone of the SMA columns. A comparative view of all plastic hinge zones of the bridge after Run 7 is shown in Figures 9 and 10.

The OpenSees model captured most of the behavior observed during the tests. As identified in the simulations after the model was updated with the new material properties, the ISO bent was the most critical component in the bridge, with the smallest of the calculated ductility capacity for the top plastic hinge zone. The model was also successful in estimating the increased displacement capacity of the SMA bent, governed by the innovative details at the bottom plastic hinge. As illustrated in Figure 10, the damage was negligible at this zone.



Figure 9. Top plastic hinge zones of ISO, PT and SMA bents after Run 7

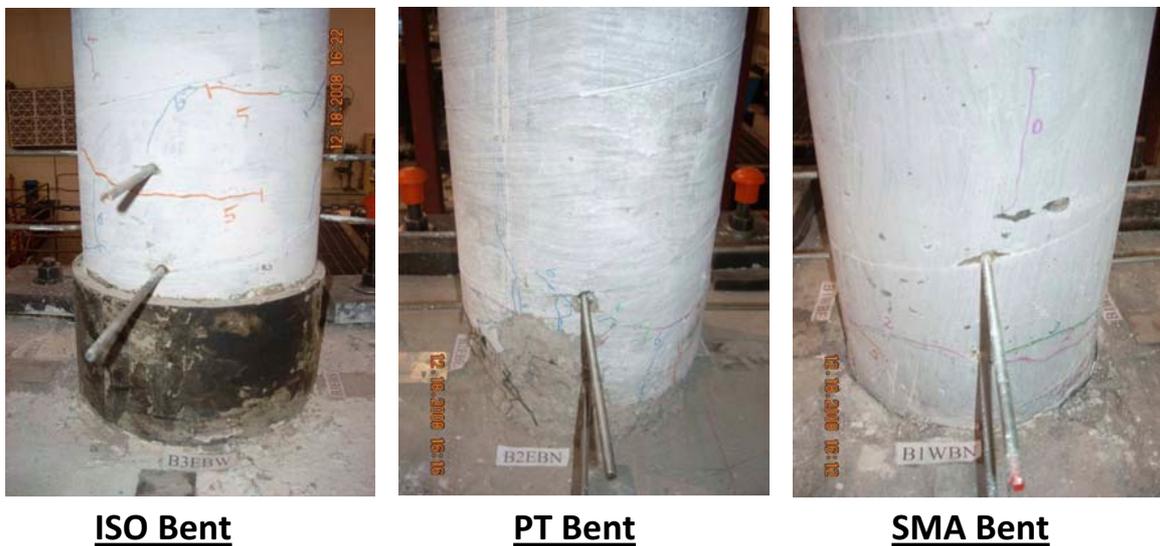


Figure 10. Bottom plastic hinge zones of ISO, PT and SMA bents after Run 7

## 6. Conclusions

This study presents the analytical study of a 4-span reinforced concrete bridge specimen tested on the three shake table system at University of Nevada, Reno and the correlation studies of the analytical model with experimental results. The bridge specimen incorporates unconventional materials and details at the plastic

hinge zones of the columns to improve their seismic performance. A finite element program, OpenSees, was used to model the bridge and define the position of the bents. The program has been used in the past to predict with reasonable accuracy the response of large nonlinear bridge systems.

Pre-defined OpenSees material and element models were used to represent the actual properties of the innovative components. Essential characteristics of different materials and details were captured and simple assumptions were used to select appropriate element formulations. Several configurations of bents were tested in the model until a target performance was achieved. Comparable analytical displacement demands in the transverse response of all three bents were obtained with the arrangement of South Abutment, ISO bent, PT bent, SMA bent and North Abutment. The experimental results showed that this target performance was met by the PT and SMA bents, while the ISO bent had slightly larger peak displacements (16% more).

In terms of estimating displacements, the model showed limitations when representing the bridge-abutment interaction, which translated in significant overestimation of transverse displacements during Runs 1 and 2. The model estimated the experimental bent displacements for Runs 3 and 7 within reasonable accuracy. Regarding shear forces at the base of the bents, the model showed its ability to reproduce adequately the measured shears during Runs 3 to 7.

Adequate seismic response was determined in the bridge columns in terms of ductility capacity. Calculated ductility capacity using static push-over analyses was comparable to that of conventional reinforced concrete columns, which represents a desirable feature for new materials.

The analyses conducted with OpenSees for sequentially-increasing input motions showed that the bridge may only survive up to Run 5 (PGA of 0.75 and 1.00g in transverse and longitudinal direction, respectively). According to the results obtained with the OpenSees model, the ISO bent was identified as the most critical component during the experiment. Experimental observations agreed well with the model assessment. Complete failure occurred at ISO bent during Run 7 at the conventional reinforced concrete plastic hinges at the top of the columns. Bottom plastic hinge zones at ISO and SMA bent performed remarkably well during the experiments, while all the damage was located at the bridge zones without innovative details. The ability showed by the OpenSees model to estimate key features of the bridge performance is encouraging for the engineering community when it comes to implement these innovative details in future designs, although improvements in modeling of the abutment superstructure interaction is warranted.

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