Performance Evaluation of Bridge Piers Reinforced with Shape Memory Alloys in Plastic Hinge Region: Part 1 – Statistical Analysis

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Abstract. Bridge piers are the most perilous structural elements under the effect of enormous earthquake ground motions. The large residual deformation of a bridge pier turns out into the failure of an entire bridge structure. Thus, in the last decades, numerous novel materials were developed to reduce the residual displacement after the post-earthquake events. Shape Memory Alloys (SMA) is a special class of composite material, which can sustain enormous deformations and reappears to its parent state. The numerical results of SMA-reinforced bridge piers using non-linear finite element tools are compared with the experimental results. Two methods of statistical analysis are adopted for this study: One-Factor-at-a-Time (OFAT) Method, and Full-Factorial Design Method. Three variable material parameters, such as the compressive strength of concrete, the yield strength of steel, and the type of SMA composition are considered. Three levels for each factor are considered. The results of this research are presented in terms of drift values at various performance criteria, i.e., cracking, spalling, yielding, and crushing. Further, the regression analysis is performed to determine the relationship between material properties of SMA-reinforced bridge piers and the drift values at various performance criteria.

1. Introduction

1.1. General

Bridge piers are the most hazardous structural elements under the effect of enormous earthquake ground motions. The loss of infrastructure directly leads to the loss of the economy for any country. The maintenance and repair of bridges consume plenty of currency and time. Previous research indicates that the reinforced concrete (RC) bridges are susceptible to severe residual displacement because of tremendous earthquake vibrations [1]. This residual displacement causes permanent damage/collapse of RC bridges. The maximum damage of a bridge pier is concentrated in a small region, defined as a plastic hinge region [2]. Several innovative materials are invented in order to improve the performance of civil infrastructure, i.e., Shape Memory Alloys (SMA).

SMA is a novel composite material, exhibiting the self-cantering phenomena. SMA can sustain enormous deformations and reappear to a parent shape after removal of loading (super-elasticity) or by removal of heat (shape memory effect) [3]. This phenomenon of SMA is a unique feature for
applications in structural engineering. Austenite and martensite are two crystal phases of SMA. It gets converted from one phase to another phase by applying/removing stresses/temperature. SMA can be composed of several compositions, i.e. nickel, titanium, copper, iron, manganese, etc. Nickel-titanium based SMA is proven to be the most suitable for the applications in structural elements.

1.2. Previous research
Over the last decade, super-elastic SMA reinforcements received significant attention to the researchers, which is reflected through an increasing number of researches conducted on SMA-equipped structural members and elements. SMA offers numerous structural applications, namely, reinforcement in reinforced concrete elements, connectors in steel and concrete structures, damping devices, base isolation devices, etc. [4]. Several applications of SMA in bridges have been explored to enhance the performance of bridge structures under the effect of a seismic event. Since last decades, numerous researchers studied the behaviour of SMA-reinforced bridge piers to mitigate seismic energy demand after severe seismic events [5].

Furthermore, there is a limited investigation of the parametric study as an alternate of steel reinforcement in 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. Modeling of bridge piers
Following numerical analysis methods, material properties, geometrical data, material constitutive models, FE parameters, and modeling techniques are adopted for this study.

2.1. Static pushover analysis
Static pushover analysis is a nonlinear analysis methodology in which a monotonic lateral load is applied to the structure in an incremental manner. This monotonic loading is applied in such a way to determine the entire performance of a structure from the elastic phase to inelastic phase and failure. Figure 1(a) and illustrates the schematic diagram for typical pushover analysis of a pier. Figure 1(b) demonstrates the values of base shear, and displacement for flexural limit states, i.e., the values at which first cracking, spalling, yielding, crushing, buckling and fracture.

Figure 1. Schematic of a typical pushover analysis of pier (a) deformed and un-deformed shape, and (b) load vs. drift curve with limit states [6]

2.2. Flexural limit states
The performance points and their flexure limit states are essentials to be defined for the performance evaluation of SMA-reinforced bridge piers. Damages at several flexural limits are defined by the strain-based method [2]. The following flexural limits are taken into consideration to estimate the
performance SMA-reinforced circular bridge piers, e.g., cover concrete’s cracking and spalling, longitudinal SMA rebar’s yielding, and core concrete’s crushing.

2.3. The geometry of bridge piers
In this study, a 0.2 scaled circular bridge pier [7] has been considered for the nonlinear static pushover analysis. The geometry of the pier used in this study is, as shown in Figure 2.

![Figure 2. Reinforcement and geometrical details of SMA-reinforced bridge pier](image)

The diameter of a pier is 254 mm, and the height of a pier is 1270 mm. The height of a pier is calculated from the top of footing to the centreline of loading head, where the lateral load is applied. Axial load ratio is selected as 10% of the axial capacity of a pier, and a longitudinal reinforcement ratio (\(\rho_t\)) is used as 2%. The aspect ratio is selected as 5. Figure 2(a) illustrates the geometry of the pier, and section A-A in Figure 2(b) shows the vertical section of the pier with the longitudinal and lateral reinforcement details of the bridge pier. Plastic hinge length is calculated as 205.7 mm, according to Paule and Pristley [9] equation.

**Table 1. Materials Properties used for piers reinforced with steel and SMA**

| Material      | Property                         | Value  | Reference |
|---------------|----------------------------------|--------|-----------|
| Confined      | Elastic Modulus (GPa)            | 33.23  |           |
| Confined      | Compressive strength (MPa)       | 50     |           |
| Confined      | Tensile strength (MPa)           | 5      |           |
| Confined      | Corresponding strain             | 0.005  |           |
| Longitudinal  | Elastic Modulus (GPa)            | 200    |           |
| Longitudinal  | Yield stress (MPa)               | 415    |           |
| Longitudinal  | Fracture strain                  | 0.10   |           |
| Longitudinal  | Strain hardening parameter       | 0.05   |           |
| Super-elastic | Yield strength- \(f_s\) (MPa)     | 210, 401, 750 |        |
| Super-elastic | Modulus of elasticity-E (GPa)    | 28, 62.5, 46.9 |       |
| Super-elastic | Super-elastic plateau strain length- \(\varepsilon_s\) (%) | 9, 6, 13.5 |       |
| Super-elastic | A to M starting stress- \(f_s\) (MPa) | 210, 401, 750 |       |
| Super-elastic | A to M finishing stress- \(f_{P1}\) (MPa) | 275, 510, 1200 |       |
| Super-elastic | M to A starting stress- \(f_{T1}\) (MPa) | 200, 370, 300 |       |
| Super-elastic | M to A finishing stress- \(f_{T2}\) (MPa) | 150, 130, 200 |       |

Where A is the austenite phase, and M is the martensite phase.
2.4. Material constitutive models
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 [13] steel constitutive model is adopted to assign the properties of steel reinforcement in FE tool. To represent NiTi reinforcement in a finite element model, Fugazza [14] model is implemented for this study. To predict the stress-strain behavior of confined concrete in this study, the stress-strain model by Mander et al. [15] is adopted. Table 1 depicts the material properties of steel-reinforced and SMA-reinforced bridge piers used for a numerical investigation.

2.5. Finite element modeling
To study the performance of super-elastic SMA-RC and steel-reinforced bridge piers under the effect of a seismic event, a finite element (FE) program SeismoStruct [16] is adopted. The piers are modeled using the displacement-based inelastic system owing to its modeling requirements. There are 300 fibers considered across the section for the mesh refinement. The bar-slippage of super-elastic SMA rebar inside the coupler is neglected. The load is assigned as an axial load at the top of a pier.

2.6. Validation
The precision of the proposed model has been validated through experimental results proposed by Zadeh et al. [7] under the Highway Idea Project, University of Nevada, Reno (Figure 3). They conducted an experimental program on 0.2 scaled circular columns utilizing SMA in the plastic hinge zone under the effects of dynamic loads.

3. Design of experiment (DoE)
The design of experiments (DoE) is the orderly procedure to define a correlation between factors affecting a process and the output of that process. This research emphasis on the performance assessment of SMA-RC bridge piers under the effect of static pushover loads. Moreover, the effect of different materials properties, such as yield strength of steel, compressive strength of concrete, and composition of SMA along with their interactions are explored using full factorial design and Analysis of Variance (ANOVA). ANOVA is a statistical method used to test differences between two or more means. A significance level of 0.05 is selected. The results of SMA reinforced bridge piers are compared in terms of the performance criteria of limit state of design, e.g., cracking, yielding, spalling, and crushing.

3.1. Factors and Levels for DoE

| Sr. No. | Factors                        | Levels         |
|---------|--------------------------------|----------------|
| 1       | Compressive Strength of Concrete, \( f_c \) (MPa) | 35, 50, 65    |
| 2       | Yield Strength of Steel, \( f_y \) (MPa)         | 250, 415, 500 |
| 3       | Composition of SMA               | CuAlMn, NiTi, FeNCATB |

In this study, three factors, each having three levels have been defined. The no. of experiments to be performed in the one-factor-at-a-time (OFAT) method will be \( 3 \times 3 = 9 \), and full factorial design will be \( 3^3 = 3 \times 3 \times 3 = 27 \). The considered factors based on comprehensive literature and their levels are defined as shown in Table 2. Static pushover analysis is performed for 9 bridge pier models as per the OFAT method and 27 models as per the full factorial method of DoE (Table 2). These models are statistically analyzed using Minitab, and run orders are defined using Minitab.
4. Results and discussion

The non-linear static pushover analysis is performed for SMA-reinforced circular bridge piers as per the data described in previous sections. 9 models are prepared as per the OFAT method, and 27 models are prepared as per the full factorial method in the FE-software tool.

4.1. Capacity curves of SMA-RC bridge piers with OFAT method

By modelling 9 models (3 factors and each having 3 levels) under the OFAT method, the following results were derived:

Figure 4 shows the capacity curves of SMA-reinforced bridge piers for concrete compressive strengths, 35 MPa, 50 MPa, and 65 MPa. As seen from the figure, the capacity of a pier to attract base shear and displacement increases with the increment in concrete compressive strength until certain limits. Piers start to behave inversely after that limit, reducing the capacity with the further surge in concrete compressive strength.

Figure 5 demonstrates the capacity curves of SMA-reinforced bridge piers for steel yield strengths 250 MPa, 415 MPa, and 500 Mpa. It can be observed from the figure that the capacity of a pier to attract base shear and displacement is almost the same for the different yield strengths of steel. Thus, there is no significant consequence of yield strength of steel on the seismic performance of SMA-reinforced circular bridge pier.

**Figure 4.** Capacity curves of SMA-reinforced bridge piers for variable concrete compressive strengths ($f_c = 35$ MPa, $50$ MPa, and $65$ MPa)

**Figure 5.** Capacity curves of SMA-reinforced bridge piers for variable steel yield strengths ($f_y = 250$ MPa, $415$ MPa, and $500$ MPa)

**Figure 6.** Capacity curves of SMA-reinforced bridge piers for variable SMA composites (CuAlMn, NiTi, and FeNCATB)
Figure 6 outlines the capacity curves of SMA-reinforced bridge piers for three types of SMA composites (CuAlMn, NiTi, and FeNCATB). As observed from the figure, Pier with Cu-based SMA reinforcement in the plastic hinge region has the minimum capacity to attract base shear and displacement owing to the less yield strength of Cu-based SMA. The capacity of a pier with NiTi-based SMA is found to be more than piers with Cu-based SMA, as the yield strength of NiTi-based SMA is more than Cu-based SMA. Pier with Fe-based SMA demonstrates the maximum capacity to attract base shear and displacement, because of the higher value of yield strength of Fe-based SMA.

4.2. Drift of SMA-RC bridge piers at various flexural limit states with full factorial design

The 27 pier models using a full factorial method of statistical analysis are modeled in a non-linear FE software tool. The outputs of those models are analyzed with the condition of “larger is better” for the drift-based outputs. Further, the main effects plots’ and interaction plots for each output are determined. The slope in the main effects plot is directly proportional to the significance of a particular factor on the output. One-way ANOVA is performed for this study. The main effect plots and interaction plots for the distinct flexural limit states are presented in Figure 7 to Figure 16.

Figure 7. Main effects plot for cracking drift

Figure 8. Interactions plot for cracking drift

Figure 9. Main effects plot for spalling drift

Figure 10. Interactions plot for spalling drift
**Figure 11.** Main effects plot for yielding drift

**Figure 12.** Interactions plot for yielding drift

**Figure 13.** Main effects plot for crushing drift

**Figure 14.** Interactions plot for crushing drift

**Figure 15.** Main effects plot for maximum drift

**Figure 16.** Interactions plot for maximum drift
Figure 7, Figure 9, Figure 11, Figure 13 and Figure 15 express the significance of the three factors on cracking, spalling, yielding, crushing, and maximum drift, respectively. As seen from these figures, $f_c$ is the most significant factor for cracking, spalling, and crushing drift. Further, $f_{y-SMA}$ is the most significant factor for the yielding, and maximum drift. $f_y$ is the least significant factor for each of the outputs. The results of main effect plots confirm with the results of OFAT method. Figure 8, Figure 10, Figure 12, Figure 14 and Figure 16 demonstrate the interaction effects for each factor with other factors on cracking, spalling, yielding, crushing, and maximum drift, respectively. As seen from these figures, $f_c$ and $f_y$ exhibit higher interaction effects with each other for each of the outputs. $f_{y-SMA}$ exhibits negligible interaction effects with $f_c$ and $f_y$.

4.3. ANOVA
By performing ANOVA, $f_c$, and $f_{y-SMA}$ are the most significant factors for each of the outputs. Further, $f_y$ does not exhibit any significance on the outputs. These results confirm the results of OFAT method and full factorial design method. The R$^2$ values for all the outputs in general linear models are more than 97 percent.

5. Conclusions
By performing a parametric investigation on RC bridge piers reinforced with SMA in the plastic hinge region, the following conclusions are drawn:

5.1. OFAT method
The capacity of a pier to attract base shear and displacement increases with the increment in concrete compressive strength until certain limits. There is no significant effect of yield strength of steel on the seismic performance of SMA-reinforced circular bridge pier. Pier with Cu-based SMA reinforcement in the plastic hinge region has the minimum capacity to attract base shear and displacement owing to the less yield strength of Cu-based SMA. The capacity of a pier with NiTi-based SMA is found to be more than piers with Cu-based SMA. Pier with Fe-based SMA demonstrates the maximum capacity to attract base shear and displacement.

5.2. Full factorial design
The compressive strength of concrete and the composition of SMA are the most significant factors for cracking, spalling, yielding, crushing, and maximum drift. The yield strength of steel does not exhibit any significance on the drift values of SMA-RC bridge piers at various flexural limits.

6. Acknowledgements
The first author would like to acknowledge the financial support provided by Ministry of Human Resources Development (MHRD), Government of India, through the Ph.D. fellowship program. Further, the authors would like to acknowledge the online and offline library of SVNIT.

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