Performance Evaluation of Bridge Piers Reinforced with Shape Memory Alloys in Plastic Hinge Region: Part 2 – Optimization

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Abstract. Shape Memory Alloy (SMA) rebars are emerging as a potential solution to mitigate the permanent/residual deformation of bridge piers in recent decades. The maximum damage of a bridge pier being concentrated in the plastic hinge region and SMA being the expensive material to be utilized in the large-scale structural elements, the bridge piers are reinforced with SMA in the plastic hinge regions only. The bridge piers are modeled with a non-linear finite element tool. Three variable material parameters are adopted for this study, such as the compressive strength of concrete, the yield strength of steel, and the type of SMA composition. The bridge pier models considering One-Factor-at-a-Time (OFAT) Method, and Full Factorial Design Method in the previous study (Part 1) are considered. In this paper, the results of full factorial design of the previous research are optimized using optimization techniques in order to determine the best suitable combination of these three material properties. The performance of SMA-reinforced bridge piers is evaluated based on the drift values at various performance criteria, i.e., cracking, spalling, yielding, and crushing. The results are presented in terms of the rank-wise significance for each possible combination of the considered material properties of bridge piers.

1. Introduction

1.1. General

The nation’s development is directly proportional to its transportation network. Bridges are the backbone of a transportation network of any nation. Bridge pier is the most significant structural element in the entire bridge structure, as it transfers the lateral and horizontal loads to a foundation. It is observed from the previous research that a huge amount of displacement was detected in reinforced concrete (RC) bridges after the occurrence of massive earthquakes [1]. The maximum damage of a bridge pier is concentrated in a small region, defined as a plastic hinge region [2]. With an aim to improve the performance of structures, numerous innovative composite materials are invented. One such novel composite materials are Shape Memory Alloys (SMA).

SMA has two unique properties, named as super-elasticity and shape memory effect. 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]. SMA exhibits self-centering phenomena,
which leads the structure to re-center its original position after removal of the loading. This phenomenon of SMA is a unique feature for applications in structural engineering. There are two crystal phases of SMA, austenite and martensite. SMA gets converted from austenite to martensite phase and martensite to austenite phase by applying/removing stresses/ temperature. There are various constituents of SMA, e.g., nickel, titanium, copper, iron, manganese, etc. Amongst these all SMA, nickel-titanium based SMA has been confirmed its potential for the applications in structural elements.

This research is focused on the performance assessment of bridge piers reinforced with SMA in the plastic hinge region with three variable parameters. The factors are varied altogether using a full factorial method for bridge pier models in the previous study. In this study, the best combination of the values for each factor is defined using several optimization methods.

Optimization is the process of defining the best utilization of a particular resource for the desired outcome. The purpose of optimization is to achieve the best design for a set of prioritized criteria or constraints. There are some functions associated with the demand of a specific optimization process, e.g., maximizing functions and minimizing functions. This decision-making process is known as optimization [4].

Multi-Criteria Decision Making (MCDM) is a category of methods existing for the decision making with more than one contradictory criterion. MCDM methods are classified primarily into two groups, such as Multiple Attribute Decision Making (MADM) and Multiple Objective Decision Making (MODM). In MODM methods, there are more than one goals to be achieved by the optimization process. Whereas in MADM methods, there are more than one criterion and only one goal to be achieved by the optimization process. There are numerous MADM methods, i.e., Analytic hierarchy process (AHP) method, Weighted product model (WPM) method, Simple Additive Weighting (SAW) method, Promethee method, Topsis method, etc. [4]. For this research, AHP, SAW, and WPM are the three methods selected for optimization.

![Figure 1. Selected methods of MADM](image)

1.2. Scope of previous research
The applications of super-elastic SMA reinforcement in structural engineering is increasing hastily in recent decades. SMA offers numerous structural applications, namely, reinforcement in reinforced concrete elements, connectors in steel and concrete structures, damping devices, base isolation devices, etc. [5]. Numerous applications of SMA in the bridge structures are explored to improve the seismic performance of bridge structures. Since the last decades, several researchers have studied the behavior of SMA-reinforced bridge piers to mitigate the seismic energy after massive earthquake events [6].

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. 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 2(a) and illustrates the schematic diagram for typical pushover analysis of a pier. Figure 2(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 2. Schematic of a typical pushover analysis of pier (a) deformed and un-deformed shape, and (b) load vs. drift curve with limit states [7]](image)

2.2. Flexural limit states

The performance points and their flexure limit states are essentials to be defined for the performance assessment of SMA reinforced bridge piers. Damages at several flexural limits are determined by 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. Geometry of bridge piers

In this study, a 0.2-scaled circular bridge pier [8] has been considered for the nonlinear static pushover analysis. The geometry of the pier used in this study is, as shown in Figure 3.

![Figure 3. Reinforcement and geometrical details of SMA-RC bridge pier](image)

![Figure 4. Validation of numerical model [8]](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 centerline of loading head, where the lateral load is applied. Axial load ratio is selected as 10% of the axial capacity of a pier, and longitudinal reinforcement ratio ($\rho_t$) is used as 2%. The aspect ratio is selected as 5. Figure 3(a) illustrates the geometry of the pier, and section A-A in Figure 3(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 [6] equation.

2.4. Material constitutive models

| Table 1. Materials properties used for Steel-RC and SMA-RC piers |
|-------------|-----------------|-----------------|
| Material    | Property         | Value           | Reference |
| Confined concrete | Elastic Modulus (GPa) | 33.23           | -          |
|              | Compressive strength (MPa) | 50              | -          |
|              | Tensile strength (MPa)     | 5               | -          |
|              | Corresponding strain      | 0.005           |            |
| Longitudinal steel | Elastic Modulus (GPa) | 200             | -          |
|              | Yield stress (MPa)        | 415             | -          |
|              | Fracture strain           | 0.10            |            |
|              | Strain hardening parameter | 0.05           |            |
| Super-elastic SMA | Yield strength- $f_y$ (MPa) | 210, 401, 750 | [10]       |
|             | Modulus of elasticity-E (GPa) | 28, 62.5, 46.9 | [11]       |
|             | Super-elastic plateau strain length- $\varepsilon_s$ (%) | 9, 6, 13.5 | [12]       |
|             | A to M starting stress- $f_{T1}$ (MPa) | 210, 401, 750 | [13]       |
|             | A to M finishing stress- $f_{T2}$ (MPa) | 275, 510, 1200 | [14]       |
|             | M to A starting stress- $f_{T1}$ (MPa) | 200, 370, 300 | [15]       |
|             | M to A finishing stress- $f_{T2}$ (MPa) | 150, 130, 200 | [16]       |

Where A is the austenite phase, and M is the martensite phase.

In this study, three different material constitutive models are considered for the modelling 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 the 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 constitutive behavior 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 seismic performance of super-elastic SMA-RC and steel-reinforced bridge piers, 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-slipage of super-elastic SMA rebar inside the coupler is neglected. Axial load is applied to 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. [8] under the Highway Idea Project, University of Nevada, Reno (Figure 4). 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. Optimization of bridge piers
This research emphasis on the performance assessment of SMA-RC bridge piers under the effect of static pushover loads. In this study, three factors, each having three levels, are defined. The considered factors based on comprehensive literature and their levels are defined as shown in Table 2. The no. of experiments performed in the previous study for one-factor-at-a-time (OFAT) method were $3 \times 3 = 9$, and full factorial design method were $3^3 = 3 \times 3 \times 3 = 27$. Static pushover analysis is performed for 27 bridge pier models as per the full factorial method of Design of Experiment (DoE), shown in Table 3.

| Table 2. Factors and levels |
|----------------------------|
| Sr. No. | Factors | Levels |
|        |         | Low (-1) | Intermediate (0) | High (+1) |
| 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 (210 MPa) | NiTi (401 MPa) | FeNCATB (750 MPa) |

| Table 3. Factors and levels for each run order |
|-----------------------------------------------|
| Sr. No. | Run | Factor-1 $f_c$ (MPa) | Factor-2 $f_y$ (MPa) | Composition of SMA |
| 1       | 1   | 35              | 250             | CuAlMn (210 MPa) |
| 2       | 2   | 35              | 250             | NiTi (401 MPa) |
| 3       | 3   | 35              | 250             | FeNCATB (750 MPa) |
| 4       | 4   | 35              | 415             | CuAlMn (210 MPa) |
| 5       | 5   | 35              | 415             | NiTi (401 MPa) |
| 6       | 6   | 35              | 415             | FeNCATB (750 MPa) |
| 7       | 7   | 35              | 500             | CuAlMn (210 MPa) |
| 8       | 8   | 35              | 500             | NiTi (401 MPa) |
| 9       | 9   | 35              | 500             | FeNCATB (750 MPa) |
| 10      | 10  | 50              | 250             | CuAlMn (210 MPa) |
| 11      | 11  | 50              | 250             | NiTi (401 MPa) |
| 12      | 12  | 50              | 250             | FeNCATB (750 MPa) |
| 13      | 13  | 50              | 415             | CuAlMn (210 MPa) |
| 14      | 14  | 50              | 415             | NiTi (401 MPa) |
| 15      | 15  | 50              | 415             | FeNCATB (750 MPa) |
| 16      | 16  | 50              | 500             | CuAlMn (210 MPa) |
| 17      | 17  | 50              | 500             | NiTi (401 MPa) |
| 18      | 18  | 50              | 500             | FeNCATB (750 MPa) |
| 19      | 19  | 65              | 250             | CuAlMn (210 MPa) |
| 20      | 20  | 65              | 250             | NiTi (401 MPa) |
| 21      | 21  | 65              | 250             | FeNCATB (750 MPa) |
| 22      | 22  | 65              | 415             | CuAlMn (210 MPa) |
| 23      | 23  | 65              | 415             | NiTi (401 MPa) |
| 24      | 24  | 65              | 415             | FeNCATB (750 MPa) |
| 25      | 25  | 65              | 500             | CuAlMn (210 MPa) |
| 26      | 26  | 65              | 500             | NiTi (401 MPa) |
| 27      | 27  | 65              | 500             | FeNCATB (750 MPa) |
The results of SMA-reinforced bridge piers are evaluated in terms of the performance criteria of limit state of design, e.g., cracking, yielding, spalling, and crushing. These five outputs are considered to be the maximizing functions. Furthermore, the effect of different materials properties, such as yield strength of steel, compressive strength of concrete, and the composition of SMA, are explored using three methods of optimization. The adopted methods of optimization are AHP method, WPM method, and SAW method. Moreover, the performance-wise rankings are assigned to a total of 27 bridge pier models.

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. The results of these models in terms of cracking drift, spalling drift, yielding drift, crushing drift, and maximum drift, are adopted for the optimization process. These drift values are desirable to be maximum; hence, they are selected as maximizing functions. The results of the three optimization methods are discussed in the following section.

Table 4 demonstrates the significance-wise ranking of bridge piers as per AHP method. It can be observed from the table that run no. 3 (Rank no. 1) having $f_c = 35$ MPa, $f_y = 250$ MPa, and $f_{y-SMA} = 750$ MPa gives the maximum values for drift at various flexural limit states, e.g., cracking drift, spalling drift, yielding drift, crushing drift, and maximum drift. It indicates that the low compressive strength of concrete, low yielding strength of steel, and high yielding strength of SMA lead to the higher drift values of a bridge pier. Further, the higher strain value of Fe-based SMA ($f_{y-SMA} = 750$ MPa) makes a bridge pier more flexible to reduce permanent deformations. Further, run no. 11 having $f_c = 50$ MPa, $f_y = 250$ MPa, and $f_{y-SMA} = 401$ MPa stand for rank no. 2. Run no. 23 having $f_c = 65$ MPa, $f_y = 415$ MPa, and $f_{y-SMA} = 401$ MPa stand for rank no. 3.

Table 5 expresses the significance-wise ranking as per SAW method. The results of AHP method and SAW method are similar to each other.

Table 4. Significance-wise ranking as per AHP method

| Rank | Run | Factor 1 | Factor 2 | Factor 3          |
|------|-----|----------|----------|-------------------|
| 1    | 3   | 35       | 250      | FeNCATB (750 MPa) |
| 2    | 11  | 50       | 250      | NiTi (401 MPa)   |
| 3    | 23  | 65       | 415      | NiTi (401 MPa)   |
| 4    | 24  | 65       | 415      | FeNCATB (750 MPa) |
| 5    | 6   | 35       | 415      | FeNCATB (750 MPa) |

Table 5. Significance-wise ranking as per SAW method

| Rank | Run | Factor 1 | Factor 2 | Factor 3          |
|------|-----|----------|----------|-------------------|
| 1    | 3   | 35       | 250      | FeNCATB (750 MPa) |
| 2    | 11  | 50       | 250      | NiTi (401 MPa)   |
| 3    | 23  | 65       | 415      | NiTi (401 MPa)   |
| 4    | 24  | 65       | 415      | FeNCATB (750 MPa) |
| 5    | 6   | 35       | 415      | FeNCATB (750 MPa) |

Table 6 demonstrates the significance-wise ranking of bridge piers as per WPM method. It can be observed from the table that run no. 3 (Rank no. 1) having $f_c = 35$ MPa, $f_y = 250$ MPa, and $f_{y-SMA} = 750$ MPa gives the maximum values for drift at various flexural limit states, e.g., cracking drift, spalling...
drift, yielding drift, crushing drift, and maximum drift. It indicates that the low compressive strength of concrete, low yielding strength of steel, and high yielding strength of SMA lead to the higher drift values of a bridge pier. Further, the higher strain value of Fe-based SMA ($f_{y-SMA} = 750 \text{ MPa}$) makes a bridge pier more flexible to diminish permanent deformations. Further, run no. 11 having $f_c = 50 \text{ MPa}$, $f_y = 250 \text{ MPa}$, and $f_{y-SMA} = 401 \text{ MPa}$ stand for rank no. 2. Run no. 6 having $f_c = 65 \text{ MPa}$, $f_y = 415 \text{ MPa}$, and $f_{y-SMA} = 401 \text{ MPa}$ stand for rank no. 3.

Table 6. Significance-wise ranking as per WPM method

| Rank | Run | Factor 1 | Factor 2 | Factor 3 |
|------|-----|----------|----------|----------|
| 1    | 3   | 35       | 250      | FeNCATB (750 MPa) |
| 2    | 11  | 50       | 250      | NiTi (401 MPa)    |
| 3    | 6   | 35       | 415      | FeNCATB (750 MPa) |
| 4    | 19  | 65       | 250      | CuAlMn (210 MPa)  |
| 5    | 17  | 50       | 500      | NiTi (401 MPa)    |

5. Conclusions
By optimizing the results of parametric investigation of RC bridge piers with SMA reinforcement in the plastic hinge region using three methods of optimization (AHP method, SAW method, and WPM method), following conclusions are drawn:

- The significance-wise ranking is assigned based on the demand for outputs from static pushover analysis. The outputs of static pushover analysis on SMA-RC bridge piers (cracking drift, spalling drift, yielding drift, crushing drift, and maximum drift) are used as input factors for AHP method, SAW method, and WPM method. These drift values are designated as maximizing functions.
- AHP method and SAW method give the same results for the rank-wise significance of bridge pier models.
- The $f_c$ as 35 MPa, $f_y$ as 250 MPa, and $f_{y-SMA}$ as 750 MPa possess rank 1 for AHP method, SAW method, and WPM method of optimization.
- The $f_c$ as 50 MPa, $f_y$ as 250 MPa, and $f_{y-SMA}$ as 401 MPa possess rank 2 for AHP method, SAW method, and WPM method of optimization.
- The $f_c$ as 50 MPa, $f_y$ as 250 MPa, and $f_{y-SMA}$ as 401 MPa possess rank 2 for AHP method, SAW method, and WPM method of optimization.
- The $f_c$ as 65 MPa, $f_y$ as 415 MPa, and $f_{y-SMA}$ as 401 MPa possess rank 3 for AHP method, and SAW method of optimization.
- The $f_c$ as 35 MPa, $f_y$ as 415 MPa, and $f_{y-SMA}$ as 750 MPa possess rank 3 for WPM method of optimization.

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