SEISMIC PERFORMANCE ASSESSMENT
OF STEEL BRIDGE PIERS WITH SHAPE MEMORY ALLOY IN PLASTIC HINGE LENGTH

A. Rahmzadeh¹ and M.S. Alam²

ABSTRACT

Since the 1995 Kobe earthquake in which many steel bridge piers suffered extensive damages, efforts have been devoted to improving the seismic performance of such piers. Various techniques such as reducing width/thickness ratio by adding stiffeners, using inner cruciform plates, attaching steel ductile grids to the base and partially filling the section with concrete have been proposed to prevent progressive local buckling. Regardless of the method and its efficiency, plasticity evolution in plastic hinge length is inevitable and eventually leads to the excessive residual drift of the pier. Presented herein is a feasibility study of the application of shape memory alloys (SMAs) in steel piers, with the aim of utilizing the SMA re-centering feature. SMA has two characteristics: super elastic and shape memory effect; in the former, developed inelastic strain under mechanical loading is recovered upon unloading while in the latter, thermal loading should be applied in order to eliminate residual deformations. First, a 3D finite element (FE) model is generated to simulate the cyclic response of a previously tested steel pier. The validated FE model is then used as the basis to develop models with SMA in the plastic region. The effect of several parameters including SMA type, mechanical properties and length is investigated. FE results show that although utilizing SMA decreases residual drifts significantly, energy dissipation property of the pier reduces as well, depending on the SMA type.

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Since the 1995 Kobe earthquake in which many steel bridge piers suffered extensive damages, efforts have been devoted to improving the seismic performance of such piers. Various techniques such as reducing width/thickness ratio by adding stiffeners, using inner cruciform plates, attaching steel ductile grids to the base and partially filling the section with concrete have been proposed to prevent progressive local buckling. Regardless of the method and its efficiency, plasticity evolution in plastic hinge length is inevitable and eventually leads to the excessive residual drift of the pier. Presented herein is a feasibility study of the application of shape memory alloys (SMAs) in steel piers, with the aim of utilizing the SMA re-centering feature. SMA has two characteristics: super elastic and shape memory effect; in the former, developed inelastic strain under mechanical loading is recovered upon unloading while in the latter, thermal loading should be applied in order to eliminate residual deformations. First, a 3D finite element (FE) model is generated to simulate the cyclic response of a previously tested steel pier. The validated FE model is then used as the basis to develop models with SMA in the plastic region. The effect of several parameters including SMA type, mechanical properties and length is investigated. FE results show that although utilizing SMA decreases residual drifts significantly, energy dissipation property of the pier reduces as well, depending on the SMA type.

Introduction

Following the 1995 Kobe earthquake, in which extensive damages to the bridges crippled the city’s transportation system, a great deal of research has been dedicated to improving the performance of the bridge piers as the front liners in resisting seismic forces. Among different types of failures observed in the steel bridge piers after the Kobe earthquake, local buckling was reported in most cases [1]. Various techniques such as reducing width/thickness ratio by adding stiffeners [2], using inner cruciform plates [3], attaching steel ductile grids to the base [4], partially filling the section with concrete [5], and using linearly tapered plates [6] have been proposed to prevent progressive local buckling in such bridge piers. Regardless of the method and its efficiency, plasticity evolution in plastic hinge length is inevitable and eventually leads to the excessive residual drift of the pier.

Smart materials such as SMAs have been gaining popularity in the structural applications

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in the recent years. Due to having a self-centering characteristic, super-elastic SMAs in different configurations have been used in seismic resisting systems in order to reduce damages [7]. Alam et al. investigated the effect of using super-elastic SMA in a form of reinforcing bars in the concrete beam-column elements [8]. Hedayati-Dezfuli and Alam proposed two types of smart elastomeric bearings with SMA wires [9]. Farmani and Ghassemieh used SMA bolts in extended end-plate steel connections [10]. Aryan and Ghassemieh utilized SMA cables to reduce the effects of vertical and horizontal seismic excitations on highway bridges [11]. Other than wires and bars, SMAs have been investigated in the form of plates. The buckling behavior of SMA plates as energy dissipative elements was evaluated by Suzuki et al. [12]. The application of super-elastic SMA plates in the steel beam-column connections was investigated by Moradi and Alam [13]. Rahmzadeh and Alam utilized super-elastic SMA plates as the energy dissipaters in unbounded post-tensioned steel connections [14].

This paper attempts to investigate the feasibility of utilizing super-elastic SMA in the steel bridge piers to take advantage of its unique self-centering behavior. First, a 3D FE model is generated to simulate the cyclic response of a previously tested steel pier. The validated FE model is then used as the basis to develop models with SMA in the plastic region. The effect of several parameters including SMA type, mechanical properties and length on the important response quantities of the pier is investigated.

Validation Study

To validate the FE model, a tested specimen (No.6) from Ref. [2] was chosen. The schematic presentation of the experimental setup that was used by Ref. [2] is depicted in Figure 1. The specimen consists of a hollow circular section with an outer diameter of 900 mm and a wall thickness of 16.1 mm. The height of the column, from the fixed base to the top of the cap plate, is 3173 mm. The constant vertical and quasi-static lateral loads were applied using an actuator positioned at a height of 3403 mm from the base. SM490 steel with a yield stress of 344.3 MPa and a Young’s modulus of 206 GPa, was selected as the material for the components.

![Figure 1. Schematic of the test specimen (2).](image-url)
To simulate the cyclic behavior of the specimens, three-dimensional FE models are developed using ANSYS Mechanical APDL [15]. It should be mentioned that residual stresses due to welding and fabrication process were neglected in the FE simulations. A nonlinear kinematic model (the Chaboche model) from the ANSYS [15] material library was selected for the SM490 steel. The three-dimensional SOLID185 element which has eight nodes, each having three transitional degrees of freedom, was used to mesh the pier. The FE model was generated utilizing a mapped mesh which produces shapes with regular patterns and less number of nodes. Fine meshes with a length of 15 mm were used near the base and gradually increased in length to 75 mm near the cap plate. The circular section of the specimens was divided into 160 segments along its circumference. To introduce initial imperfections, first, a preliminary linear buckling analysis was done. Then, the perturbed geometry was established by adding a sum of the first ten mode shapes extracted in the preliminary buckling analysis. A reduction factor of 0.2 was used when updating the geometry with mode shapes. This procedure induced a maximum out of plane deformation of 1.7 mm which equals to 0.38% of the cross-section radius.

To apply loads, rigid elements were used to connect the point of loading to the top nodes of the cap plate. The amount of vertical load, as reported by Ref. [2], was 0.138 of the axial yield load of the section. The cyclic lateral loading was applied as a multiple of yield displacement which increased step-by-step. For the boundary condition, all degrees of freedom of the nodes at the base of the pier were constrained to be zero in all directions. Comparison of the hysteresis response obtained from the FE analysis and test is shown in Figure 2 (a). The damaged specimen at the end of the FE analysis is illustrated in Figure 2 (b). This type of failure which is known as “elephant foot bulge mode” occurs in cylindrical specimens due to the development of local buckling [16].

![Hysteretic Curve](image1.png)

**Figure 2.** (a) Experiment and FE analyses load-displacement hysteretic curves, (b) Final configuration.

**Application of SMA in Steel Bridge Piers**

Since the plastic straining in a circular steel bridge pier near its base is interrupted by the elephant foot buckling evolution, it is more convenient to work with the buckling wave length rather than the plastic hinge length. The length of the buckling wave in a hollow cylinder with simply supported boundary conditions under axial compression can be obtained using the following formula [17].
\[ \lambda = \pi \sqrt{\frac{t_c^2 d_c^2}{3(1-\nu^2)}} \]  

(1)

in which, \( t_c \) is the cylinder wall thickness, \( d_c \) is the outer diameter and \( \nu \) the Poisson ratio. To account for other types of boundary conditions, as well as the initial imperfections, a factor is added to the above formula,

\[ \lambda = \pi \sqrt{\frac{\gamma^2 t_c^2 d_c^2}{3(1-\nu^2)}} \]  

(2)

where, \( \gamma \) is the knock-down factor and can be calculated using the below equation [18],

\[ \gamma = 1 - 0.901 \left(1 - e^{-\frac{1}{16\sqrt{2}\nu}}\right) \text{ for } d_c/t_c < 3000 \]  

(3)

The above equations yield in a buckling wave length of 254.2 mm for the considered specimen herein.

Figure 3 illustrates a typical flag-shaped hysteresis of super-elastic SMA. The properties of SMAs considered in this study are given in Table 1, wherein \( E_{\text{SMA}} \) is the modulus of elasticity, \( f_y \) the austenite to martensite starting stress, \( f_{p1} \) the austenite to martensite finishing stress, \( f_{T1} \) the martensite to austenite starting stress, \( f_{T2} \) the martensite to austenite finishing stress, and \( \varepsilon_s \) the super-elastic plateau strain length.

<table>
<thead>
<tr>
<th>Case</th>
<th>Alloy</th>
<th>( E_{\text{SMA}} ) (GPa)</th>
<th>( f_y ) (MPa)</th>
<th>( f_{p1} ) (MPa)</th>
<th>( f_{T1} ) (MPa)</th>
<th>( f_{T2} ) (MPa)</th>
<th>( \varepsilon_s ) (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMA1</td>
<td>Fe-Mn-Al-Ni</td>
<td>46.9</td>
<td>320</td>
<td>443</td>
<td>300</td>
<td>211</td>
<td>6.1</td>
<td>Ref. [19]</td>
</tr>
<tr>
<td>SMA2</td>
<td>Fe-Mn-Al-Ni</td>
<td>98.5</td>
<td>390</td>
<td>490</td>
<td>360</td>
<td>200</td>
<td>6.3</td>
<td>Ref. [20]</td>
</tr>
</tbody>
</table>
For a height of half, one and two buckling wave lengths from the bottom, the SMA materials listed above are used instead of steel in the validated specimen. The connection between the SMA and steel cylinders is assumed as fully bonded. A detailed discussion on the welding of SMA and steel components can be found in Ref. [21].

Table 2. Details of the numerical models.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>SMA type</th>
<th>Length of the SMA tube (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No6-0.5L-SMA1</td>
<td>SMA1</td>
<td>125</td>
</tr>
<tr>
<td>No6-1L-SMA1</td>
<td>SMA1</td>
<td>250</td>
</tr>
<tr>
<td>No6-2L-SMA1</td>
<td>SMA1</td>
<td>500</td>
</tr>
<tr>
<td>No6-0.5L-SMA2</td>
<td>SMA2</td>
<td>125</td>
</tr>
<tr>
<td>No6-1L-SMA2</td>
<td>SMA2</td>
<td>250</td>
</tr>
<tr>
<td>No6-2L-SMA2</td>
<td>SMA2</td>
<td>500</td>
</tr>
<tr>
<td>No6-0.5L-SMA3</td>
<td>SMA3</td>
<td>125</td>
</tr>
<tr>
<td>No6-1L-SMA3</td>
<td>SMA3</td>
<td>250</td>
</tr>
<tr>
<td>No6-2L-SMA3</td>
<td>SMA3</td>
<td>500</td>
</tr>
</tbody>
</table>

Figure 6 shows the cyclic response of the specimens with SMA1 over three different lengths. The lateral load capacity of the specimens depends on the column buckling strength. The elastic buckling strength in hollow cylinders under axial compression is a function of the Young modulus and diameter-over-thickness ratio. Beyond the material yield point, the critical buckling stress becomes relevant to the secant modulus as well, and its rate decreases with plastic evolution [22]. In specimen No6-0.5L-SMA1, a portion of the buckling wave happens in the steel cylinder, resulting in permanent local buckling and following that large residual displacements. In the other two, local buckling takes place in the SMA cylinders and the specimens experience a transient local buckling owing to the super-elastic behavior of SMA. By virtue of this characteristic, the initial shape of the pier is retrieved and the system self-centers. Since the demand-over-capacity ratio in the SMA part of specimen No6-2L-SMA1 is lower than its corresponding in specimen No6-1L-SMA1, inelastic local buckling occurs at a higher lateral load and controls the maximum load. It should be noted that the initial stiffness of the specimens decreases with using a longer SMA cylinder at the base due to the low elastic modulus of the SMA material.
Figure 4. Load-displacement hysteresis response of models with SMA1.

The cyclic response of the specimens with SMA2 over three different lengths are shown in Figure 5. The behavior is the same as before except that plastic buckling occurred at higher lateral loads due to the higher yield stress of SMA2.

Figure 5. Load-displacement hysteresis response of models with SMA2.

The effect of post-yield stiffness and following that the scant modulus is evident from the comparison of the behavior of the specimens having SMA3 with the other two. As can be seen in Figure 6, the degradation of the behavior in the specimens with SMA3 is less, compared to the ones with SMA1 or SMA2.
Figure 6. Load-displacement hysteresis response of models with SMA3.

Table 3 lists the response quantities for the considered specimens.

Table 3. Response quantities of the specimens.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Initial stiffness</th>
<th>Lateral load capacity</th>
<th>Total dissipated energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.6</td>
<td>61543 kN/m</td>
<td>1553.7 kN</td>
<td>1536 kN.m</td>
</tr>
<tr>
<td>No6-0.5L-SMA1</td>
<td>44162 kN/m</td>
<td>1178.3 kN</td>
<td>494.7 kN.m</td>
</tr>
<tr>
<td>No6-1L-SMA1</td>
<td>36953 kN/m</td>
<td>1121.4 kN</td>
<td>230.6 kN.m</td>
</tr>
<tr>
<td>No6-2L-SMA1</td>
<td>27527 kN/m</td>
<td>1145.3 kN</td>
<td>185.1 kN.m</td>
</tr>
<tr>
<td>No6-0.5L-SMA2</td>
<td>52885 kN/m</td>
<td>1418.8 kN</td>
<td>733.5 kN.m</td>
</tr>
<tr>
<td>No6-1L-SMA2</td>
<td>49691 kN/m</td>
<td>1379.5 kN</td>
<td>460.7 kN.m</td>
</tr>
<tr>
<td>No6-2L-SMA2</td>
<td>43709 kN/m</td>
<td>1451 kN</td>
<td>320.6 kN.m</td>
</tr>
<tr>
<td>No6-0.5L-SMA3</td>
<td>41560 kN/m</td>
<td>1179.4 kN</td>
<td>539 kN.m</td>
</tr>
<tr>
<td>No6-1L-SMA3</td>
<td>31712 kN/m</td>
<td>1152.2 kN</td>
<td>276.1 kN.m</td>
</tr>
<tr>
<td>No6-2L-SMA3</td>
<td>22150 kN/m</td>
<td>1263.8 kN</td>
<td>210.4 kN.m</td>
</tr>
</tbody>
</table>

Conclusions

The feasibility of using SMA in highly stressed regions of a steel bridge pier was investigated. After a validation study, three different types of SMA were used over three different lengths. Cyclic behavior of each specimens along with their initial stiffness, maximum load and
cumulative dissipated energy was presented. The results illustrated that local buckling inevitably occurs in the plastic hinge region regardless of the SMA tube length. However, if the buckling wave is within the SMA tube, the column can revert to its initial state after unloading and the self-centering behavior of SMA is reflected into the behavior of the pier. The use SMA yields in less initial stiffness, lateral load capacity and dissipated energy, while, a fully self-centering behavior can be achieved with a proper choice of the SMA type and the region it is utilized in.

Acknowledgments

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References

18. NASA(SP-8007). *Buckling of Thin-Walled Circular Cylinder*. National Aeronautics and Space Administration; 1968.