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Numerical Studies on the Seismic Retrofit of Bridges Using Shape Memory Alloys

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Recent earthquakes have highlighted the seismic vulnerability of bridges due to excessive movements at the joints (in simply supported deck bridges) or concentration of seismic forces in a few piers (in multi-span continuous deck bridges). Steel-based seismic restrainers and viscous shock transmitters are used to limit the joint openings in simply supported deck bridges or to redistribute the seismic force among all piers in continuous deck bridges, respectively. Currently used devices, however, have some limitations such as large dimensions, no energy dissipation, possible large residual displacements, bad control of the force transmitted to the substructure (steel restrainers), large dimensions, difficulty of installation in existing structures, need of maintenance, and sensitivity to the earthquake characteristics (viscous shock transmitters). Shape memory alloys (SMAs) with superelastic behavior show the potential to overcome the limitations involved in the current technologies. In this article, 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 SMA devices is assessed through a number of nonlinear time-history analyses on two bridge structures representative of existing Italian highway bridges. Results are compared to the seismic response of the bridges in the as-built configuration.

Keywords bridges, nonlinear time-history analysis, seismic retrofit, shape memory alloys

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 in the majority of cases can be attributed to the old elastic-based design philosophy, coupled with a lack of attention to design details of the past seismic codes (Ref 1). This produced some deficiencies in strength and ductility of bridge piers, shear capacity of bearing devices and inadequate deck seat lengths on abutments and piers. Typical damages observed during past earthquakes (see Fig. 1) are pounding between adjacent decks, bearing failure with consequent deck unseating, especially in multi-span simply supported structures, and flexural/shear failure of bridge 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 1970s in the US and Japan. However, following earthquakes (1989 Loma Prieta, 1994 Northridge, and 1995 Kobe earthquake) demonstrated a number of cases of inefficiency of steel restrainers, with serious damage (e.g., restrainer failure, pounding damage, and permanent hinge opening) or collapse (e.g., unseating of supports and deck unseating) of many retrofitted bridges. Experimental tests of steel cable restrainers have also shown the main critical aspects of this retrofit technique, as 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 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 (FB) 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 dynamic excitation (e.g., 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 behavior to the earthquake characteristics.

Shape memory alloys (SMAs) with superelastic behavior (Ref 2) appear to be suitable candidates for the seismic retrofit of bridges (Ref 3-5), as they show the potential to overcome the limitations of steel restrainers and shock transmission units discussed before.

The superelastic properties of SMAs attractive for seismic retrofit applications include their hysteretic damping capacity, the excellent fatigue properties at large strain amplitudes, the strain hardening at the end of the forward transformation, the good force control during the phase transformation and the ability to return to their original (undeformed) shape at the end of the earthquake.

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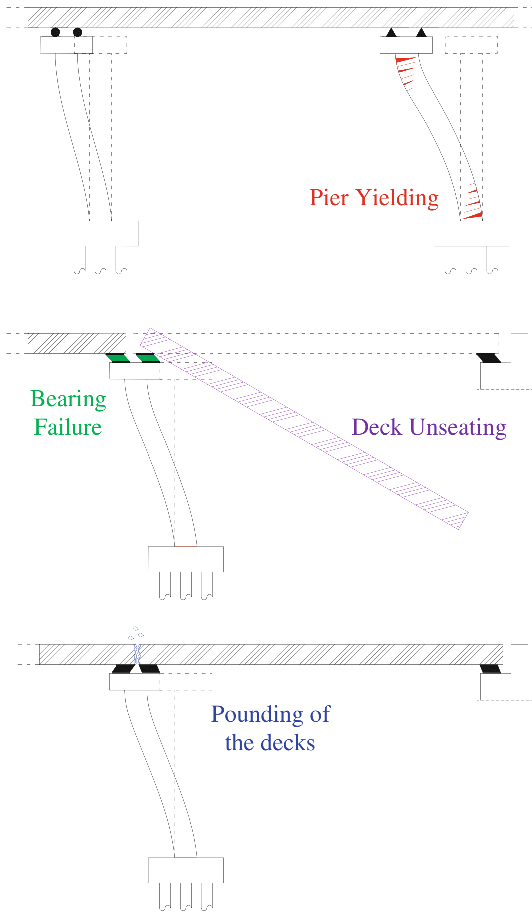

Fig. 1 Typical earthquake damages to bridges

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 (Ref 3, 6), SMA-based restrainers have been proposed to avoid deck unseating, while allowing pounding between adjacent decks.

In this article, 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. Basically, the SMA-based seismic restrainer is aimed at controlling the deck displacements while the SMA-based seismic absorber is aimed at controlling the seismic forces transmitted to the piers. 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. Shape Memory Alloys

2.1 Cyclic Behavior

SMAs are unique alloys that have the ability to undergo large deformations while returning to their undeformed shape by heating (shape memory effect) or on unloading (superelastic effect). Recently, there has been an increasing interest in using superelastic SMAs, usually in the form of bars or wires, for the applications in seismic resistant design of structures.

There are two crystal phases in SMAs: the austenite phase, stable at high temperatures, and the martensite phase, stable at low temperatures. The superelastic effect is based on a stress-induced martensite formation.

The austenitic phase of the material is stable before the application of stress. On loading, stress-induced martensite is formed up to large deformations of the order of 6-8%. After the conversion to stress-induced martensite, SMA experiences a sharp increase in stiffness, through the so-called detwining mechanism. On unloading, however, the material reverts to austenite at a lower stress, thereby resulting in the superelastic behavior.

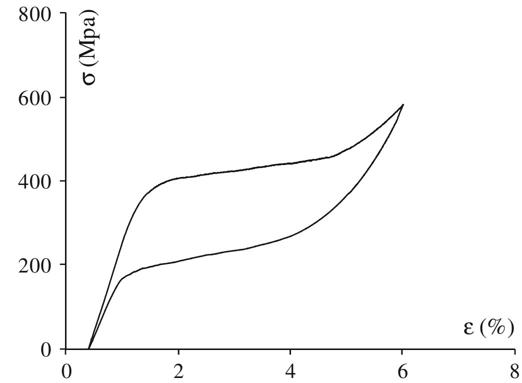

Fig. 2 Experimental loading-unloading stress-strain relationship of superelastic SMA wire

The cyclic behavior of SMA is sensitive to the number of cycles, especially in the first 10-15 cycles (Ref 7). For this reason, it is often desirable to submit the virgin material to a number of training cycles before applications. The cyclic behavior of SMA also depends on strain rate, especially when passing from very low frequency (0.01 Hz or less) to the frequency range of interest for seismic applications (0.2-4 Hz) (Ref 7). The SMA behavior is quite stable within the useful range for seismic applications (0.2-4 Hz), thus encouraging the use of superelastic wires.

Figure 2 shows the experimental stress-strain relationship considered for the calibration of the numerical model of the SMA devices described in the next section. It has been derived from a loading-unloading tensile test at 20 °C air temperature, 1 Hz frequency of loading, and 7% strain amplitude on a SMA wire previously trained by applying 20 cycles at the same strain amplitude.

2.2 Phenomenological Model for Seismic Applications

A rate independent constitutive model has been considered to describe the SMA superelastic behavior 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 behavior exhibited by SMA wires during cyclic tensile tests at 1 Hz frequency of loading (see Fig. 2), which represents a typical natural frequency of vibration of bridge structures.

Four spring elements have been used to reproduce the mechanical behavior of the proposed SMA-based seismic devices. The first element is an elastic spring element with

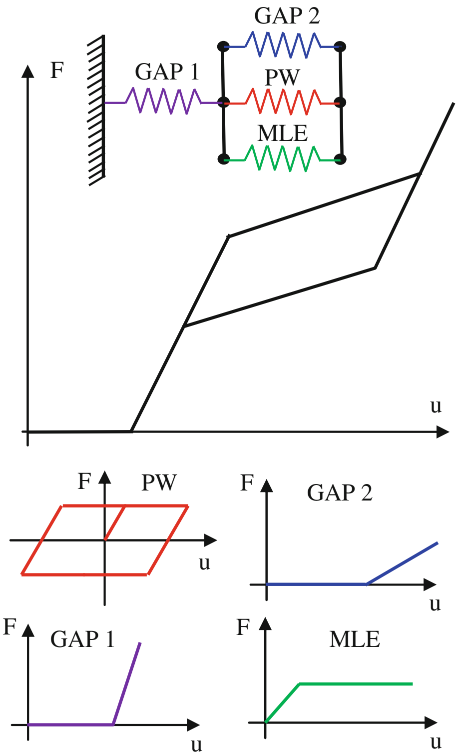

Fig. 3 Phenomenological model of SMA seismic devices for bridges

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 the absence of seismic excitation).

The GAP1 element is put in series with three nonlinear springs, working in parallel under the same horizontal displacement, modeling the axial force-displacement cyclic behavior of SMA wires. A multilinear elastic spring element (MLE in Fig. 3) is used to describe the nonlinear elastic behavior 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 (GAP2 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.

3. SMA-Based Seismic Devices for the Retrofit of Bridge Structures

3.1 Performance Objectives

The proposed SMA-based seismic restrainer has been designed to achieve a number of performance objectives (POs), which can be summarized as follows: (i) avoid bearing failure (PO1), (ii) avoid pounding between adjacent decks, as well as between deck and abutment (PO2), (iii) prevent span unseating (PO3), (iv) recenter the decks in their initial position at the end of the seismic excitation (PO4), (v) allow the thermal movements of the decks (PO5), (vi) give an adequate margin of safety for the structure in case of near-fault ground motions (PO6). The same device can be also used as shock absorber

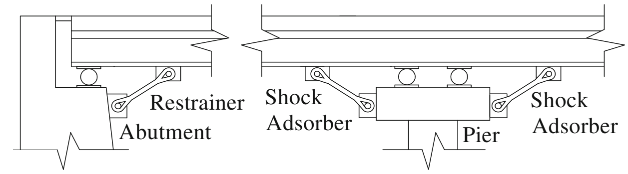

Fig. 4 Installation of the SMA devices on abutment (left) and pier (right)

system in continuous deck bridges to (vii) control the force transmitted to piers and abutments (PO7).

The achievement of the first four POs (PO1, PO2, PO3, and PO4) is strictly related to the superelastic properties of SMA wires, particularly to their large working strain range and hysteretic energy dissipation capability. The performance objective PO6 is realized by designing the SMA device to respond to "standard" seismic ground motions (i.e., far-fault earthquakes) within the superelastic strain range (typically with upper limit of the order of 6-7%) associated to the martensite transformation, while relying on the increase of stiffness, due to the elastic deformation of detwinned martensite found at the end of the phase transformation, to avoid damage under near-fault earthquakes. The performance objective PO7 is accomplished by exploiting the low post-elastic stiffness exhibited by superelastic SMA wires during the martensite transformation.

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. 4).

3.2 Case Studies

Two typical bridge configurations have been selected as case studies. The main structural characteristics of the two bridges have been derived from the examination of the bridge inventory of the A16 Italian highway. The schematic layout of the selected bridges is shown in Fig. 5.

The first bridge (Fig. 5a) 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 50 mm. The bridge has a regular layout, the deck being supported by two identical RC piers with 7.5 m height. The pier-deck connections are realized by neoprene pads (NP) and sliding bearings (SB), respectively. NP have 300 × 600 mm plan dimensions, 50 mm thickness, and approximately 1 MPa shear modulus. The mass of each deck is equal to 720 tons.

The bridge has been equipped with two systems of SMA restrainers working alternatively in the positive and negative longitudinal displacements of the decks. Each system includes three groups of SMA restrainers consisting in either 1000 (R2, R4, and R5 in Fig. 5a), 2000 (R6 in Fig. 5a) or 2500 (R1 and R3 in Fig. 5a) SMA wires with 2 mm diameter and 550 mm free length. The design displacement of the SMA restrainers has been set equal to 48 mm, based on the clearance of the available expansion joints (50 mm).

The second bridge (Fig. 5b) 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 50 mm. Also in this case, the bridge has a regular layout, the deck being supported by four identical RC piers with 7.5 m height. The pier-deck connections are realized by a series of FB, placed on the top of pier no. 4 and SB, placed

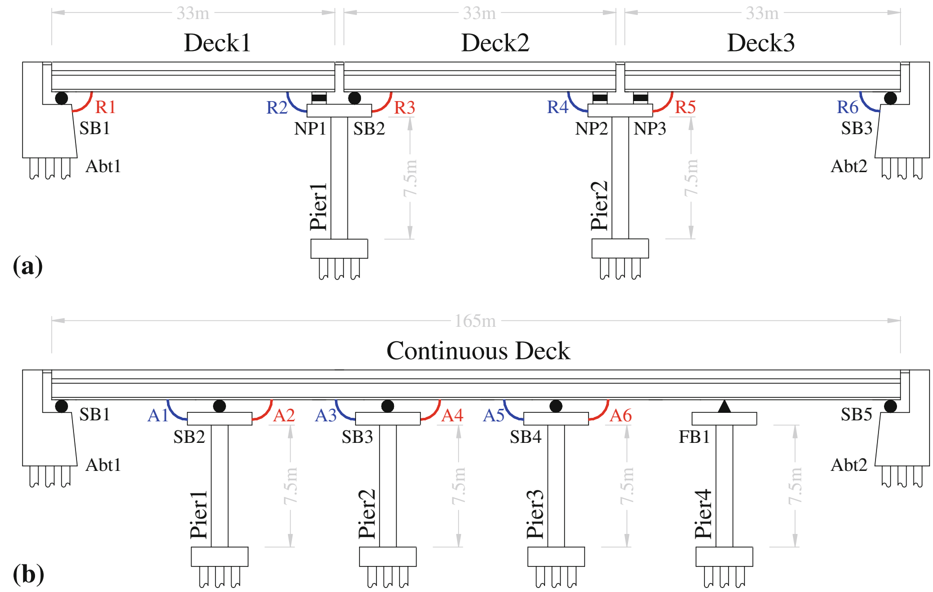

Fig. 5 Schematic layout of the examined (a) 3-span simply supported deck bridge and (b) 5-span continuous deck bridge

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 two systems of SMA shock absorbers working alternatively in the positive and negative longitudinal displacements of the decks. Each system includes three groups of SMA devices consisting in either 3500 SMA wires with 2 mm diameter and 350 mm free length. The design displacement of the SMA shock absorbers has been set equal to 35 mm, based on the yield displacement of the critical pier (40 mm).

3.3 Structural Modeling

In order to examine the longitudinal seismic response of the bridge structures described before, two 2-dimensional nonlinear numerical models have been implemented, using the finite element package SAP2000 Nonlinear (Ref 8). According to the structural component modeling (SCM) approach (Ref 1), 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 (see Fig. 6). The deck mass has been lumped in the center of mass of each deck. A tributary mass of the pier mass has been also taken into account.

A linear viscous-elastic behavior has been considered for NP, 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 NP and the friction resistance between neoprene and concrete sliding surfaces. In the case study under consideration, the shear resistance of NP 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 FB 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 FB has been estimated based on the geometric data available. During the analysis, the maximum shear force in the FB has been monitored. When the shear strength was prematurely exceeded, a post-failure frictional behavior, 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 behavior of the SB. As known, the friction coefficient depends on many parameters and factors, such as bearing type, sliding interfaces, state of lubrication and maintenance, bearing pressure, air temperature, sliding velocity, etc. (Ref 9). In the present study, a friction coefficient of 5% has been assumed for SB. Moreover, the maximum displacement capacity of the SB has been assumed equal to 100 mm.

Piers are supposed to remain elastic. The maximum shear force in the piers has been monitored and compared to the pier strength assumed equal to 10,000 kN. The horizontal stiffness of the piers has been taken equal to 250,000 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 (see Fig. 6). 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. Prior to gap closure, the deck force is transmitted through the bearing devices to the abutment wall and subsequently to piles and backfill, in a series system. After gap closure, the deck pushes directly on the abutment back wall, with the risk of mobilizing the passive backfill pressure. In this study, the horizontal stiffness and ultimate strength of the abutment have been derived from a combination of design recommendations (Ref 10) and experimental test results on seat-type abutments

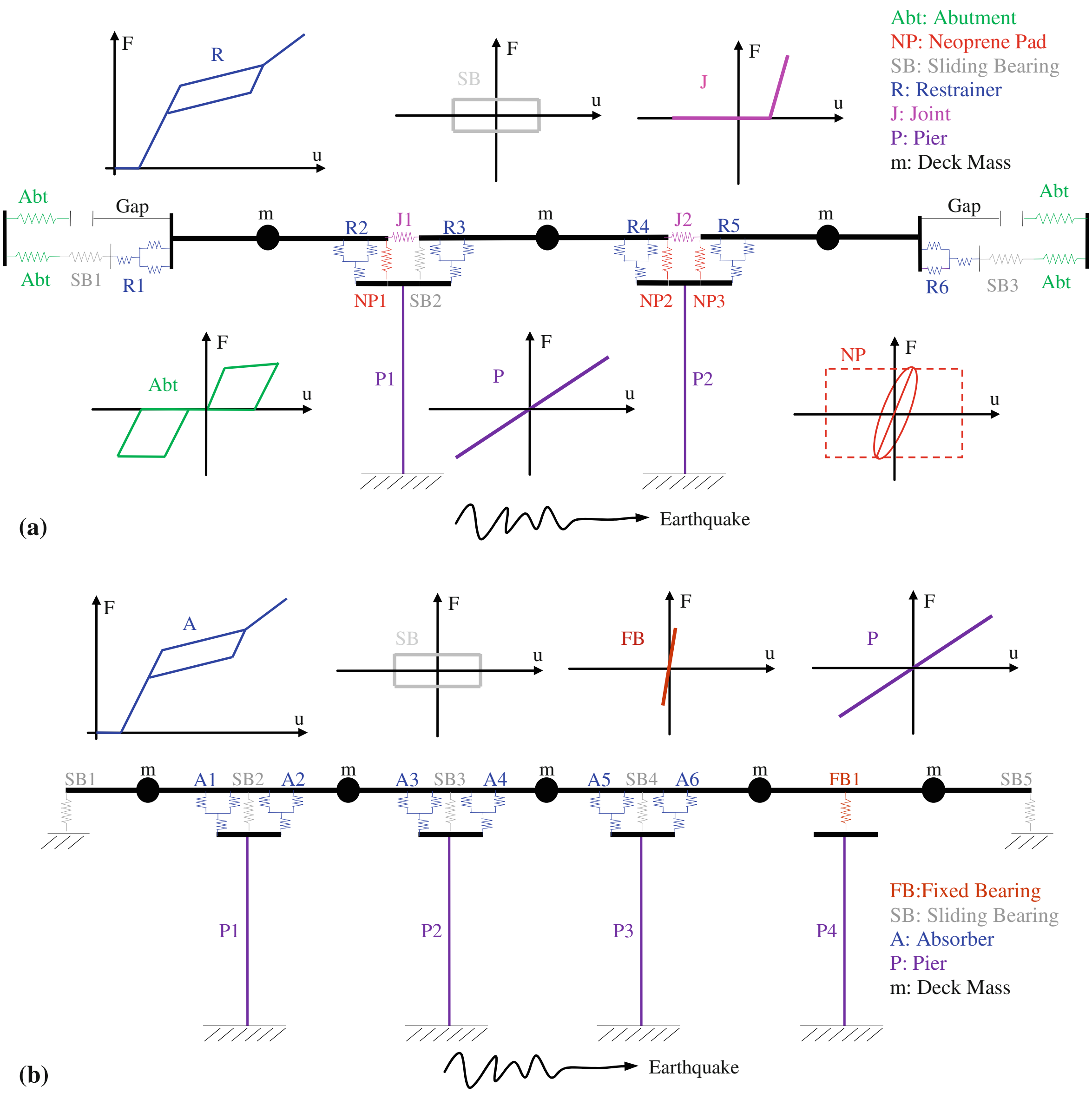

Fig. 6 Bridge numerical models and force-displacement relationships for the (a) multi-span simply supported deck bridge and (b) multi-span continuous deck bridge

with piles (Ref 11), as a function of the abutment back wall dimensions and pile characteristics.

The nonlinear numerical models of SMA-based seismic restrainers and shock absorbers have been described in Section 2.2.

3.4 Nonlinear Time-History Analyses

The effectiveness of SMA restrainers and shock absorbers has been evaluated through a number of 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 used (see Fig. 7), including (i) an artificial accelerogram compatible with the 5%-damped acceleration response spectrum provided by the Eurocode 8 for soil type C (Ref 12), (ii) the 0° component of the near-fault (0.3 km 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 (1.1 km 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 0.48 g 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 (Ref 12). Reference to the original (recorded) PGA values has been made for the natural near-fault records, equal to 0.61 and 0.57 g for the Kobe and Taiwan earthquakes, respectively.

Figure 8 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. 8a). The piers exhibit an elastic behavior with maximum shear force lower than 40% compared to their ultimate strength. The use of

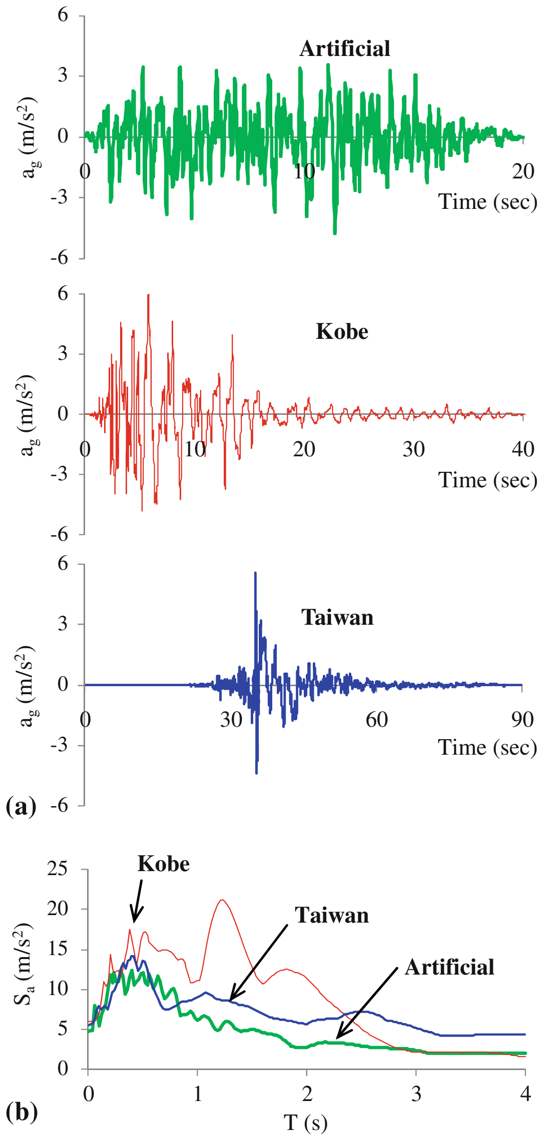

Fig. 7 (a) Input acceleration profiles used for numerical analyses and (b) associated 5%-damped response spectra

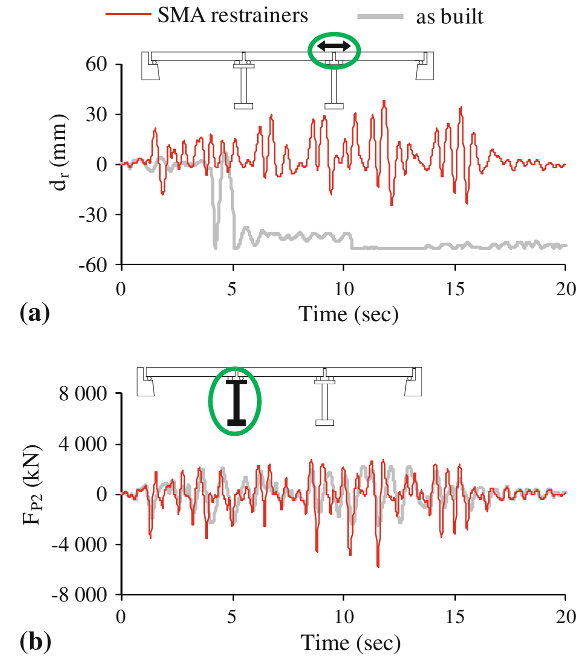

Fig. 8 Comparison between (a) joint (J2) displacement time histories and (b) pier (P1) force time histories, for the multi-span simply supported deck bridge subjected to the artificial accelerogram, with (thin line) and without (thick line) SMA restrainers

SMA restrainers determines a significant reduction of the relative displacements of the joints, which never exceed 40 mm, and a perfect recentering behavior while residual deck displacements of the order of 150 mm 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 the presence of SMA devices does not exceed the 60% of the pier yielding strength (see Fig. 8b).

The bridge in the as-built configuration suffers various damages, such as the attainment of the passive resistance of the abutments with consequent permanent deformations (Fig. 9a), the attainment of the maximum displacement capacity of SB (Fig. 9b), and the failure of NP (Fig. 9c). The presence of the SMA restrainers significantly reduces displacement and force levels, both in abutments and bearings, bringing them below the corresponding damage threshold values (see Fig. 9). The maximum displacement of the SB, in particular, does not exceed the 50% of their displacement capacity. NP respond elastically, attaining a maximum force that does not exceed the 90% of their shear resistance.

As shown in Fig. 10, all the SMA restrainers work perfectly within the strain range associated to the forward phase transformation (from austenite to detwinned martensite). The maximum displacements experienced by the SMA restrainers are very close to the design displacement of the device (48 mm), corresponding to the end of the martensite transformation in the SMA wires at 7% axial strain.

In the presence of near-fault seismic ground motions, the increase of stiffness due to the elastic deformation of detwinned martensite found at the end of the phase transformation (see Fig. 11), is fundamental to guarantee the respect of the performance objective of the design.

Under the Kobe earthquake (see Fig. 11), the SMA restrainers attain a maximum displacement of the order of 58 mm, which produces a maximum strain in the SMA wire close to that associated to the appearance of plastic deformations (9%).

Figure 12 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 FB considerably overcomes (by about two times) the shear strength of the pier. The activation of the SMA shock absorbers placed on the three piers with SB determines a redistribution of the seismic force between the piers that avoid the failure of the pier with fixed bearing (see Fig. 12a). At the same time, the increment of shear force in the piers with SB does not cause any damage (see Fig. 12b), 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 40 mm, i.e., lower than the clearance of the abutment joints.

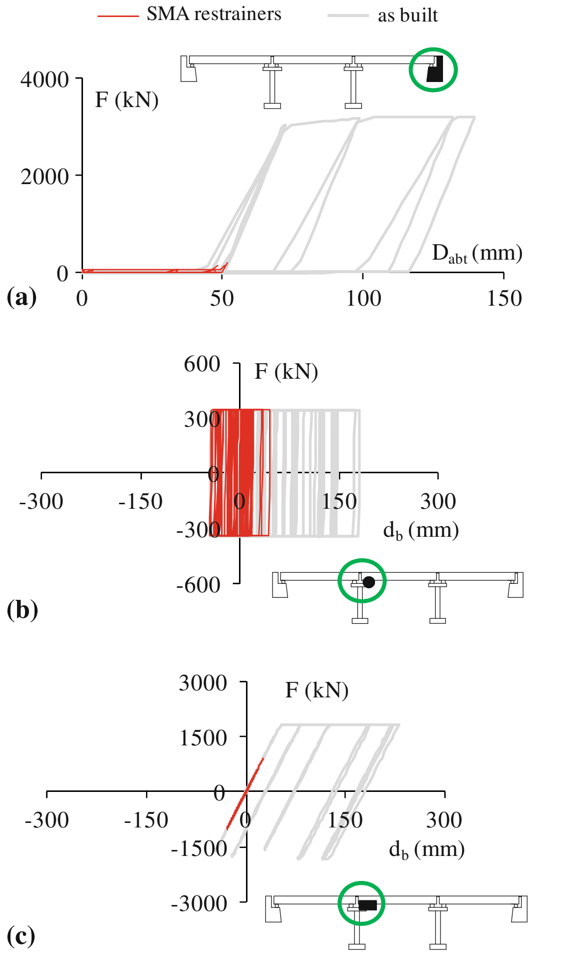

Fig. 9 Comparison of the cyclic behaviors of (a) abutment (Abt2), (b) sliding bearings (SB2), and (c) neoprene pads (NP1), for the multi-span simply supported deck bridge subjected to the artificial accelerogram, with (thin line) and without (thick line) SMA restrainers

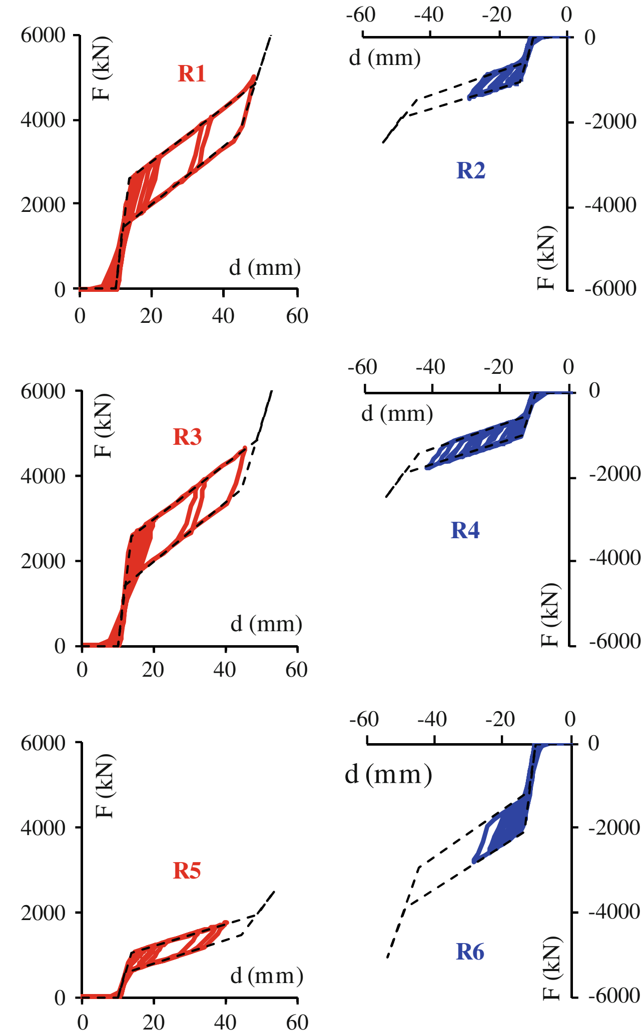

Fig. 10 Cyclic behavior of the SMA restrainers for bridge subjected to the artificial accelerogram

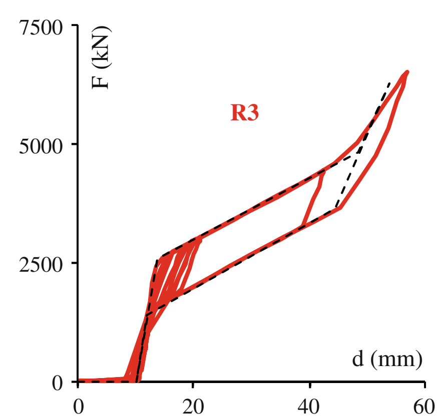

Fig. 11 Cyclic behavior of the SMA restrainers for bridge subjected to the Kobe near-fault earthquake

As shown in Fig. 13, 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 30 mm, i.e., compatible with the design displacement of the device (35 mm).

The SMA shock absorbers are able to ensure a good redistribution of the seismic force between all the piers also for near-fault earthquakes. Also in this case, a fundamental role in the attainment of the performance objective of the seismic retrofit is played by the rapid increase of stiffness at the end of the martensite transformation (see Fig. 14). The use of SMA shock absorbers, indeed, determines a reduction of the maximum (elastic) seismic demand to the pier with FB by about three times, which results compatible with the pier yielding strength. At the same time, also for the piers with SB the maximum force transmitted by the SMA shock absorbers never exceeds the pier yielding strength.

4. Conclusions

In this article, 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

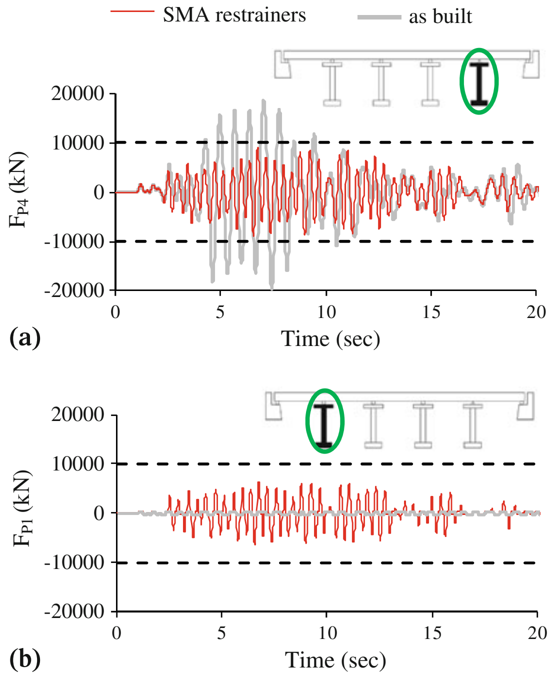

Fig. 12 Comparison between the shear force-time histories of the pier (a) with fixed bearings (P4) and (b) with sliding bearings (P1), for the continuous deck bridge subjected to the artificial accelerogram, with (thin line) and without (thick line) SMA shock absorbers

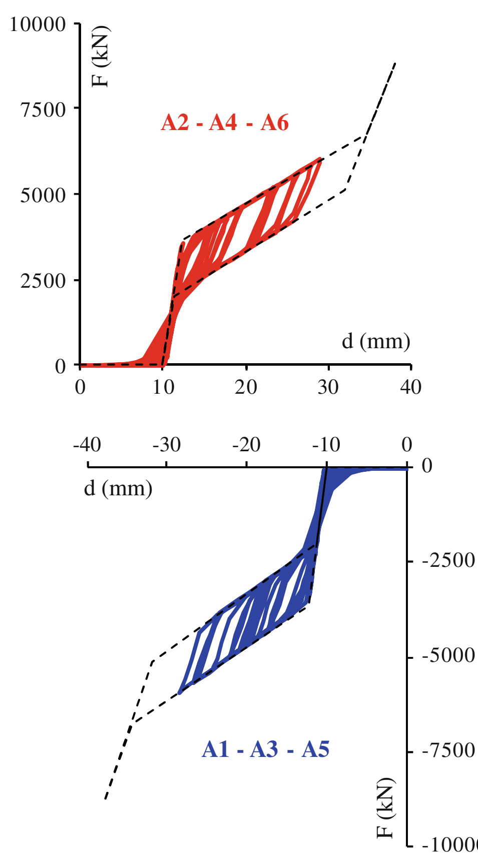

Fig. 13 Cyclic behavior of the SMA shock absorbers for bridge subjected to the artificial accelerogram

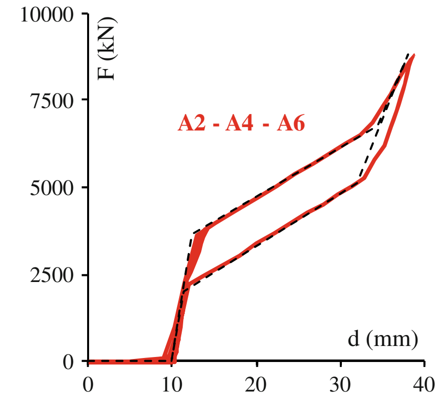

Fig. 14 Cyclic behavior of the SMA shock absorbers for bridge subjected to the Taiwan near-fault earthquake

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 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 (by about 70%, based on the analyses conducted) of the deck displacements with an increase (by about 50%, based on the analyses conducted) 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. Based on the outcomes of this study, the ratio between the maximum force and the pier yielding strength does not exceed 90%, in the presence of SMA-based shock absorbers, for all the piers of the bridge. At the same time, the maximum deck displacements are compatible with the available joint clearance.

In the presence of near-fault seismic ground motions, the attainment of the POs 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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