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Application of shape memory alloy dampers in the seismic control of cable-stayed bridges

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ABSTRACT

This paper focuses on introducing and investigating the performance of a new passive seismic control device for cable-stayed bridges made with shape memory alloys (SMAs). The superelasticity and damping capability of SMAs is sought in this study to develop a supplementary recentering and energy dissipation device for cable-stayed bridges. Three-dimensional long-span bridge model, including the effect of soil-structure interaction is developed and utilized in the study. SMA dampers are implemented at the bridge's deck-pier and deck-tower connections. The bridge is subjected to three orthogonal components from two historic ground motion records. The effectiveness of the SMA dampers in controlling the deck displacement and limiting the shear and bending moment demands on the bridge towers is assessed. Furthermore, a study is conducted to determine the sensitivity of the bridge response to the hysteretic properties of the SMA dampers. The analytical results show that SMA dampers can successfully control the seismic behavior of the bridge. However, the effectiveness of the new dampers is significantly influenced by the relative stiffness between the dampers used at the deck-tower and deck-pier connections. The results also show that the variation in the SMAs' strain hardening during phase transformation has a small effect on the bridge response compared to the variation in the unloading stress during reverse phase transformation.

1. Introduction

Cable-stayed bridges are flexible extended-in-plane structures, which constitute an integral part of many local and national highway systems. They provide an aesthetic and practical solution for spans up to approximately 1 km. Rapid progress has been made over the last decade in the design and construction technologies of cable-stayed bridges. There had also been a large number of studies aimed at characterizing and studying the dynamic behavior of cable-stayed bridges under extreme dynamic loads such as earthquakes [1–3]. These studies have proven that although restraining the bridge deck completely at the pier and tower locations could limit the deck displacement, it would cause a significant increase in the demands on the piers and towers in terms of bending moment and shear forces. Therefore, there is an agreement among many researchers that the main deck should neither be fixed to the towers nor to the piers, but rather be allowed to experience some sort of relative movement at these locations, which would lead to a reduction in the overall forces transmitted between the superstructure and the substructure. In order for this solution to be implemented successfully, and since cable-stayed bridges possess little damping characteristics that may not always be enough to help alleviate vibration under severe ground motions, supplementary damping devices are often sought. This fact introduces new challenges to the earthquake engineering community in terms of seeking and developing new damping technologies that could improve the seismic performance of cable-stayed bridges.

In the last two decades a large number of studies have focused on developing effective and reliable dynamic control devices for cable-stayed bridges. These devices could be divided into passive, semi-active, and active control devices. The most basic device type that had been studied extensively is metallic damper [4–6], which provides energy dissipation through plastic deformation. Although this class of devices is simple and cost-effective it loses the majority of its effectiveness after yielding and thus needs to be immediately replaced after any seismic event which could result in high costs and disrupted functionality for major bridges. The need for immediate replacement of metallic dampers could also lead to seriously weak performance during after-shocks which are likely to occur after strong seismic events. Another type of dampers that has been studied and used in the past is fluid viscous dampers (FVD) [7,8]. FVDs are considered to be among the most powerful dynamic control devices for bridges. Despite their effectiveness, their performance could be highly unpredictable since it is frequency-dependent. Therefore, FVDs

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could exert extremely large and unnecessary forces on the bridge components even at low shaking intensities. Therefore, many researchers have studied the application of fluid dampers with semi-active capability such as in the case of Magnetorheological (MR) fluid dampers where the rigidity of the fluid is altered by subjecting it to an electric current [9,10]. Although these devices have shown promise, their wide application in structures faces many challenges due to their relatively high cost and maintenance requirements. Among the damping technologies that have been either studied or applied recently are friction dampers, where the energy is primarily dissipated by the friction induced between two surfaces when the force exceeds certain limit (slip load) [11,12]. This type of damper constrains the force in the damper to a certain limit which depends on the damper's slip load rather than the applied load. This could lead to excessive deformations under extreme excitations. The previous studies illustrate that there is still need for further improvement in the field of passive control of bridges. This study presents a new class of dampers that could overcome many of the shortcomings which have been previously discussed. The new damper is made of superelastic Shape Memory Alloys (SMAs); a relatively new class of metallic alloys, which exhibit unique thermomechanical characteristics. A description of the SMA damper and its unique characteristics are presented in the following section.

2. Background on shape memory alloys

SMAs form a relatively new class of metallic alloys that was originally discovered in 1932 [13]. SMAs have unique capability to restore their original shape after being deformed excessively to a strain that could reach up to 8%. The key behind such a unique feature lies in the ability of the SMA to transform from the parent phase (austenite), which is microstructurally symmetric to the less symmetric martensitic phase and revert back either by heating or by simply removing the load which caused the phase transformation. Based on the manufacturing process and chemical composition, a SMA could be categorized as either austenite which is also known as superelastic (i.e. recover its original shape when unloaded) or martensite (i.e. recover its original shape when heated). This study will focus on the former SMA type.

Fig. 1 shows a schematic of the stress–strain relation typically observed in superelastic SMAs. As shown in the figure, the stress–strain behavior of superelastic SMAs could be divided into three phases: (1) linear austenite, (2) phase transformation, and (3) linear martensite. The phase transformation is characterized by a very low modulus and thus resembles yielding in materials with typical plastic behavior. When the applied stress is removed, the martensite becomes unstable and thus converts back to austenite resulting in the "flag shape" hysteresis shown in the figure. As shown in the figure, superelastic SMAs possess several characteristics that make them ideal for seismic applications including hysteretic damping, recentering capability (i.e. ability of the material to return to its undeformed configuration upon unloading), ability to undergo strain hardening at large strain levels (>6%-strain), and the formation of stress plateau during phase transformation which controls the forces transmitted to the structure. The number of studies focusing on the feasibility of using SMAs in seismic applications has grown in the past decade and is still growing. Many researchers have proposed using SMAs in various structural applications such as in cross-bracing cables [14], passive structural control dampers [15–20], steel moment connections [21], seismic restrainers for bridges [22–24], dampers for mitigating the vibration of stay-cables [25], and actuators for adjusting fluid dampers [26,27]. The work presented in this paper is primarily directed towards the potential application of SMAs as seismic passive damper devices for vibration mitigation of cable-stayed bridges. The effect of variability in the SMAs hysteretic shape on their effectiveness as dampers for cable-stayed bridges is also addressed.

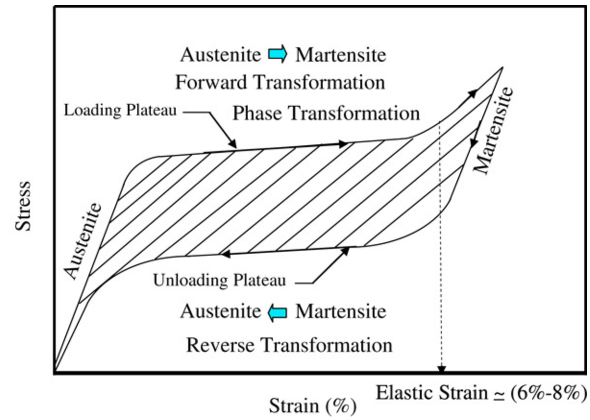

Fig. 1. Typical stress–strain relationship of superelastic SMAs.

3. Cable-stayed bridge

3.1. Bridge description

The three-dimensional hypothetical bridge model suggested by Nazmy and Abdel-Ghaffar [28] was adopted in this study. Fig. 2 shows a schematic elevation of the bridge and its A-shaped towers. As shown in the figure, the bridge has a center span of 670.5 m and side spans of 292.6 m. The two A-shaped central towers supporting the bridge had a height of 170.8 m and a width at the foundation level equal to 36.0 m. The end spans of the bridge were supported by two piers. The structural properties of the elements were based on examining several proposed bridges in the eastern region of the United States. The relevant data for the bridge was provided in the paper by Nazmy and Abdel-Ghaffar and used by a wide number of researchers.

3.2. Analytical model of reference bridge

The 3-D finite element model of the reference bridge (i.e. bridge with no SMA dampers) that was used as the basis for the comparison in this study is depicted in Fig. 3. The model was developed and analyzed using the open-source finite element program

OpenSees [29], which was developed to simulate the seismic behavior of structures. The models of the bridge deck and towers were developed using 94 nodes, 121 elastic beam–column elements and 48 elastic truss elements. In the original bridge model presented by Nazmy and Abdel-Ghaffar [28], the effect of soil-structure interaction (SSI) was neglected. However, in this study the SSI was considered and modeled using a series of translational and rotational springs and dashpots introduced at the base of the bridge towers. A more detailed description of the SSI system that was adopted in this study is presented in the next section. The tower-deck connection in the reference bridge was modeled using two horizontal and one vertical elastic link elements. Shock-transmission devices were assumed at the deck-tower connection to limit the displacement of the deck. These devices allow the movement of the deck due to temperature changes, but rigidly connect the tower and deck together under a strong motion. On the other hand, bearings at both piers of the reference bridge were modeled such that they would permit movement in the longitudinal direction and rotation about the transverse and vertical axes i.e. the Y-axis and Z-axis, respectively (see Fig. 3). The selection of these boundary conditions was based on the benchmark problem results and the recommendations of the ASCE Committee on Structural Control. The committee suggested using these boundary conditions as a basis for the comparison with various structural control devices [30,31].