Application of Shape Memory Alloy to Seismic Design of Multi-column Bridge Bents Using Controlled Rocking Approach

R. Davoudi, M. Khanmohammadi, M. Ghassemieh & S. Rafiee
School of Civil Engineering, University of Tehran, Iran

SUMMARY
In the new methods of seismic design or retrofit, new approaches are considered due to giant hazards of the recent earthquakes. One of these approaches is controlled rocking, and recent studies have shown that it would be more beneficial to reduce the strength and rigidity of structures while still increasing damping to reach self centering behavior. The major aim of this new approach is avoiding damage in order to ensure post-earthquake serviceability. Due to lack of sufficient energy dissipation in rocking systems, providing additional mechanism to reduce residual drift and adequate energy dissipation are vital. This study presents the use of rocking columns in multi-column bridge bents along with shape memory alloy bars to enhance the system. In this research the results of nonlinear static and dynamic analysis from a conventional design are compared with proposed rocking system. For both systems residual displacements, as well as energy dissipation are explored.

Keywords: multi-column bridge bents, rocking, SMA, self centering

1. INTRODUCTION

Conventional seismic design of ductile reinforced concrete bridges implies the non-linear behavior of the system to be accommodated through the formations of flexural plastic hinges in structural elements. As a consequence of the inelastic structural response, a significant level of damage is thus expected and has so far been accepted. Mazzoni and Moehle investigated on poorly detailed joints in conventional bridges, especially exterior knee joints that are the most vulnerable location in the bridge bents under cyclic loading condition. The concrete shear failure in the form of diagonal tension is a common mode of failure in joints with inadequate transverse reinforcement. Pauley and Priestley's study indicated that in some cases bond failure in the longitudinal bars are also observed as another undesirable failure mode, especially where the main bars are not properly anchored in cap beam. The advantage of self-centering approach eliminates permanent drift, maintains post-earthquake serviceability and reduces damages after earthquakes. The first study intended to simulate the self-centering effect in structures was carried out by Priestley and Tao.

On the other hand, recent studies have shown that it would be more beneficial to reduce the strength and rigidity of structures while still increasing damping. The first applications and extensions of controlled rocking approach to bridge piers, proposed by Mander and Chen, were based on experimental and analytical investigations. They developed a self-centering design method for bridge piers referred to as Damage Avoidance Design (DAD). The philosophy of DAD is to cut the longitudinal reinforcement bars at beam-column joint to avoid its large plastic strain due to seismic loading, and let column free to rock on the surface of cap or foundation beams. Stanton et al proposed a hybrid system, in which mild steel reinforcement was combined with unbounded tendons in the critical connections. The objective of using mild steel reinforcement was to provide hysteretic energy absorption to the system. Marriott et al investigated experimental response of 1:3 scale unbounded post-tensioned cantilever bridge piers, subjected to quasi-static and pseudo-dynamic loading protocols, and compared with an equivalently reinforced monolithic benchmark. Minimal physical damage was observed for the post-tensioned systems, which exhibited very stable energy dissipation and re-centring properties. Ou et al proposed new precast segmental concrete bridge columns with high performance (HP) steel reinforcing bars, The cyclic behavior of proposed model and conventional precast segmental concrete bridge columns with steel reinforcing bars as energy dissipation (ED) bars were investigated. The HP steel reinforcing bars are characterized by higher strength, greater ductility, and superior corrosion resistance compared with the conventional steel reinforcing bars. Test results showed that the column with the HP bars had greater drift capacity, higher lateral strength, and larger energy dissipation than that with fully bonded conventional ED bars. ElGawady et al investigated the cyclic behavior of four self-centering bridge bents having different construction details including external energy dissipaters and neoprene isolation. The columns of these bents consisted of precast post-tensioned concrete filled fiber tubes (PPT CFFT). The PPT-CFFT bents without external energy dissipaters displayed a lateral drift of approximately 9.2% without experiencing significant damage or residual displacement.

This study presents the use of rocking columns in multi-column bridge bents along with shape memory alloy bars to enhance behavior of poorly detailed joints in conventional bridges.

2. SHAPE MEMORY ALLOY

Shape Memory Alloys (SMA's) are class of alloys that display unique characteristics such as the shape memory effect and the super elasticity behavior. Shape memory effect is the ability of the deformed alloy to recover its original shape upon heating, whereas the super elasticity behavior is the ability of the SMAs to recover its undeformed shape upon unloading. SMAs are found in two phases, austenite (high temperature phase) and martensite (low temperature phase). Transformation from one phase to the other is attained by applying either thermal loading or mechanical loading. Fig. 2.1 shows a schematic of the mechanical (stress–strain) behavior of superelastic (auste- nitic) SMAs. As illustrated from Fig. 2.1, the superelasticity phenomenon provides SMAs with high recentering capability, which is demonstrated by the large elastic strain range (typically 6–8%). Superelastic SMAs are also characterized by a nonlinear stress–strain hysteresis which provides constraints on the forces transmitted to the connected members. However, at large deformations (larger than 6% strain) the material experiences a sharp increase in stiffness. The increase in stiffness and strength plays an important role in preventing bridge unseating according to DesRoches and Delemont's study.

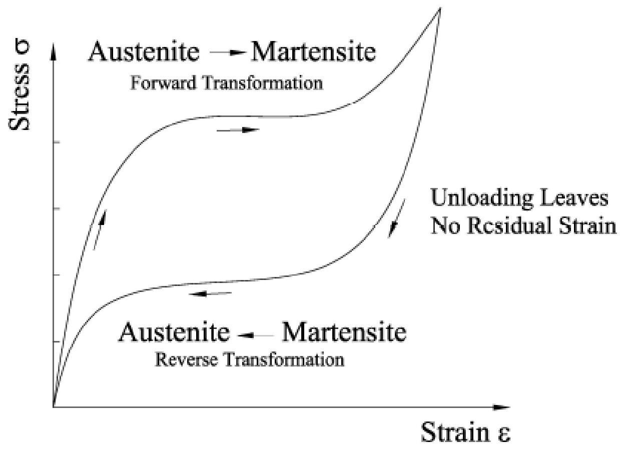


Figure 2.1. Stress-strain relationship for superelastic SMA

2.1. Application of SMAs in Bridge Piers

Saiidi and Wang in 2006 presented the application of SMA bars instead of steel bars in a plastic hinge zone on reinforced concrete bridge to reduce permanent displacements and damage. later in 2009, the feasibility of superelasticity in increasing ductility and decreasing residual displacement of concrete bridge column was investigated by Saiidi et al. Roh and Reinhorn in 2010 presented use of unbounded SMA bars with post tension tendon in precast segmental bridges to ensure self centering effect.

3. CONVENTIONAL BRIDGE BENT

Common design practice of bridge in late 1980 to early 1990 in Iran did not require the control of the relative flexural capacity of column-cap, shear force transfer from the joint and designing capacity protected members. Contrary to the current seismic code requirements, they were designed with strong column and weak cap-beam where desirable plastic hinge and proper hierarchy would not form in the bents. Members were not designed for the shear demand based on flexural capacity. Hence, occurrence of an undesirable failure mechanism in these bridges during earthquake is expected.

Bahrani et al investigated a 30% scaled conventional bridge bent with deficiencies confinement and the shear reinforcement of joints, according to flexural point of column in bridge bent that was in middle of column, the columns were constructed in half of scaled length on pin constraint, the specification of specimen as follows: Longitudinal reinforcement ratio was 1.3%, cap-beam flexural top and bottom rebar ratio was 0.3% and 0.2%, respectively and the axial force on the column was 6% of the section capacity. The actual yield stress of Longitudinal and Stirrups bars respectively was 521.5 and 352.3 MPa. Standard cylindrical compression strength of the 28-day old concrete was 24 and 31*MPa* for the cap beam and the columns of the specimen. The dimensions of specimen and test setup are described respectively in Fig. 3.1 and Fig. 3.2.

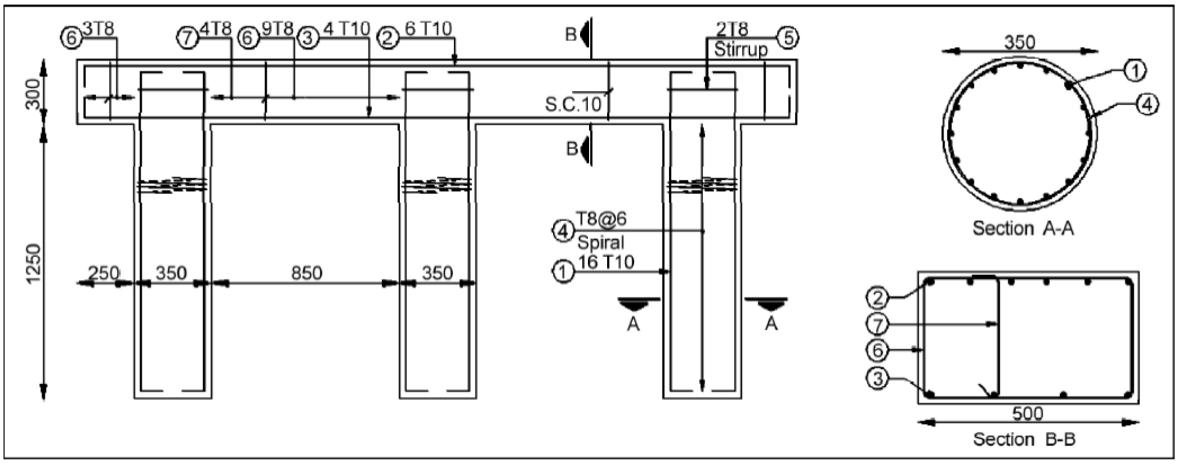


Figure 3.1. Dimensions and specifications of specimen

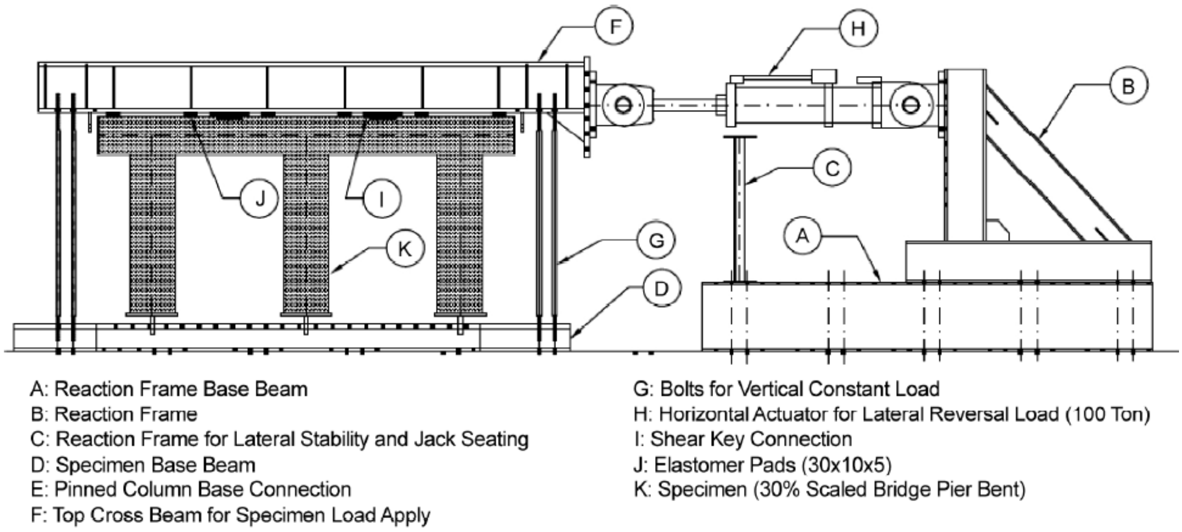


Figure 3.2. Test Setup and main components

Column bars were anchored in the joint by 90 degrees inward standard hook but there was not sufficient transverse joint reinforcement around the longitudinal column bars. Result indicated that the major degradation and loss of lateral strength were occurred because of longitudinal bars slippage and a large amount of in-cycle degradation was observed after longitudinal bars slippage. The conventional bridge bent was modeled analytically and calibrated with experimental result to compare with proposed bridge bent.

3.1. Modeling of Conventional Bridge Bent

The 2-D finite element model of the reference bridge as well as the test setup is developed and analyzed using the open-source finite element program, OpenSees. The plastic hinge approach is utilized for analytical modeling. The columns and cap beam are modeled with an elastic material in which the effect of cracking is considered in elasticity modulus as per their reinforcement. The effect of loading beam height is modeled by rigid elements. Also the columns and cap beam are simulated with their center lines. Based on the test results, slippage of the column's longitudinal bar is the main contributing factor for the pinched hysteresis behavior. In order to model this behavior, pinching4 material in OpenSees is used at the connection between column and cap beam and with the direction of moment rotation. The amounts of pinching4's moment and rotations are respectively obtained according to the moment capacity of column and behavior of weak joint as explained in Priestley's study in 1993. Other parameters, related to cyclic degradation of strength and stiffness, are desirably assumed to approach to the experimental behavior. In pinchin4 material, the cyclic degradation of strength and stiffness occurs in three ways which are unique advantages: first, unloading stiffness degradation. Second, reloading stiffness degradation. Third, strength degradation. According to the mentioned advantages, this material is chosen to reach actual behavior of specimen. Since displacements in an elastic location should not be aggregated with each other, initial slope of pinchin4 material is considered 10 times greater than the slope of effective elastic columns. In Fig. 3.1.1, the result of analytical model under the cyclic loading properly corresponds to the experimental result.

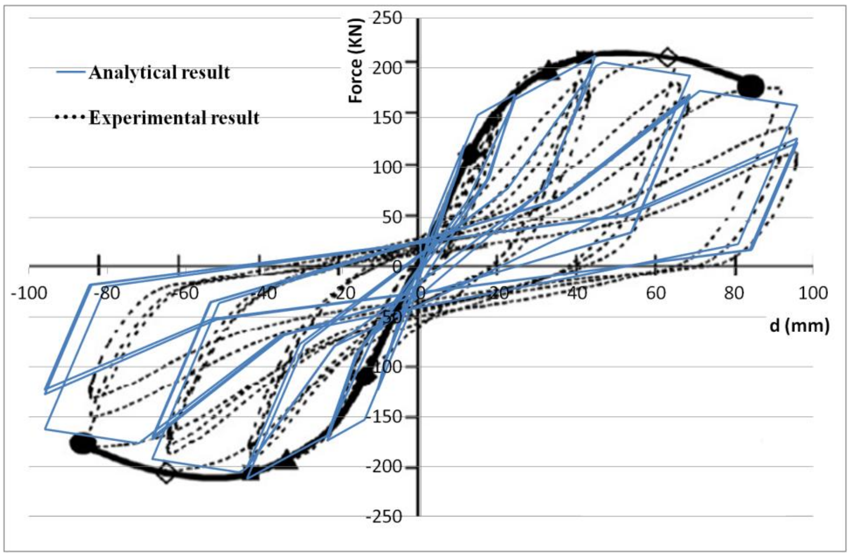


Figure 3.1.1. Experimental and analytical results of cyclic test of conventional bridge bent

4. CONTROLLED ROCKING BRIDGE BENT

4.1. Modeling of Rocking Column

In order to validate the proposed model of rocking column, a 1:3 scale reinforced concrete specimens with dimensions of $178mm \times 178mm \times 1219mm(7\ in \times 7\ in \times 48\ in)$ of depth, width, and height, respectively, from Roh and Reinhorn's study is selected. The detail of column is shown in Fig. 4.1.1 Other specification of specimen is as follows: compressive strength of the unconfined concrete is 36.12 Mpa, the axial force on the column is 5% of the section capacity and yielding stress of reinforcement is 257.8 MPa (40 ksi).

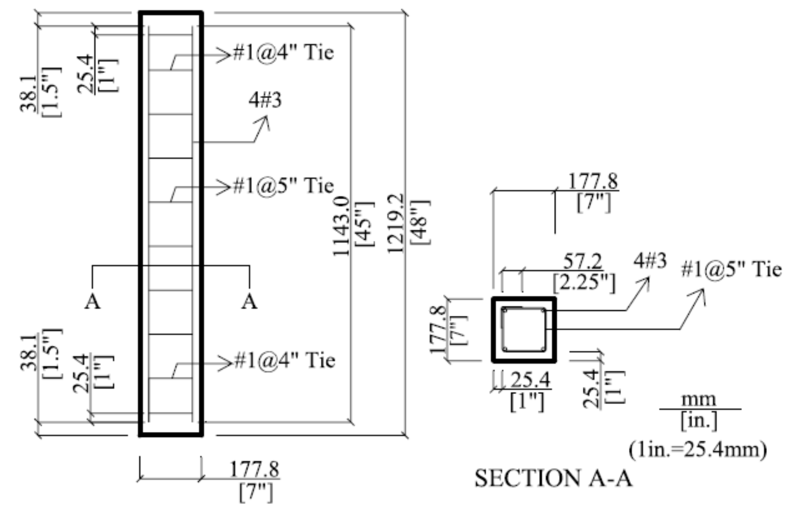


Figure 4.1.1. Geometry, detail of reinforcement

The 2-D finite element model of the reference column as well as test setup is developed and analyzed using OpenSees. In their test setup precast columns are tested for evaluating of rocking in top and end of a column. In order to model rocking interface, zero length element section with concrte01 material is used in OpenSees. Also, another multi-spring model with concrete01 material is used to model the rocking interface. Both of the modeling approaches indicate similar result in the rocking column. Since changing of neutral axis and location of element are considered in the multi-spring modeling this method is suggested for rocking wall modeling. The result of the analytical model and the experimental test is shown in Fig. 4.1.2. The initial slop and post capping slop of analytical model are similar to the experimental result of Roh and Reinhorn's study. Energy absorption of experimental result occurs in crushing of the column, but in the analytical model this effect does not occur as well as the experimental result. This point is not significant, because energy absorption in rocking column is much less than rocking column with supplemental energy devices. In this case, energy absorption occurs in a high drift ratio under a special test setup; however, in a practical loading condition at bridges, that much energy absorption will no longer occur.

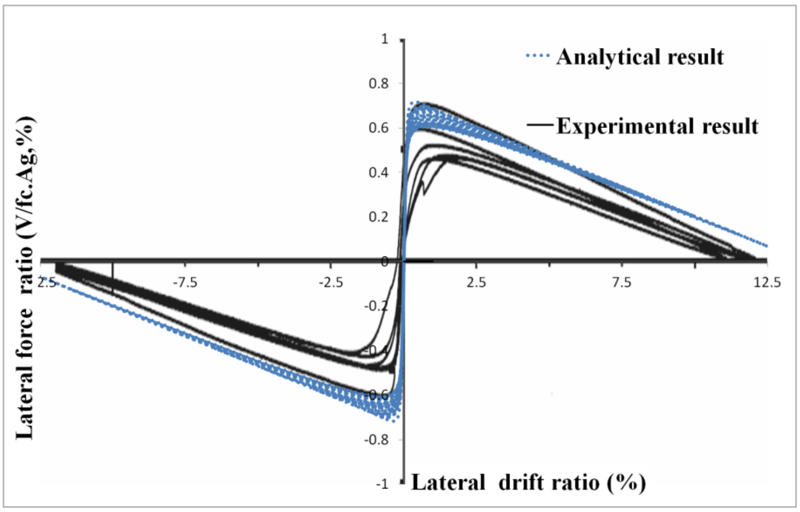


Figure 4.1.2. Experimental and analytical results of cyclic test of the rocking column

4.2. Proposed Bridge bent

Multi-column bridge bents using controlled rocking approach are proposed to compare with conventional bridge bent. For better comparison, dimensions and other mechanical properties of the proposed model material is considered as same as the conventional bridge. Most of anchored longitudinal bars in the joints are cut to reach rocking behavior, however, some of anchored longitudinal remain to transfer shear force. For each column, two external SMA bars are used to enhance self-centering and energy absorption in the controlled rocking zone. Scheme of the proposed model is indicated in Fig. 4.2.1. Due to limited elastic strain of SMA material and displacement demands on SMA bars, adequate length of SMA bars should be employed, but the length of SMA bars should not be longer than the length causes to malfunction of energy dissipation in rocking motion. This maximum length of SMA bars is also assumed the plastic length of the conventional columns. In order to reach minimum residual drift and less damage in a structure, other structural elements of bridge bents must be elastic. Thus, Diameters of SMA bars have to be limited until the yield of SMA bars happen earlier than other structural elements. Mechanical properties of shape memory alloy are quite sensitive to its chemical components. The yield strength of SMA bars is assumed to be 500 MPa with unloading yield strength of 140 Mpa. Five percent strain hardening is assumed up to the level of 6 percent strain and recoverable elongation was set to 8 percent. It is also assumed that the yielding occurs at 0.6% strain. In this study, diameters of SMA bars are chosen 5 values of 1.5, 1.6, 1.7, 2 and 2.5 cm with various length of 25, 30 and 35 cm.

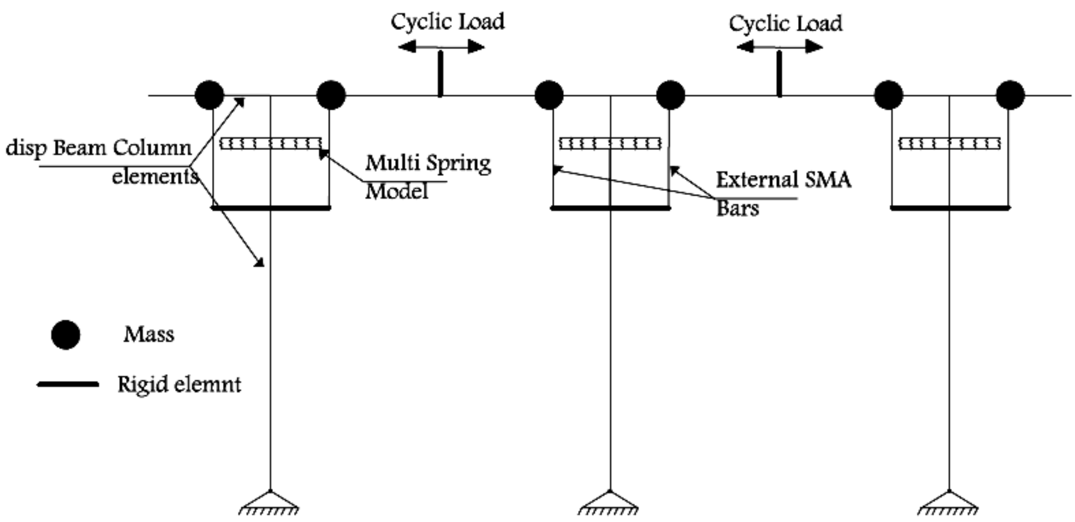


Figure 4.2.1. Scheme of analytical model

The cap beam is modeled using 10 dispbeamcolumn element in OpenSees which is separated into both steel and concrete fibers. Each fiber had a uniaxial stress-strain relationship representing confined and unconfined concrete or longitudinal reinforcing steel. Each column is modeled using 5 dispbeamcolumn which is also separated into both steel and concrete fibers. Rocking zone is situated in the connection between the column and the cap beam. Rocking column is modeled as well as what is described in the part 4.1. SMA bars are modeled by a one dimensional tension only SMA material model which is developed and implemented in the OpenSees material library.

5. ANALYSIS RESULTS

Results clarifies that energy absorption in the proposed bridge bent is less than the conventional bridge bent under static cyclic loading, however, the other structural elements such as columns and cap beam remain elastic in the new bridge bent. Although, increasing the diameter of SMA bars results in more energy absorption, it leads to implying the non-linear behavior of the columns. On the other hand, increase in the length of SMA bars causes to increase of the ductility capacity. In Fig. 5.1., cyclic behavior of bridge bent using SMA bars with diameter of 2 Cm and length of 35 Cm is shown in which self-centering behavior is obviously observed.

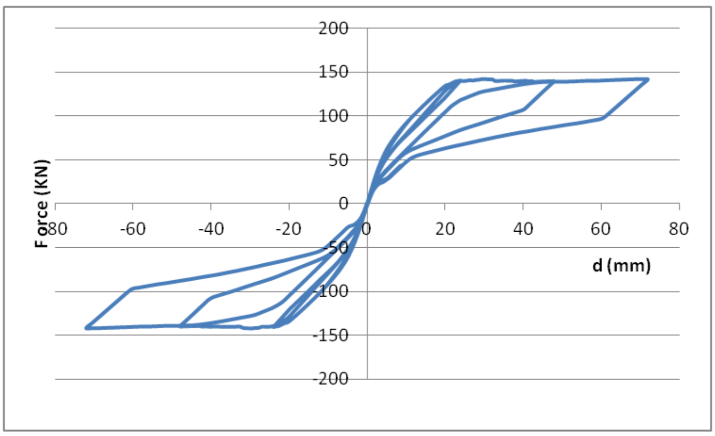
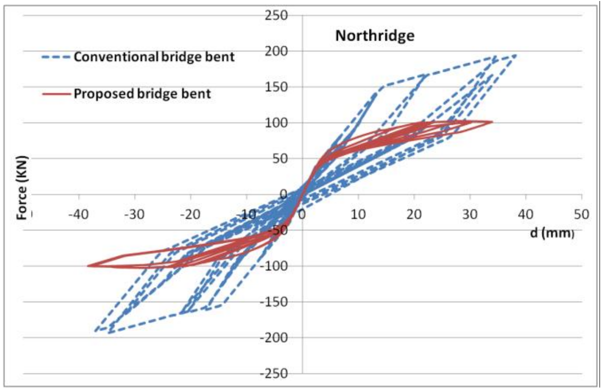


Figure 5.1. Cyclic behavior of bridge bent using SMA bars with diameter of 2 Cm and length of 35 Cm

In order to verify the actual behavior of the proposed bridge bent, bridge bent using SMA bars with diameter of 1.5 Cm and length of 35 Cm is compared with the conventional bridge bent. To that end, a nonlinear dynamic analysis is conducted using three Far-Field ground motion records selected from the PEER NGA database. Records are selected to have magnitude, PGA, and PGV greater than 6.5, 0.2g, and 15 cm/s, respectively. Chosen records contain Northridge, Loma Prietaand and San Fernando earthquakes. As s consequence of three Far-Field ground motion records, the base shear in the proposed bridge bent is considerably less than the conventional one. Proposed bridge bent deflects more than the conventional one just in LomaPrieta record. Hysteresis behavior of the proposed bridge bent and the conventional one is demonstrated in Fig. 5.2-4.



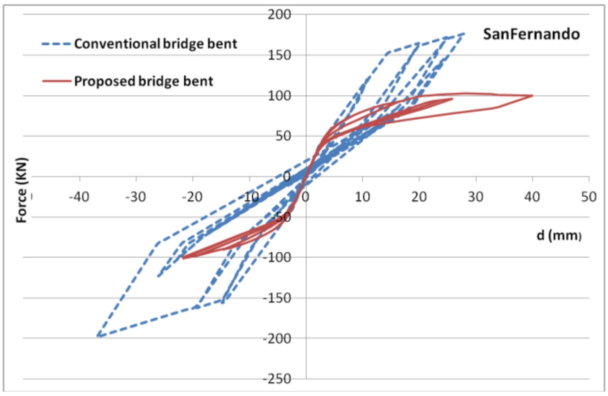


Figure 5.2. Hysteresis behavior in Northridge record **Figure 5.3.** Hysteresis behavior in SanFernando record

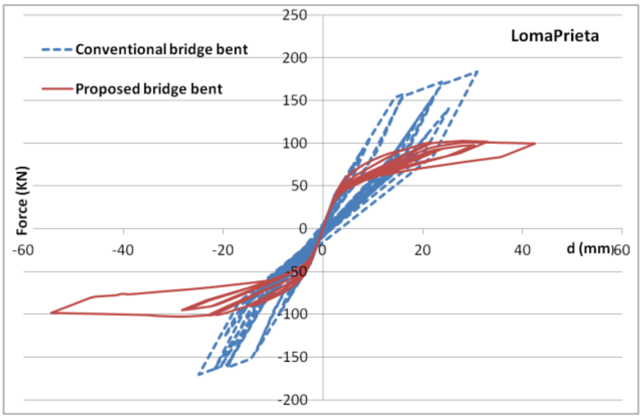


Figure 5.4. Hysteresis behavior in LomaPrieta record

6. CONCLUSION

Large lateral displacement capacity of the proposed bridge bents is the major advantage. Also, the lack of structural damage associated with large displacements, their ability to return to the previous position upon unloading, decreasing base shear force that leads to constructing weak foundation are the most crucial benefits. SMAs are a exclusive class of materials that can experience large deformations, while going back to their un-deformed shape through the removal of stress (superelastic effect). It was also found that the increase in the length of SMA bars would improve the ductility capacity until reaching the length causes to malfunction of energy dissipation in rocking motion.

REFERENCES

Bahrani, M.K. ,Vasseghi, A., Esmaeily, A. and Soltani, M.(2010). Experimental Study on Seismic Behavior of Conventional Concrete Bridge Bents. *JSEE* **Vol. 12**, No. 3

DesRoches,R. and Delemont,M. (2002) Seismic retrofit of simply supported bridges using shape memory alloy.

Engineering Structures **vol. 24**, **pp**. *325-332*.
DesRoches,R., McCormick, J. and Delemont, M. (2004). Cyclic properties of superelastic shape memory alloy wires and bars. *J Struct Eng* **130:1**,38_46.
Elgawady, MA. and Shalan, A. (2010) Seismic behavior of self-centering precast segmental bridge bents. *J Bridge Eng ASCE* **123:3**,435-4.
Mander J.B., Chen, C.T.(1997).Seismic Resistance of Bridge Piers Based on Damage Avoidanc Design *Technical Report NCEER-97-0014*(National Centre for Earthquake Engineering Research). State University of New York, Buffalo.
Marriott, D., Pampanin, S. and Palermo, A. (2009). Quasi-static and pseudo-dynamic testing of unbonded post-tensioned rocking bridge piers with external replaceable dissipaters. *Earthquake Engng Struct. Dyn* **38:3**,31–354.
Mazzoni, S. and Moehle, J.P. (2001). Seismic Response of Beam Column Joints in Double- Deck Reinforced Concrete Bridge Frames. *ACI Structural Journal* **98**:**3**, 259-269.
Mazzoni, S., McKenna, F., Scott M., Fenves, G. and et al. (2007). OpenSees Command Language Manual, College of Engineering, University of California, Berkeley.
Ou, Y.CH., Tsai, M.S., Chang, K.CH. and Lee, G.C. (2010). Cyclic behavior of precast segmental concrete bridge columns with high performance or conventional steel reinforcing bars as energy dissipation bars. *Earthquake Engng Struct. Dyn.* **39**:**11,**81–1198.
Pauley, T. and Priestley, M.J.N. (1992). Seismic Design of Reinforced Concrete and Masonary Buildings. *John Wiley & Sons*, Inc., New York.
Priestley, M.J.N. (1993). Assessment and Design of Joints for Single-Level Bridges with Circular Columns. UCSD Structural Systems Research Project **Report No. SSRP** 93/02.
Priestley, M.J.N. and Tao, JR. (1993). Seismic response of precast prestressed concrete frames with partially debonded tendons. *PCI Journal* **38:1**: 58-66.
Roh, H. and Reinhon, A.M. (2010). Hysteretic behavior of precast segmental bridge piers with superelastic shape memory alloy bars. *Engineering Structures* **32**,3394_3403.
Roh, H. and Reinhon, A.M. (2010). Modeling and seismic response of structures with concrete rocking columns and viscous dampers. *Engineering Structures* **32** ,2096_2107.
Saiidi, S., O'Brien,M. and Sadrossadat-Zade M. (2009). Cyclic Response of Concrete Bridge Columns Using Superelastic Nitinol and Bendable Concrete. *ACI Structural Journal* **Vol. 106,** No. 1, pp *69-77*.
Saiidi, S. and Wang, H. (2006). Exploratory Study of Seismic Response of Concrete Columns with Shape Memory Alloys Reinforcement. *ACI Structural Journal* **vol. 3,** pp 436-443.
Song, G., Ma, N. and Li, HN.(2006). Applications of shape memory alloys in civil structures. *Eng Struct* **28:9**,1266_74.
Stanton, J.F. and Nakaki, S.D. (2002). Design Guidelines for Precast Concrete Structural Systems.*PRESSS Report* No. 01/03-09, (Available from PCI).