Seismic Performance of Bridge Piers Reinforced with Shape Memory Alloys in Plastic Hinge Region

Kanan Thakkar¹ and Anant Parghi²
¹Research Scholar, Department of Applied Mechanics, S. V. National Institute of Technology, Surat – 395 007, Gujarat, India
²Assistant Professor, Department of Applied Mechanics, S. V. National Institute of Technology, Surat – 395 007, Gujarat, India
Email: kananrthakkar@gmail.com, anantparghi@gmail.com

Abstract. The recent earthquake reconnaissance reports revealed that a large residual displacement had led to the devastation of bridge piers due to serviceability concerns. Shape Memory Alloys (SMA) is the distinctive category of smart materials, which can sustain enormous deformations and reappear to a parent shape after removal of loading or by removal of heat. Replacing the typical steel reinforcement with SMA reinforcement in the potential plastic hinge regions of bridge piers could reduce the residual displacement of a pier. This study is focused on the numerical investigation of circular bridge piers with SMA-based reinforcement in the plastic hinge regions to mitigate the residual displacement. The numerical model of a bridge pier is validated using the experimental results of SMA-reinforced bridge pier. Dynamic time history analyses are performed to compare the performance of SMA-reinforced bridge piers with steel-reinforced bridge piers under the effect of various earthquake ground motions. The results are represented in terms of displacement, base shear, and ductility. Moreover, the influence of several parameters on the performance of bridge piers is investigated, i.e., aspect ratio, axial load ratio, and compositions of SMA. The numerical results have indicated the effectiveness of bridge piers reinforced with SMA by reducing the residual displacement after major earthquake events.

1. Introduction

1.1. General
Bridges are the most important structures for the infrastructure network of a country. The damages of bridges could interrupt the traffic flow and cause substantial economic loss. The reinforced concrete (RC) bridges situated in the regions of high seismicity and designed according to the current seismic design guidelines are liable to significant damages during large earthquakes, which showed the large residual displacements [1]. The past earthquake investigation report showed that the bridge structures with high residual displacements were unserviceable for future use [2]. Subsequently, post-disaster respite and release operations were rigorously affected. Generally, it is presumed that the utmost seismic demand in the bridge piers focuses in a small zone, which has a supreme inelastic curvature and defined as the plastic hinge length [3]. To improve the performance of structures, numerous research has been carried out in the domain of smart materials, such as shape memory alloys (SMA).
SMA is a distinctive category of smart materials that can sustain enormous deformations and reappear to a parent shape after removal of loading (super-elasticity) or by removal of heat (shape memory effect) [4]. The re-centering phenomenon of SMA-RC structure is a unique and interesting feature for structural applications [5]. There are two crystal phases of SMA: high and low-temperature phase, named as austenite phase and martensite phase, respectively. SMA gets converted from one phase to another phase by applying/removing stresses/temperature. SMA can deform up to six-to-eight percent strain limits [6]. There are various compositions of SMA. Among them, NiTi-SMA is proven to be the most suitable for applications in structural engineering.

1.2. Scope of previous research

The applications of super-elastic SMA are significantly expanded, and researchers have conducted extensive investigations exploring different structural applications and developing innovative devices making use of the distinctive characteristics of this smart material [2, 7]. Numerous innovative structural systems are developed incorporating NiTi-based and Cu-based SMA with an aim to dissipate earthquake forces, damping control, structural retrofit, etc. [8]. SMA offers numerous structural applications, namely, reinforcement in reinforced concrete, connectors in steel and concrete structures, damping devices, base isolation devices, seismic retrofit, serving as an active or passive confinement technique in terms of pre-stressing and post-tensioning [7, 9, 10]. There are various shapes in which SMA could be integrated into these structural systems, i.e., single and stranded wires, ribbons, strips, tubing, and bars.

Over the last decade, several applications of SMA in bridges are investigated for enhancing the dynamic performance of structures. Since the last decades, numerous researchers studied the behavior of super-elastic SMA-reinforced structures replacing conventional steel in plastic hinge locations to mitigate the seismic energy demand after severe seismic events.

The above literature shows that RC structures are susceptible to go through substantial deface during strong earthquakes with higher residual/permanent deformation, SMA could be used as the most suitable reinforcements at the plastic hinge area of RC structure. Furthermore, there is a limited investigation of the parametric study as an alternate of steel reinforcement at the plastic hinge location with super-elastic SMA-based reinforcement on the dynamic performance of the bridge piers. Recently, there is no code/guidelines available in the existing literature for the use of super-elastic SMA as an alternative reinforcement with conventional steel.

2. Numerical Investigation of Bridge Piers

This research is focused on the seismic performance of bridge piers with super-elastic SMA reinforcement in the plastic hinge region under dynamic loads. SMA is an expensive material, and large-scale structural elements require a massive quantity of reinforcing materials. As the maximum damage of a bridge pier is concentrated in a plastic hinge region, SMA reinforcement is provided only in the plastic hinge region of a bridge pier. The behaviour of super-elastic SMA-reinforced piers under the effect of various time histories is investigated and compared with conventional steel-reinforced piers using finite element program [11]. This section discusses the parameters for geometrical design and finite element analysis of a bridge pier. Additionally, a parametric investigation has been performed for bridge piers with SMA reinforcement in plastic hinge region under the effect of various ground motions. The parametric study has been conducted by selecting three variable parameters based on the existing literature, i.e. axial load ratio, aspect ratio, and the composition of SMA material.

2.1. Geometry of the bridge piers

In this research, a circular bridge pier has been considered for the nonlinear analysis [2]. The bridge pier is presumed to be situated in India (Seismic Zone-V) and seismically designed following the Indian Standard (IS) Codes and Indian Road Congress (IRC) guidelines. The geometry of the pier is used in this study, as shown in Figure 1. The diameter and height of the pier are 1.524 m and 7.62 m, respectively. The axial load ratio is used as 5% of the axial capacity of the pier, and the longitudinal
reinforcement ratio (\(\rho_t\)) is used as 1%. Figure 1(a) illustrates the geometry of the pier in section A-A, and Figure 1(b) shows the vertical section of the pier with the longitudinal and lateral reinforcement details of bridge pier. It defines the steel rebar, SMA rebar, and their connection through a coupler, incorporated for this study.

![Figure 1. Geometry of SMA-reinforced bridge pier](image)

2.2. Finite element modeling

To study the dynamic performance of SMA-RC and steel-RC bridge piers, a finite element (FE) tool is adopted [11]. This FE tool has the capability to predict both geometric nonlinearity and inelastic material behaviour of the structures under seismic load. To model a pier, a displacement-based nonlinear beam-column element has been chosen. The fiber section is used to discretize pier into three parts: core fiber, cover fiber, and steel/SMA fiber. The piers are modeled incorporating a force-based inelastic system owing to its accuracy. As shown in Figure 2(a) and Figure 2(b), there are 250 fibers, and 5 integration sections from the section are considered for mesh refinement. It has been discretized into 11 FE frames (Figure 2 (a)). The pier length is divided into a total of 11 sections, among which 3 sections represent plastic hinge length, and the remaining sections represent steel rebar.

![Figure 2. (a) Idealized numerical model (b) fiber discretization of cross-section and FE modeling of bridge piers](image)
The link element has been introduced to connect two different types of nodes. The rotating spring was provided at the bottom of a bridge pier. Figure 2(b) describes the FE model of a bridge pier. As shown in Figure 2(b), dimension-less rotational spring is assigned at the lowermost part of a pier, which represents a mechanical coupler used to connect steel and SMA rebar. Axial load is applied on the top of a pier, and the footing is assumed to be fixed support.

2.3. Material constitutive models
While modeling the cross-section of a pier, concrete, and longitudinal steel/SMA reinforcement of each fiber element, their own constitutive stress-strain relationships are incorporated. In this study, three different material constitutive models are considered for the modeling of bridge piers: steel reinforcement, SMA reinforcement, and concrete.

Menegotto and Pinto [12] steel constitutive model is adopted to assign the properties of steel reinforcement in FE tool. NiTi (Nitinol) SMA having two metals (nickel and titanium), is chosen based on its performance. To represent NiTi reinforcement in the finite element model, Fugazza [12] model is implemented for this study. To predict the stress-strain behavior of confined concrete in this study, the stress-strain model by Madas [13] and the constitutive behavior by Mander et al. [14] are adopted. Table 1 depicts the material properties of steel-reinforced and SMA-reinforced bridge piers used for a numerical investigation.

| Material | Property                           | Value  |
|----------|------------------------------------|--------|
| Concrete | Compressive strength (MPa)         | 35     |
|          | Corresponding strain               | 0.0029 |
|          | Tensile strength (MPa)             | 3.5    |
|          | Elastic Modulus (GPa)              | 23.1   |
| Steel    | Elastic Modulus (GPa)              | 200    |
|          | Ultimate stress (MPa)              | 692    |
|          | Yield stress (MPa)                 | 475    |
|          | Ultimate strain                    | 0.14   |
|          | Plateau strain                     | 0.016  |
| SMA      | Yield strength- \( f_y \) (MPa)    | 401    |
|          | Modulus of elasticity-\( E \) (GPa)| 62.5   |
|          | Super-elastic plateau strain length- \( \varepsilon_s \) (%) | 6      |
|          | A to M starting stress- \( f_{A1} \) (MPa) | 401.0  |
|          | A to M finishing stress- \( f_{A2} \) (MPa) | 510    |
|          | M to A starting stress- \( f_{M1} \) (MPa) | 370    |
|          | M to A finishing stress- \( f_{M2} \) (MPa) | 130    |

Where \( A \) is the austenite phase, and \( M \) is the martensite phase.

2.4. Model validation
The precision of a proposed bridge pier model is validated through the experimental results by various researchers [16,17,18]. The proposed numerical model using a non-linear FE program [11] is compared with the experimental outcomes by Zadeh et al. [17] for the exactness of modeling techniques. They had conducted an experimental program on one-fifth scaled circular columns utilizing SMA in the plastic hinge region. The RNC (SMA reinforcement in the plastic hinge region) model is validated in this study. The structural displacement of RNC column in the experimental model and numerical model are 114 mm and 122 mm, respectively. The proposed numerical model is validated with the experimental results with an error of 6.56%. Thus, the local responses of SMA-reinforced bridge piers under the effect of dynamic loads can be assessed reasonably with an implemented nonlinear FE modeling technique.
3. Parametric investigation of the bridge piers

In the previous section, a numerical FE model is generated for steel and SMA-reinforced circular concrete bridge pier using a fibre modeling approach [2]. Nine different pier models with three variable parameters and one conventional pier model are generated. These selected variable parameters are aspect ratio (3, 5, and 7), axial load ratio (5, 10, and 20 %), and compositions of SMA (NiTi, Fe, and Cu), as shown in Table 2. A total of ten numerical models are analyzed for the parametric investigation. The models are named as P-S, P-AR-3, P-AR-5, P-AR-7, P-AL-05, P-AL-10, P-AL-20, P-NiTi, P-Fe, and P-Cu. The details of these models are described in Table 3. The plastic length of the piers is estimated using Paule and Pristley [19] equation (1),

\[ L_p = 0.08L + 0.022f_yd_b \]  

Where, \( L_p \) is the plastic hinge length, \( L \) is the total height of a pier, \( f_y \) is the yield strength of rebar, and \( d_b \) is the diameter of rebar. A bridge pier’s plastic hinge length depends on several parameters, i.e., axial load, aspect ratio, properties of SMA, reinforcements (longitudinal and transverse), and strength of confined concrete [3].

| Parameters            | Values          |
|-----------------------|-----------------|
| Diameter (D) (m)      | 1.524           |
| Height (L) (m)        | 7.62            |
| Aspect ratio (L/D)    | 3, 5, 7         |
| Axial load ratio P (%)| 5, 10, 20       |
| Longitudinal reinforcement ratio (\( \rho_l \)) (%) | 1.55 |

### Table 2. Parameters of Steel-RC and SMA-RC bridge piers

| Pier-ID | P-AR-3 | P-AR-5 | P-AR-7 | P-AL-05 | P-AL-10 | P-AL-20 | P-NiTi | P-Fe | P-Cu |
|---------|--------|--------|--------|---------|---------|---------|--------|------|------|
| L/D     | 3      | 5      | 7      | 5       | 5       | 5       | 5      | 5    | 5    |
| P/\(\rho_l\timesA_f\) | 0.05   | 0.05   | 0.05   | 0.05    | 0.10    | 0.20    | 0.05   | 0.05 | 0.05 |
| P (kN)  | 3190.63| 3190.63| 3190.63| 3190.63 | 6381.27 | 12762.5 | 3190.63| 3190.63| 3190.63|
| L (mm)  | 4572   | 7620   | 10668  | 7620    | 7620    | 7620    | 7620   | 7620 | 7620 |
| \(L_p\) (mm) | 741.96 | 985.8  | 1229.64| 985.8   | 985.8   | 985.8   | 985.8  | 985.8| 985.8|
| D (mm)  | 1524   | 1524   | 1524   | 1524    | 1524    | 1524    | 1524   | 1524 | 1524 |
| \(f_y\) (MPa) | 475    | 475    | 475    | 475     | 475     | 475     | 475    | 475 | 475 |
| \(f_y\) (MPa) | 401    | 401    | 401    | 401     | 401     | 401     | 401    | 401 | 401 |
| \(f_y\) (MPa) | 510    | 510    | 510    | 510     | 510     | 510     | 510    | 510 | 510 |
| \(f_y\) (MPa) | 370    | 370    | 370    | 370     | 370     | 370     | 370    | 370 | 370 |
| \(f_y\) (MPa) | 130    | 130    | 130    | 130     | 130     | 130     | 130    | 130 | 130 |
| E (MPa) | 62500  | 62500  | 62500  | 62500   | 62500   | 62500   | 62500  | 62500| 62500|
| \(\varepsilon\) (%) | 6      | 6      | 6      | 6       | 6       | 6       | 6      | 6    | 13.5 |
| \(f_y/E\) (Strain) | 0.0065 | 0.0065 | 0.0065 | 0.0065  | 0.0065  | 0.0065  | 0.0065 | 0.0065| 0.00159 | 0.0075 |

### Table 3. Details of parameters used for Steel-RC and SMA-RC bridge piers

### 3.1. Time history analysis

A time-history analysis is a time-dependent analysis to predict the responses of a structure under the effect of dynamic loads. Dynamic time history analysis is performed on bridge pier models to predict the behavior of bridge piers under the effect of earthquake ground motions.

### Table 4. Indian Major Earthquakes

| Earthquake       | Location            | Occurrence         | Magnitude | PGA (g) | Time (sec) | Seismic Zone |
|------------------|---------------------|--------------------|-----------|---------|------------|--------------|
| Bhuj             | Kutch, Gujarat, India | January 26th, 2001 | 7.7       | 0.88    | 133.53     | V            |
| Chamoli          | Chamoli, Uttar Pradesh, India | March 29th, 1999  | 6.8       | 0.55    | 87.05      | V            |
| Uttarkashi       | Garhwal, Himalayas, Northern India | October 20th, 1991| 6.8       | 0.14    | 21.34      | V            |
The actual earthquake time-history accelerograms are chosen for the dynamic analysis of bridge piers in this study. Three different accelerograms are selected, such as they represent the actual responses of a structure for a particular geometric condition. Table 4 shows the details about Bhuj, Chamoli, and Uttarkashi earthquakes, respectively.

4. Results and Discussion
Figure 3 demonstrates the comparison of maximum top displacement of the piers with axial load ratios (5, 10, and 20 %) under the effect of Bhuj, Chamoli and Uttarkashi Earthquakes, respectively. As seen from these figures, the top displacement of piers upsurges with the raise in axial load ratio. The displacement was found to be a minimum for a 5% axial load ratio and maximum for a 20% axial load ratio. Further, base shear rises with the increment in axial load ratio.

Figure 4 describes the comparison of top displacement and base shear for the piers with aspect ratios (3, 5 and 7) under the effect of Bhuj, Chamoli, and Uttarkashi Earthquakes, respectively. It is evident from the figure that the top displacement of pier is minimum for aspect ratio 3 and maximum for aspect ratio 5. It can be stated that the lateral displacement and base shear increases with the surge in aspect ratio up to some extent. A similar observation has been made by Billah and Alam [3] also.

Figure 5 reveals the comparison of maximum top displacement and base shear of the piers with various compositions of SMA under the effect of Bhuj, Chamoli, and Uttarkashi Earthquakes, respectively.
respectively. It is evident from the figure that the displacement and base shear are maximum for the piers with Fe-based SMA due to its higher super-elasticity. The top displacement and base shear of Cu-based piers are found to be less than Fe-based and NiTi-based piers, due to less super-elasticity of Cu-based SMA. These phenomena could be attributed that higher displacement is because of the super-elastic shape memory effect of SMA reinforcement. The higher yield strength of SMA leads to greater ductility of a pier. A similar study has also been done by Andrawes and Shin [20], and Dong et al. [21]. They have researched the improvement of ductility capacity of bridge piers. They determined that utilizing SMA in bridge piers upsurges the ductility, and reduces the residual displacement of a pier under the effect of earthquake ground motions.

Figure 6 shows the ductility of piers with three variable parameters. As shown in the figure, ductility rises with the increase in axial load ratio and reduces with the increase in aspect ratio. Ductility was found to be maximum for a pier with Cu-based SMA and minimum for a pier with NiTi-based SMA. Ductility of a pier with Fe-based SMA was less than the ductility of a pier with Cu-based SMA, and more than the ductility of a pier with NiTi-based SMA.

5. Conclusions
The numerical works were focussed on the consequence of several factors on the performance of circular bridge piers. By analyzing circular bridge piers for three aspect ratios, three axial load ratios and three compositions of SMA under the effect of three different ground motions, the following results were obtained:

Piers spectacle more deformation and higher base shear for larger values of axial load ratio. The pier deformation was most significant for 20% axial load ratio. Thus, larger the axial load ratio, more significant the deformation and base shear.

The top deformation and base shear of piers are found to be minimum for aspect ratio of 3. They get increased with the increase of aspect ratio up to certain limits. Then, the top deformation and base shear values decreased for further increase in aspect ratio.

Piers with Fe-based SMAs deformed more than other piers, owing to higher values of base shear and superior super-elasticity of Fe-based SMAs. Piers with Cu-based SMAs deformed minimum with comparison to other piers in arrears of less super-elasticity and less capacity to attract base shear of Cu-based SMAs. Piers with NiTi-based SMAs deformed to optimum level due to its optimal super-elasticity and ideal capacity to withstand the base shear.

Ductility of a pier was found to be in direct proportion with the axial load ratio and inverse proportion with the aspect ratio. Moreover, ductility of piers with Cu-based SMAs was the highest, and ductility of piers with NiTi-based SMAs was the lowest.

There is considerable potential for the utilization of super-elastic SMA in civil infrastructures. However, the high cost of the SMA is the main obscuring issue. Because of the large size of structural elements, the related forces are also large, which needs a tremendous quantity of reinforcing materials. Hence, it is a big issue for the application of expensive super-elastic SMA in the civil infrastructures. The cost of NiTi based alloys depends on the processing of the high-strength NiTi composites in specific shapes and forms. Thus, the custom-based shape/size and matching could make them expensive two to three times, although there is a considerable drop in the cost of the NiTi over the last decade. Thus, in order to initiate the large-scale applications on SMA, the development of low-cost SMA is mandatory for the reduction of overall cost of a structure.

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References

[1] Shrestha B and Hao H 2014 23rd Australasian Conf on the Mechanics of Structures and Materials (ACMSM23) vol I (Byron Bay, NSW, Australia) p 375–80
[2] Billah M 2015 Ph. D. Thesis (University of British Columbia, Canada)
[3] Billah M and Alam M S 2016 Eng. Struct. 117 321–31
[4] Boroschek R L, Farias G, Moroni O and Sarrazin M 2007 J. Earthq. Eng. 11 326–42
[5] Abdulridha A, Palermo D, Foo S and Vecchio F J 2013 Eng. Struct. 49 893–904
[6] Desroches R and Smith B 2004 J. Earthq. Eng. 8 415–29
[7] Alam M S, Youssef M A and Nehdi M 2007 Can. J. Civ. Eng. 34 1075–86
[8] Constantinou M C, Soong T T and Dargush G F 1997 Passive energy dissipation systems for structural design and retrofit A report in Multidisciplinary Center for Earthquake Engineering Research (MCEER) (University of Buffalo, Buffalo) p 322
[9] Ozbulut O E, Hurlebaus S and DesRoches R 2011 J. Intell. Mater. Syst. Struct. 22 1531–49
[10] Menna C, Auricchio F and Asprone D 2015 Applications of shape memory alloys in structural engineering Shape Memory Alloy Engineering Elsevier pp 369–403
[11] SeismoSoft 2018 SeismoStruct- A computer program for static and dynamic nonlinear analysis of framed structures
[12] Menegotto M and Pinto P E 1973 Method of analysis for cyclically loaded R.C. plane frames including changes in geometry and non-elastic behavior of elements under combined normal force and bending A preliminary report in IABSE symposium on the resistance and ultimate deformability of structures acted on by well defined repeated loads (Lisbon) pp 15-22
[13] Madas P and Elnashai A S 1992 Earthq. Eng. Struct. Dyn. 21 409–31
[14] Mander J B 1988 J. Struct. Eng. 114 1804–26
[15] Billah M and Alam M S 2016 Eng. Struct. 117 321–31
[16] Saiidi M S and Wang H 2006 ACI Struct. J. 103 436–43
[17] Zadeh M S, Brien M O and Saiidi M S 2007 A study of concrete bridge columns using innovative materials subjected to cyclic loading A report by University of Nevada Reno and National Cooperative Highway Research Program (NCHRP) p 68
[18] Billah M and Alam M S 2012 Constr. Build. Mater. 28 730–42
[19] Paulay T and Priestley M J N 1992 Seismic design of reinforced concrete and masonry buildings John Wiley & Sons, Inc. New York, USA
[20] Andrawes B and Shin M 2008 Seismic retrofitting of bridge columns using shape memory alloys SPIE - The International Society for Optical Engineering 6928 69281K-1–9
[21] Dong J, Cai C S and Okeil A M 2011 J. Bridg. Eng. 16 305–15