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Seismic Response of Simply Supported Deck Bridges with Auxiliary Superelastic Devices

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Abstract

In this paper a multi-performance seismic device based on superelastic SMA wires is proposed for the seismic retrofit of multi-span simply supported and continuous deck bridges. The effectiveness of the proposed device has been assessed through a number of Nonlinear Time History Analyses (NTHA) on two bridge structures representative of existing Italian highway bridges. Results have been compared to the seismic response of the bridges in the as-built configuration. Based on the results of this study, the use of SMA-based restrainers determines a significant reduction (by about 70%) of the deck displacements with an increase (by about 50%) of the maximum force transmitted to the piers. Moreover, the SMA-based restrainers are effective in protecting abutments and bearing devices from damage. The use of SMA-based shock absorbers can give rise to a significant redistribution of the seismic force of the deck between all the piers, thus avoiding the failure of the pier with fixed bearing.

Keywords: Shape Memory Alloys, Bridges, Seismic Retrofit, Nonlinear Time-History Analysis.

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1. INTRODUCTION

Past earthquakes have repeatedly shown that bridges designed specifically for seismic loads have been collapsed or have been severely damaged. This unexpected poor performance can be attributed to the old elastic-based design philosophy, coupled with a lack of attention to design details of the past seismic codes. Typical damages observed during past earthquakes are pounding between adjacent decks and

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bearing failure with consequent deck unseating, especially in multi-span simply supported structures, and flexural/shear failure of piers, especially in multi-span continuous bridges.

Seismic retrofit measures based on the use of steel cable restrainers or steel bars to limit the displacements between adjacent decks have been applied during the '70s in the US and Japan. The main critical aspects of this retrofit technique are fragile failure of connections, small elastic strain range, no dissipation of energy and large residual displacements beyond the elastic range. Steel restrainers would also induce large forces in other components of the bridge, such as piers and abutments. Seismic retrofit measures based on the use of viscous shock transmitters, on the other hand, are often applied to control the force transmitted to the piers. A typical example for the use of shock transmission units is in multi span continuous deck bridges with fixed bearings on a single pier. The installation of shock transmission units on the other piers makes it possible that under service conditions all horizontal forces are transmitted to the pier with fixed pier-deck connections, while during an earthquake the longitudinal horizontal force is distributed among all the piers. The main limitation of the shock transmission units are the large dimensions, the difficulty of installation in existing structures, the need of continuous maintenance and the sensitivity of the mechanical behaviour to the earthquake characteristics.

Shape Memory Alloys (SMAs) with superelastic behaviour (Duerig and Zadno 1990) appear to be suitable candidates for the seismic retrofit of bridges as they show the potential to overcome the limitations of steel restrainers and shock transmission units discussed before. Until now, a number of experimental and analytical studies have been conducted to examine the potential of SMA in the seismic retrofit of bridges. In these studies (DesRoches 2000, Andrawes and DesRoches 2005), SMA-based restrainers have been proposed to avoid deck unseating, while allowing pounding between adjacent decks. In this paper a multi-performance seismic device based on superelastic SMA wires is proposed for the seismic retrofit of multi span simply supported and continuous deck bridges. The feasibility of the proposed SMA-based seismic restrainer and shock absorber system has been evaluated through a number of nonlinear time-history analyses (NTHA) on two bridge structures representative of the existing Italian highway bridges. The seismic responses of the bridge structure with and without SMA-based seismic devices are compared to demonstrate the effectiveness of the proposed SMA-based seismic retrofit technique.

2. SMA-BASED SEISMIC DEVICES FOR THE RETROFIT OF BRIDGE STRUCTURES

2.1 Performance objectives

The proposed SMA-based seismic restrainer has been designed to achieve a number of Performance Objectives, which can be summarised as follows: (i) avoid bearing failure, (ii) avoid pounding between adjacent decks, as well as between deck and abutment, (iii) prevent span unseating, (iv) re-center the decks in their initial position at the end of the seismic excitation, (v) allow the thermal movements of the decks, (vi) give an adequate margin of safety for the structure in case of near-fault ground motions. The same device can be also used as shock absorber system in continuous deck bridges to (vii) control the force transmitted to piers and abutments. The SMA device is installed immediately below the superstructure, between the bottom of deck girders and the top lateral surface of pier cap or abutment (see Fig. 1). The achievement of these performance objectives is strictly related to the superelastic properties of SMA wires, particularly to their large working strain range and hysteretic energy dissipation capability. The attainment of the last two performance objectives is associated to the increase of stiffness, due to the elastic deformation of detwinned martensite found at the end of the phase transformation, and the low post-elastic stiffness exhibited by superelastic SMA wires during the martensite transformation, respectively.

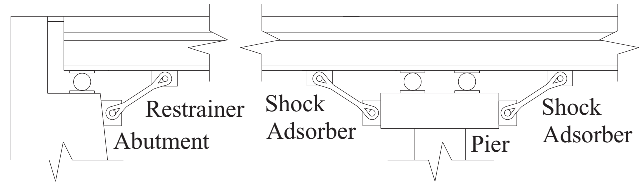


Figure 1: Installation of the SMA devices on abutment (left) and pier (right).

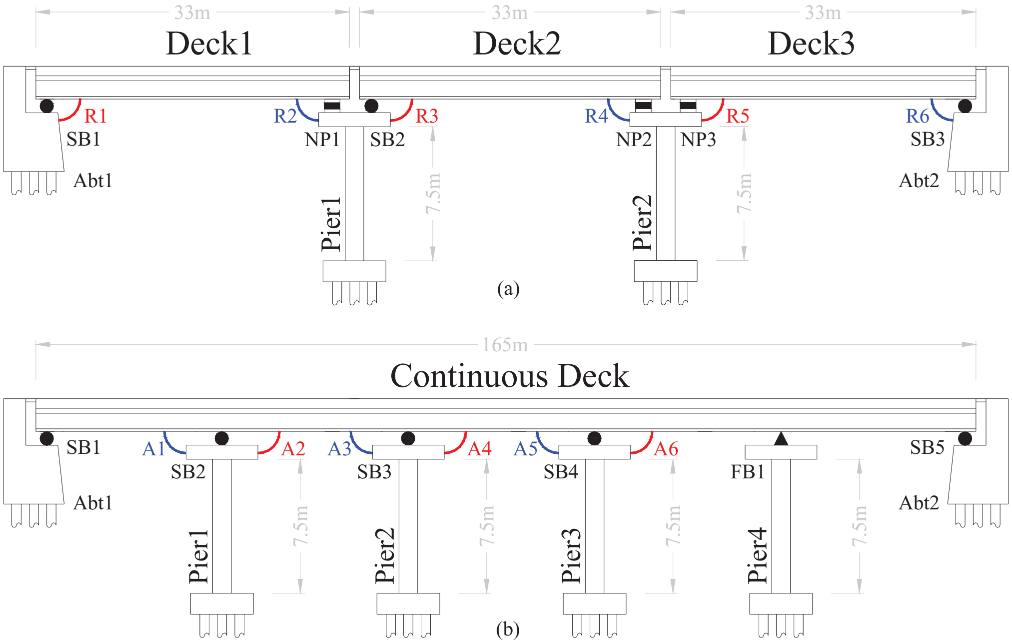


Figure 2: Schematic layout of the examined bridges.

2.2 Case Studies

Two typical bridge configurations have been selected as case studies. The schematic layout of the selected bridges is shown in Figure 2. The first bridge (Fig. 2a) is a 3-span simply supported deck bridge, with span lengths of approximately 33 m. The clearance of the expansion joints between adjacent decks as well as between deck and abutment is equal to 50mm. The bridge has a regular layout, the deck being supported by two identical RC piers with 10m height. The pier-deck connections are realized by Neoprene Pads (NP) and Sliding Bearings (SB), respectively. Neoprene pads have 300x600 mm plan dimensions, 50 mm thickness and approximately 1MPa shear modulus. The mass of each deck is equal to 720 ton. The bridge has been equipped with six SMA restrainers properly designed to achieve the performance objectives for simply supported deck bridges mentioned before (see Section 2.1). Each restrainer system consists of 2000 2mm diameter SMA wires with 550 mm free length.

The second bridge (Fig. 2b) is a 5-span continuous deck bridge, with total length of approximately 165 m. The clearance of the expansion joints between deck and abutment back wall is equal to 50mm. Also in this case, the bridge has a regular layout, the deck being supported by four identical RC piers with 7.5m height. The pier-deck connections are realized by a series of Fixed Bearings (FB), placed on the top of pier n.4 and Sliding Bearings (SB), placed on the abutments and on the top of the other piers. The total mass of the deck is equal to 3000 tons. The bridge has been equipped with six SMA restrainers properly designed to achieve the performance objectives for continuous deck bridges mentioned before (see Section 2.1). Each shock absorber system consists of 3500 wires 2mm diameter SMA wires with 350mm free length.

2.3 Structural Modelling

In order to examine the longitudinal seismic response of the bridge structures described before, two 2-D nonlinear numerical models have been implemented, using the finite element package SAP2000 Nonlinear. According to the Structural Component Modeling (SCM) approach, the bridge structure has been divided in a number of independent rigid diaphragms, modeling the bridge decks, mutually connected by means of a series of nonlinear springs, modeling bearing devices, piers, abutments, SMA restrainers and shock absorbers. The deck mass has been lumped in the centre of mass of each deck. A tributary mass of the pier mass has been also taken into account.

A linear viscous-elastic behaviour has been considered for neoprene pads, whose horizontal shear stiffness has been evaluated based on the dimensions (cross section area and thickness) of the pads and shear modulus of neoprene. The horizontal strength of the bearing system has been evaluated as the lowest between the shear resistance of neoprene pads and the friction resistance between neoprene and concrete sliding surfaces. In the case study under consideration, the shear resistance of neoprene pads has been related to the attainment of a shear strain of 150%. The friction coefficient between neoprene and concrete has been taken equal to 70%. The fixed bearings have been assumed to remain linear elastic up to failure, which is usually brittle, being due to the attainment of the shear strength of the device. The horizontal stiffness of the fixed bearings has been estimated based on the geometric data available. During the analysis, the maximum shear force in the fixed bearings has been monitored. When the shear strength was prematurely exceeded, a post-failure frictional behaviour, corresponding to sliding between deck and pier cap, has been considered. Reference to a Coulomb (rigid-perfectly-plastic) model has been made to describe the frictional behaviour of the sliding bearings, assuming a friction coefficient of 5%.

Piers have been supposed to remain elastic. The maximum shear force in the piers has been monitored and compared to the pier strength assumed equal to 10000 kN. The horizontal stiffness of the piers has been taken equal to 250000 KN/m. Both the strength and horizontal stiffness of the piers has been derived based on the examination of the geometric and mechanical characteristics of a great variety of bridge piers of the A16 Italian highway.

Possible effects due to the closure of the joints have been taken into account in the analyses by means of compression-only link elements with gap. Moreover, the seismic response of the abutments in the longitudinal direction has been described with a couple of nonlinear springs, characterized by two different elastic-perfectly-plastic backbone curves, modeling the pushing and pulling action of the abutment, respectively. The longitudinal response of the abutment, indeed, is based on the interaction between bearing devices, joint gap, abutment back wall, abutment piles and soil backfill material. In this study, the horizontal stiffness and ultimate strength of the abutment have been derived from a combination of design recommendations and experimental test results on seat-type abutments with piles, as a function of the abutment back wall dimensions and pile characteristics.

A rate independent constitutive model has been considered to describe the SMA superelastic behaviour during seismic excitations. The cyclic numerical model has been derived assembling a series of nonlinear springs, in such a way to envelop the experimental cyclic behaviour exhibited by SMA wires during cyclic tensile tests at 1 Hz frequency of loading (Dolce and Cardone 2001), which represents a typical value for the natural frequency of vibration of bridge structures.

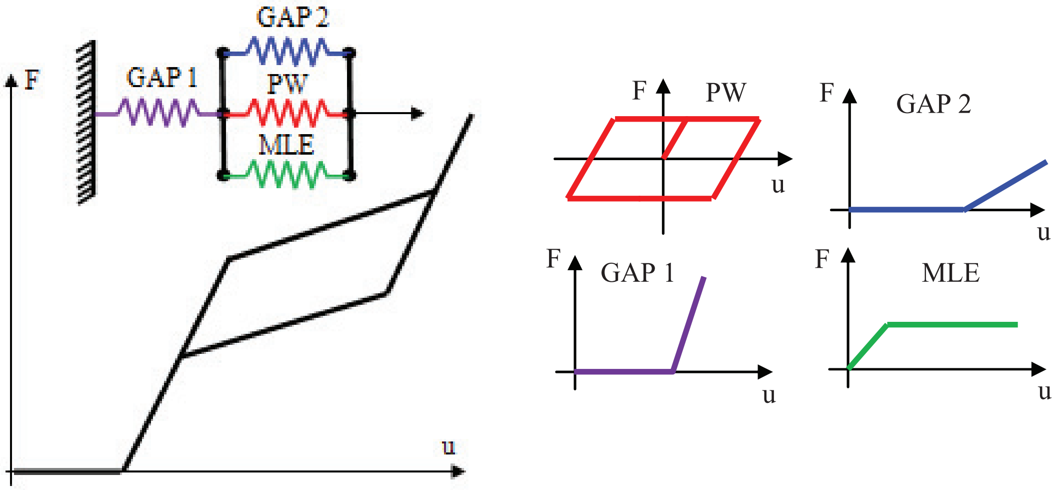


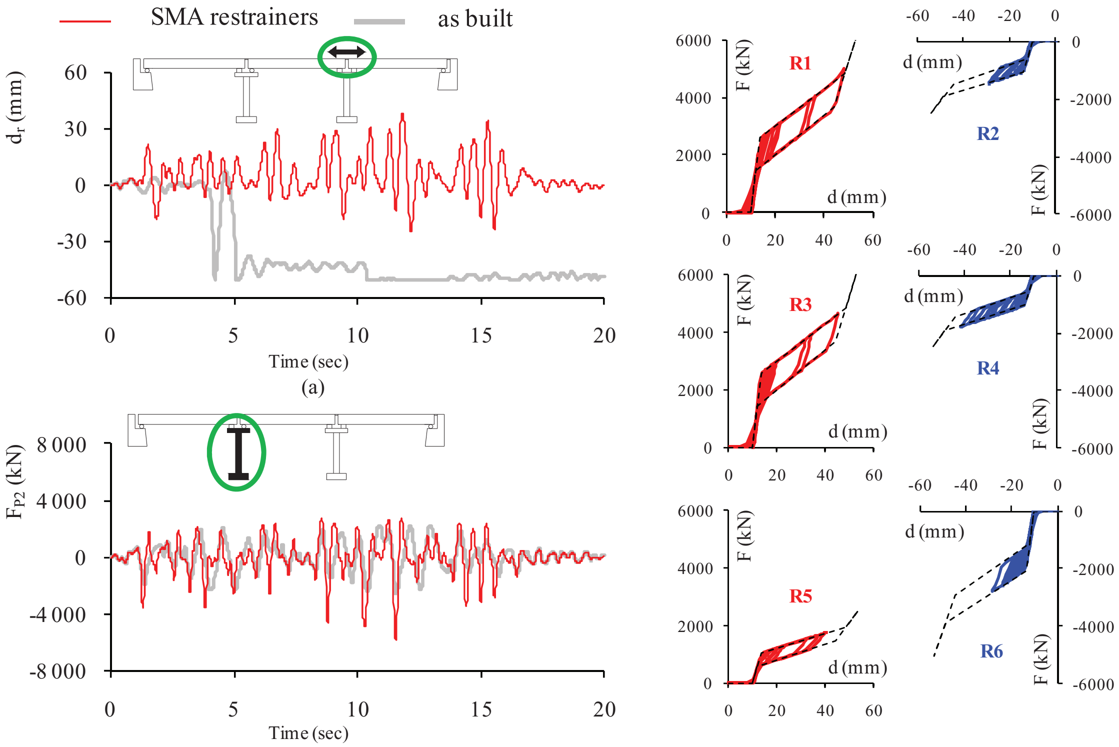
Figure 3: Phenomenological model of SMA-based seismic devices.

Four spring elements have been used to reproduce the mechanical behaviour of the proposed device. The first element is an elastic spring element with initial gap (GAP1 in Fig. 3). The initial gap is adopted, both in the numerical model and in the practical applications, to allow the thermal movements of the bridge in standard working conditions (i.e. in absence of seismic excitation). The GAP1 element is put in series with three nonlinear springs, working in parallel under the same horizontal displacement, modelling the axial force-displacement cyclic behaviour of the SMA wires. A multilinear elastic spring element (MLE in Fig. 3) is used to describe the nonlinear elastic behaviour of the SMA device. A plastic-Wen spring element (PW in Fig. 3) is used to account for the energy dissipation capacity of the SMA device. Finally, an elastic spring element with gap (GAP 2 in Fig. 3) is used to capture the increase of stiffness of the SMA device at the end of the phase transformation from austenite to detwinned martensite.

2.4 Nonlinear Time-history Analysis

The effectiveness of SMA restrainers and shock absorbers has been evaluated trough a number of Nonlinear Time-History Analyses (NTHA). NTHA have been carried out both for the bridge in the as-built configuration and for the bridge equipped with SMA devices. A set of three ground motion records have been utilized, including: (i) an artificial accelerograms compatible with the 5%-damped acceleration response spectrum provided by the Eurocode 8 for soil type C, (ii) the 0° component of the near-fault (0.3Km fault rupture distance) record (Takatori station) of the 01/16/1995 Kobe earthquake (6.9 Magnitude) and (iii) the E-W component of the near-fault (1.1Km fault rupture distance) record (TCU068 station) of the 09/20/1999 Chi-Chi Taiwan earthquake (7.6 Magnitude). The artificial accelerogram has been scaled to 0.48g Peak Ground Acceleration (PGA), which corresponds to the seismic intensity with 475 years return period for a structure of category of importance I and soil type C. Reference to the original (recorded) PGA values has been made for the natural near-fault records, equal to 0.61g and 0.57g for the Kobe and Taiwan earthquakes, respectively.

Figure 4 compares the longitudinal seismic responses of the simply supported deck bridge with and without SMA restrainers. The comparison is made in terms of time histories of joint displacement and pier shear force, caused by the artificial accelerogram. As can be seen, in the as-built condition the closure of the intermediate joints repeatedly occurs, thus producing pounding between adjacent decks (see Fig. 4a). The piers exhibit an elastic behaviour with maximum shear force lower than 40% compared to their ultimate strength. The use of SMA restrainers determines a significant reduction of the relative displacements of the joints, which never exceed 40 mm, and a perfect recentering behaviour while residual deck displacements of the order of 150mm are found at the end of seismic excitation in the as-built condition. It is worthwhile to observe that the increment of the maximum shear force experienced by the piers in presence of SMA devices does not exceed the 60% of the pier yielding strength (see Fig. 8b). As shown in Figure 8c, all the SMA restrainers work perfectly within the strain range associated to the forward phase transformation. The maximum displacements experienced by the SMA restrainers are very close to the design displacement of the device (48mm), corresponding to the end of the martensite transformation in the SMA wires at 7% axial strain. In presence of near-fault seismic ground motions (not shown in Fig. 4), the increase of stiffness due to the elastic deformation of detwninned martensite found at the end of the phase transformation, is fundamental to guarantee the respect of the performance objective of the design.

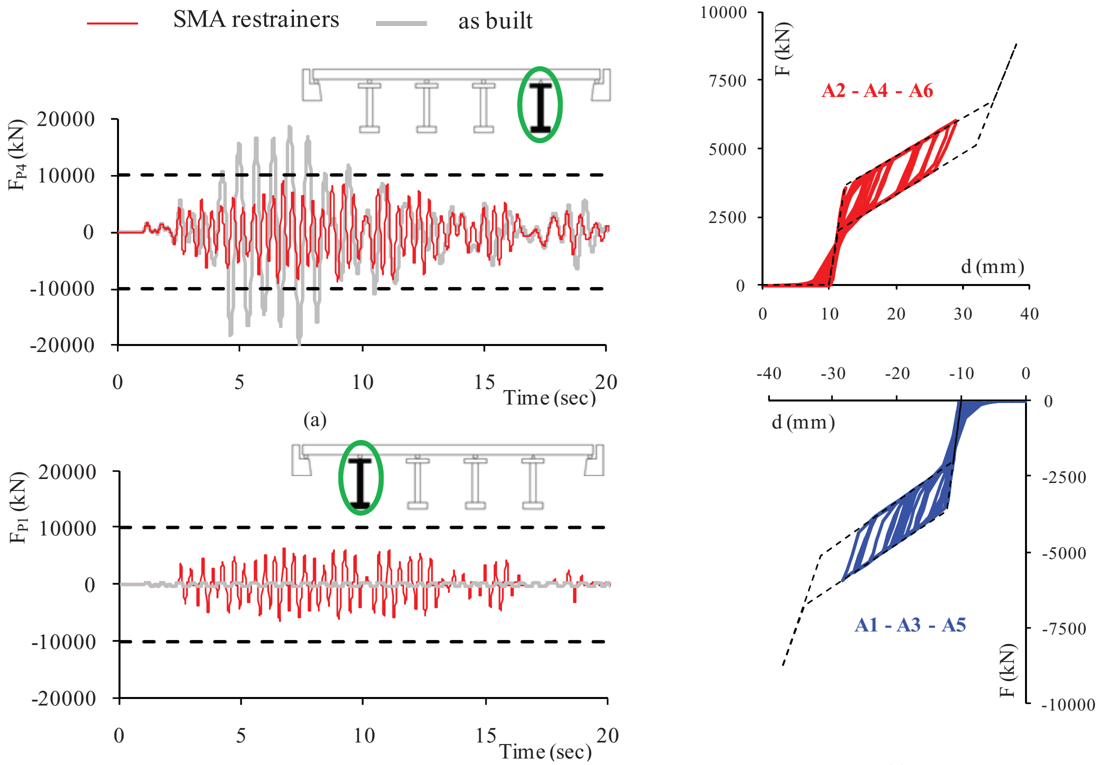


(a)

(b)

(c)

Figure 4: Comparison between (a) joint (J2) displacement time histories and (b) pier (P1) force time histories, for the multispan simply supported deck bridge subjected to the artificial accelerogram, with (red line) and without (blue line) SMA restrainers. (c) Cyclic behavior of the SMA restrainers for bridge subjected to the artificial accelerogram.



(a)

(b)

(c)

Figure 5: Comparison between the shear force-time histories of the pier (a) with fixed bearings (P4) and (b) with sliding bearings (P1), for the continuous deck bridge subjected to the artificial accelerogram, with (red line) and without (blue line) SMA shock absorbers. (c) Cyclic behaviour of the SMA shock absorbers for bridge subjected to the artificial accelerogram.

Figure 5 compares the longitudinal seismic responses of the continuous deck bridge with and without SMA shock absorbers. The comparison is made in terms of shear force-time histories of the piers, generated by the artificial accelerogram. As can be seen, in the as-built condition the seismic demand in the pier with fixed bearings considerably overcomes (by about 2 times) the shear strength of the pier. The activation of the SMA shock absorbers placed on the three piers with sliding bearings determines a redistribution of the seismic force between the piers that avoid the failure of the pier with fixed bearing. At the same time, the increment of shear force in the piers with sliding bearings does not cause any damage, since the maximum force does not exceed the 65% of the pier strength. Moreover, the presence of the shock absorber brings about a maximum displacement of the deck of the order of 40mm, i.e. lower than the clearance of the abutment joints. As shown in Figure 5c, all the SMA shock absorbers work very well within the strain range associated to the martensite phase transformation, with maximum displacements of the order of 30mm, i.e. compatible with the design displacement of the device (35mm).

3. CONCLUSIONS

In this paper a multi-performance seismic device based on superelastic SMA wires has been proposed for the seismic retrofit of bridges. The design objective of the SMA device depends on the bridge typology. For multi-span simply supported deck bridges, the overall objective is to control the deck displacements. The SMA-based device, therefore, plays the role of a seismic restrainer. For continuous deck bridges, the overall objective is to control the seismic forces transmitted to all the piers. The SMA-based device, therefore, plays the role of a seismic absorber. The feasibility of the proposed SMA-based device has been evaluated through a number of nonlinear time-history analyses (NTHA) on two bridge structures representative of the existing Italian highway bridges. NTHA have been carried out both for the bridge in the as-built configuration and for the bridge equipped with SMA devices. The NTHA results of the analyses on the multi-span simply supported deck bridge show that the use of SMA-based restrainers determines a significant reduction of the deck displacements with a limited increase of the maximum force experienced by the piers. Moreover, the SMA-based restrainers prove to be effective in protecting abutments and bearing devices from damage, as observed in the as-built bridge condition. The NTHA results of the analyses on the continuous deck bridge show that the use of SMA-based shock absorbers can gives rise to a significant redistribution of the seismic force of the deck between all the piers, thus avoiding the failure of the pier with fixed bearing, as observed in the as-built bridge condition. At the same time, the maximum deck displacements are compatible with the available joint clearance. In presence of near-fault seismic ground motions, the attainment of the performance objectives of the seismic retrofit is guaranteed by the strong increase of stiffness experienced by the SMA device at the end of the martensite transformation.

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