

Multi-Shake Table Seismic Studies of a 33-Meter Railway Concrete Bridge with High-Performance Materials

M. Saiidi^{1,*}, C. Cruz² and D. Hillis³

Received: September 2009

Accepted: February 2010

Abstract: Three unconventional details for plastic hinges of bridge columns subjected to seismic loads were developed, designed, and implemented in a large-scale, four-span reinforced concrete bridge. Shape memory alloys (SMA), special engineered cementitious composites (ECC), elastomeric pads embedded into columns, and post-tensioning were used in three different piers. The bridge model was subjected to two-horizontal components of simulated earthquake records of the 1994 Northridge earthquake in California. The multiple shake table system at the University of Nevada, Reno was used for testing. Over 300 channels of data were collected. Test results showed the effectiveness of post-tensioning and the innovative materials in reducing damage and permanent displacements. The damage was minimal in plastic hinges with SMA/ECC and those with built in elastomeric pads. Conventional reinforced concrete plastic hinges were severely damaged due to spalling of concrete and rupture of the longitudinal and transverse reinforcement. Analytical studies showed close correlation between the results from the OpenSEES model and the measured data for moderate and strong earthquakes.

Keywords: Concrete Bridge, Elastomeric pad, Reinforcement Bridge Model

1. Introduction

Except for bridges that are categorized as critical structures, bridge structures are designed to undergo substantial nonlinear deformations during strong earthquakes and experience serious damage and permanent drift. The design objective for non-critical bridges is to prevent collapse. A new approach to earthquake-resistant concrete bridge design is emerging in which the “no-collapse” target performance is considered to be inadequate. Based on this new approach, even non-critical bridges are to remain functional or nearly so after strong earthquakes. For bridges to continue to be functional the column damage (damage indicator 1) should be none or minimal and permanent lateral displacements (damage indicator 2) should be very small. One approach to accomplish the new emerging performance objective is to make use of high-performance materials and unconventional details that would address one or both damage indicators. This paper describes three high-performance column details and their application in a large-scale bridge model tested on multiple shake tables.

* Corresponding Author: email: saiidi@unr.edu

^{1,2,3} Department of Civil Engineering, University of Nevada, Reno, Nevada, USA

2. High-Performance Materials and Details

Three types of high-performance columns were studied: columns with shape memory alloy (SMA) combined with engineered cementitious composites (ECC), post-tensioned columns with built in elastomeric pads, and post-tensioned columns with conventional reinforced concrete.

3. SMA Combined with ECC

Shape memory alloys are special metallic materials that combine two or more alloys to accomplish certain features. Several types of these alloys are available and have been used in many products but their application in civil/structural engineering has been limited. The particular feature that was of interest in the current study was the superelastic memory effect that allows the SMA yield and dissipate energy but return to its original length upon stress removal under a range of temperature representing those encountered in bridges. The most common type of SMA with this feature is a combination of Nickel and Titanium of approximately equal proportions known as Nitinol (NiTi). Figure 1 shows SMA bars used in the plastic hinge zone of a column cage. The SMA bars are connected to steel bars using sleeve



Fig. 1. SMA bars connected to steel bars

couplers.

The ECC is a grout composed of cement, sand, water, and a patented polyvinyl alcohol fibers (Figure 2). The mix might include fly ash as a substitute for a part of the cement. What makes ECC unique is its ability to undergo large tensile strains of up to 5%. Micro-cracks develop but are spanned by fibers that through a special coating allow for partial slip and relatively large deformations. By using SMA/ECC in column plastic hinge zones it is possible to substantially reduce concrete spalling and damage and to minimize residual lateral displacements [1,2,3].

4. Built in Elastomeric Pads

Elastomeric materials are capable of undergoing large tensile strains without failing. They also have a relatively high damping

characteristic. Because of their relatively low stiffness, elastomeric pads have been used in civil engineering structures as base isolators to lengthen structural vibration period and take advantage of reduced seismic forces and higher damping. In 2002 a different application of elastomeric pads was explored by incorporating them into the plastic hinge region of concrete bridge columns [4]. The objective in that study was to eliminate spalling of concrete and to reduce damage in the plastic hinge region. The performance was satisfactory up to moderate levels of lateral displacements. Under large displacements, the rubber did not provide sufficient restraint for the column longitudinal bars and the bars buckled and failed due to low cycle fatigue.

A modified version of elastomeric pads was developed by the author and his research team to prevent bar buckling. Figure 3 shows a view of the new pad. The fundamental difference between this version and an earlier version of the pad was that the new pad incorporated steel shims to prevent bar buckling and the pad was relatively thick to allow for large rotation. The pad was vulcanized to steel plates at the top and bottom, and a central steel pipe was used to prevent shear deformations and to serve as a duct for a post-tensioning rod. The outer holes in Figure 1 were predrilled to allow for the passage of column longitudinal bars. The other holes were only in the end steel plates for the attachment of headed steel dowels to anchor the pad in concrete.

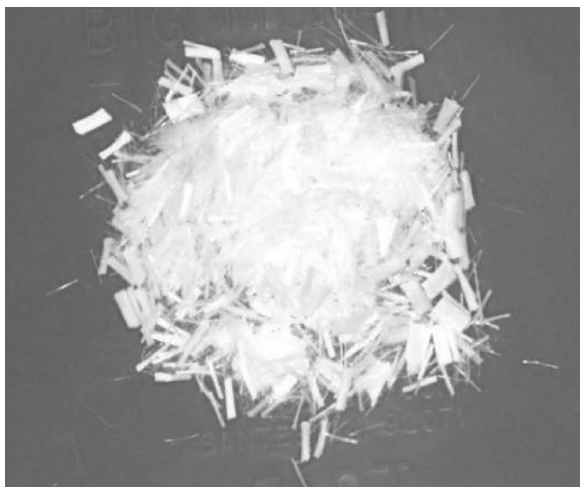


Fig. 2. PVA fibers



Fig. 3. New UNR elastomeric pad

5. Post-Tensioned Columns

One effective approach to reduce residual displacements in columns subjected to earthquake loading is post-tensioning [5]. As the column is displaced laterally an axial post-tensioned force tends to return the column to its original position and recenter the column. The post-tensioning approach addresses one of the two damage indicators, the reduction of permanent lateral displacement. However, the column is still susceptible to damage due to spalling of concrete and penetration of damage to the column core under large displacements. Another drawback with this detail is the relatively small amount of energy dissipation these columns offer. To address this problem, mild steel is used in the plastic hinges and is anchored in the footing and the superstructure.

6. Implementation in Large-Scale Bridge Model

The aforementioned details were implemented in the piers of a 4-span bridge model supported on three piers of identical geometric dimensions (Figure 4). A similar 4-span bridge model incorporating conventional reinforced concrete piers had been tested in a previous study directed by the first author [6]. The superstructure was a continuous prestressed reinforced concrete slab, 107 ft (32.6 m) long and 7.5 ft (2.30 m) wide with circular columns having a diameter of 12 in (304.8 mm) and clear height of 72 in (1830 mm). The superstructure consisted of three solid rectangular section beams in each span that were transversely and longitudinally post-tensioned, making the entire superstructure behave as a unit (Figure 5). An additional dead load of 180 kips (800 kN) was placed on the bridge model deck in order to ensure realistic representation of stresses in the columns.

The upper column plastic hinges were made with conventional concrete and steel. Detailed information for the bent design can be found in [7]. Essential details of the columns used in SMA, PT and ISO bents are shown in Figure 6. Over 300 channels of transducers were attached to the model to measure displacements, strains, accelerations, and rotations.

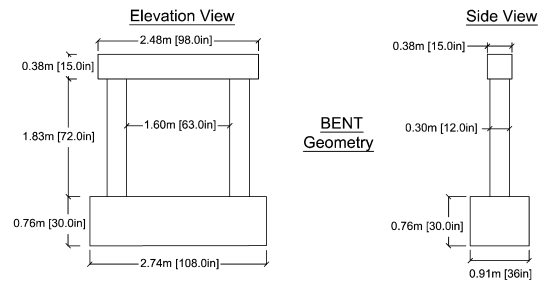


Fig. 4. Pier geometric details

The bridge model was subjected to seven coherent earthquake runs simulating the 1994 Northridge southern California earthquake record. The amplitude of the motions increased in successive runs to determine the response under different levels of earthquakes. The first five motions were applied in the two orthogonal horizontal directions. The latter two were applied only in the transverse directions because of the limitations of the abutment loading system. During test 7, several steel bars fractured in conventional reinforced concrete plastic hinges in two of the piers and hence the model was considered to have failed.

7. Summary Experimental Results

The measured displacement histories for all three piers indicated that the residual displacement was insignificant in all three piers, and that the recentering technique of post-tensioning used in the PT and ISO piers and the superelastic feature of SMA incorporated in the SMA/ECC pier were effective.

As mentioned in the previous section during the last motion the upper plastic hinges in the ISO pier failed due to rupture of the longitudinal and transverse bars. The upper plastic hinge in the PT and SMA piers underwent severe concrete damage exposing the longitudinal and transverse bars. Figure 5 shows the upper plastic hinges after the final test. Except for the post-tensioning forces, the details were conventional reinforced concrete plastic hinges meeting the current code requirements.

In the same piers, there was little damage in the lower plastic hinges in the SMA pier and ISO pier, with the damage being limited to minor

cracking (Figure 5). In the PT pier, however, the damage was severe and the spiral reinforcement fractured in one of the columns. Two conclusions are drawn: (1) that both SMA/ECC combination and the built in elastomeric pad drastically reduced the damage making the bridge potentially serviceable even after a strong earthquake that led to the failure of several plastic hinge, and (2) the plastic hinge in the PT pier was severely damaged. Post-tensioning alone was not sufficient to keep the PT pier serviceable.

8. Analytical Studies

Extensive analytical studies of the bridge model were conducted before and after the shake table tests. Computer program OpenSEES was used for analytical studies [8]. The objective of the pretest analyses were twofold: (1) finalizing the design of sections and location of different piers, and (2) planning the testing protocol. It was important that comparable displacement demands would be placed on the three piers so the performance of different details could be compared. The purpose of the post-test analysis was to determine the adequacy of the analytical modeling and to obtain more details about the internal forces and performance of different plastic hinges. The post-test analytical studies are in progress as of this writing. Thus far it has been found that the OpenSEES model leads to

close agreement with the test data when nonlinear deformations are moderate or large. Under small motions of the first two runs the correlation is not close. The reason for the lack of agreement under low-amplitude motions is currently being investigated.

Figure 9 shows a sample of the measured and calculated displacement histories in the transverse direction of the bridge at the top of the ISO pier during the last motion. It can be seen that the measured and calculated responses are close both in terms of the waveforms and amplitudes.

9. Conclusion

The material presented in this article showed that the superelastic characteristic of SMA bars observed in individual bar tests may also be observed in SMA-reinforced concrete columns. The combination of ECC and SMA was found to significantly reduce the earthquake damage compared with conventional reinforced concrete construction. The new built-in shimmed elastomeric pads used in ISO pier proved to be effective in minimizing the earthquake damage even under relatively large displacement ductilities.

In the ISO pier the presence of post-tensioning force reduced residual displacements. The post-tensioned pier (PT bent) incorporating

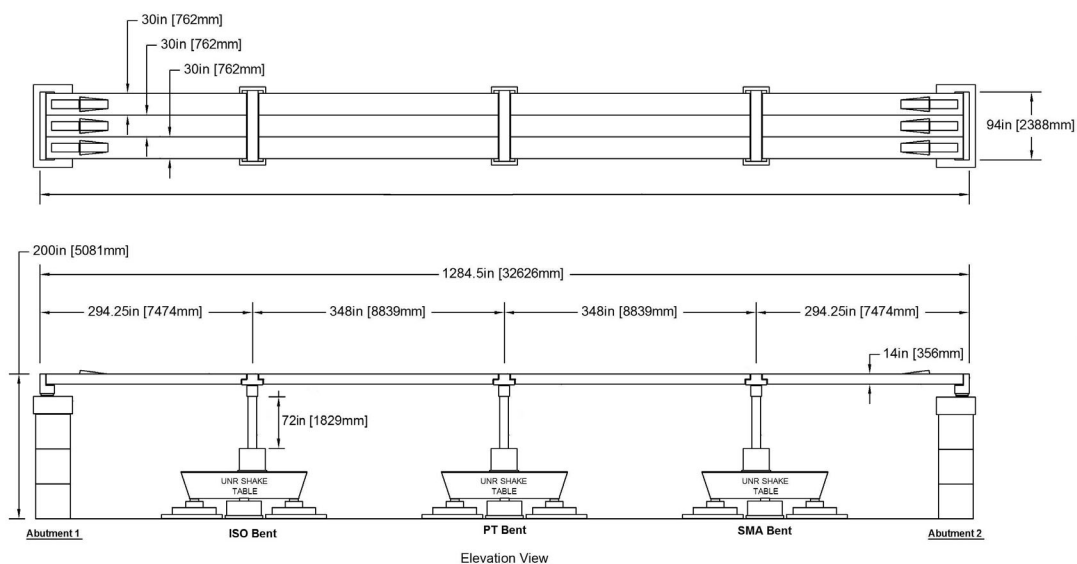


Fig. 5. Bridge model plan and elevation

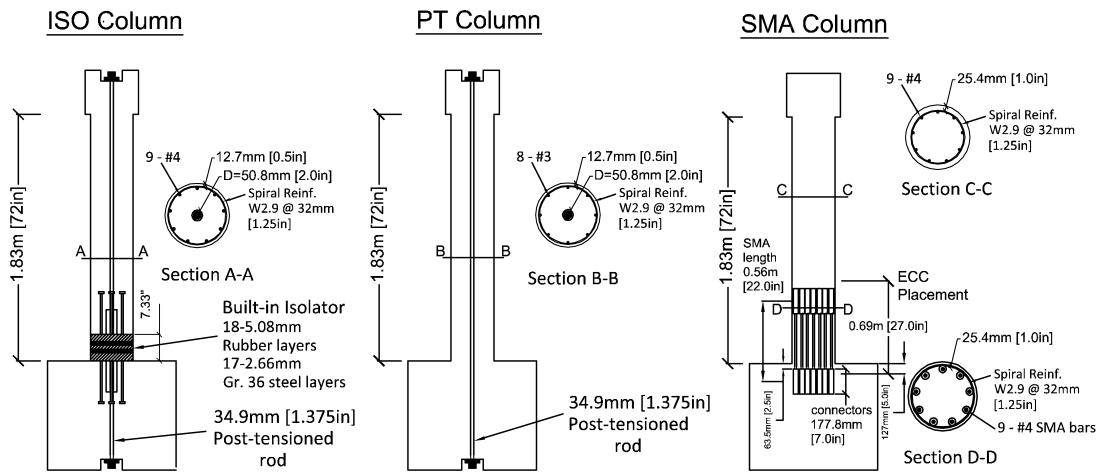


Fig. 6. Side-view column details



Fig. 7. Upper plastic hinge after final motion: left to right, SMA pier, PT pier, and ISO pier



Fig. 8. Lower plastic hinge after final motion: left to right, SMA pier, PT pier, and ISO pier

conventional reinforced concrete plastic hinges was successful in minimizing residual displacements, but suffered from severe damage due to spalling of concrete and rupture of the transverse steel. It was also noted that analytical results using OpenSEES were in close agreement

with the measured displacement histories for moderate and strong motions.

10. Acknowledgment

The study presented in this article was funded

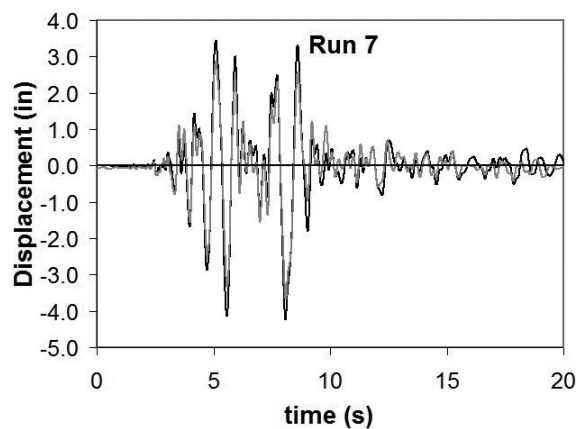


Fig. 9. Calculated (gray) and measured (black) displacement history for ISO pier during last run

by the US National Science Foundation under the NEESR Grant No. CMS-0420347 and CMS-0402490. The support of program directors Dr. Steve McCabe and Dr. Joy Pauschke is appreciated. The authors are also indebted to the staff of the structures laboratory at the University of Nevada, Reno particularly Dr. Patrick Laplace and Dr. Sherif Elfass.

References

- [1] Saiidi, M., and H. Wang, , May-June 2006, "An Exploratory Study of Seismic Response of Concrete Columns with Shape Memory Alloys Reinforcement," American Concrete Institute, ACI Structural Journal, Vol. 103, No. 3, pp. 436-443.
- [2] Saiidi, M., M. Zadeh, C. Ayoub, and A. Itani, June 2007 "A Pilot Study of Behavior of Concrete Beams Reinforced with Shape Memory Alloys," Journal of Materials in Civil Engineering, ASCE, Vol. 19, No. 6, pp. 454-461.
- [3] Saiidi, M., O'Brien, and Zadeh, M., January-February 2009, "Cyclic Response of Concrete Bridge Columns Using Superelastic Nitinol and Bendable Concrete," American Concrete Institute, ACI Structural Journal, Vol. 106, No. 1, pp. 69-77.
- [4] Kawashima, K., and Nagai, M., Development of a reinforced concrete pier with a rubber layer in the plastic hinge region, Structural and Earthquake Engineering, Proc. JSCE, 703/I-59, 113-128, 2002.
- [5] Sakai, J. and S. Mahin, "Mitigation of residual displacements of circular reinforced concrete bridge columns," 13th World Conference on Earthquake Engineering: Conference Proceedings, Vancouver, British Columbia, Canada, August 1-6, 2004, Paper No. 1622, 2004.
- [6] Nelson, R., Saiidi, M., Zadeh, S., "Experimental Evaluation of Performance of Conventional Bridge Systems," Center of Civil Engineering Earthquake Research, Department of Civil Engineering, University of Nevada, Reno, Nevada, Report No. CCEER-07-4, 2007.
- [7] Hillis, D., Saiidi, M., "Design, Construction, and Preliminary Analysis of an Innovative Bridge Model," Center of Civil Engineering Earthquake Research, Department of Civil Engineering, University of Nevada, Reno, Nevada, Report No. CCEER-09-01, 2009.
- [8] McKenna, F., and Fenves, G.L., 2000, "An Object-oriented Software Design for Parallel Structural Analysis." Proc. of the SEI/ASCE Structures Congress, Philadelphia, PA, (<http://opensees.berkeley.edu>).