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Seismic retrofit of simply supported bridges using shape memory alloys

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Abstract

Recent earthquakes in the United States and Japan have highlighted the vulnerability of bridges to collapse due to excessive movement at the intermediate hinges and abutments. This study investigates the effectiveness of shape memory alloy restrainer bars to reduce the seismic vulnerability of bridges. Full-scale tests of shape memory alloy (SMA) restrainer bars are conducted to determine their force-deformation and energy dissipation characteristics. The 25.4 mm diameter bars are subjected to cyclical strains up to 8%, with minimum residual deformation. The effectiveness of the SMA restrainer bars in bridges is assessed through nonlinear analyses of a typical multi-span simply supported bridge. The SMA restrainer bars are effective in limiting the relative displacement at the piers and abutments. In addition, the bars are shown to be very effective for near-field ground motion. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Restrainers; Shape memory alloys; Bridges; Seismic; Retrofit; Nitinol

1. Introduction

The damage to bridges in the recent Chi-Chi [1,2], Kobe [3,4], and Northridge earthquakes [5,6] indicate the need to provide better methods of reducing the damaging effects of earthquakes in bridges. Retrofit measures to reduce the likelihood of collapse due to unseating at the supports have been in place for many years. The use of restrainer cables and restrainer bars to limit the relative hinge displacement became popular in the United States following the collapse of several bridges due to loss of support during the 1971 San Fernando earthquake [7]. Recent earthquakes have demonstrated that restrainers were effective in some cases. However, many bridges with restrainers sustained serious damage or collapse [6]. Bridges that had been retrofitted with restrainer cables failed in both the 1989 Loma Prieta and 1994 Northridge earthquakes. Failure of Japanese restraining devices also occurred during the 1995 Kobe earthquake [4]. Experimental tests of restrainer cables have shown that failure occurs in the connection elements or the through-punching shear in the concrete diaphragm [8]. In addition, restrainers do not dissipate any significant amount of energy, since they are generally designed to remain elastic. Analytical studies of bridge and restrainer systems have demonstrated that a very large number of restrainers is often required to limit joint movement to acceptable levels, particularly for high seismic loads [9]. In those cases, the excessive number of restrainers would induce large forces in other components of the bridge, such as bearings and columns.

The shortcomings of traditional restrainers can potentially be addressed with the use of shape memory alloy (SMA) restrainers. The SMA restrainers, in the superelastic phase, act as both restrainers and dampers. Shape memory alloys have the ability to dissipate significant energy through repeated cycling without significant degradation or permanent deformation. Their usable strain range is on the order of 6–8%, which provides them with very high energy dissipation per unit mass of material.

Grasser and Cozzarelli [10] evaluated the use of Nitinol SMAs as seismic dampers. They studied the effect of loading frequency and history on the energy dissipation characteristics of Nitinol wires. They also proposed a one-dimensional constitutive model for the pseudo-elastic behavior and verified the model with experimental work. Inaudi and Kelly [11] studied a four-story steel-frame model with tuned mass dampers using shape

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memory alloy wires, tested on a unidirectional shaking table. They found significant improvement in the building response when the prestress tension was tuned to the first natural frequency of the isolated structure. Sweeney and Hayes [12] and Clark et al. [13] found that SMA wires can reduce displacements and accelerations in structures, though the extent of reduction varied between the different studies.

Recent studies in Japan have evaluated the use of SMAs in bridges. Wilde et al. [14] performed an analytical study of a base isolation system with an SMA device. They found that the device can limit displacement and dissipate energy from an earthquake. Adachi and Unjoh [15] performed a reduced-scale study of an SMA plate damper used as an energy dissipator in bridges. Their study found that shape memory alloys are most effective when used in the martensitic or 'shape memory' phase, as opposed to the austenitic or 'superelastic' phase.

While the studies above have focused on either reduced-scale tests or analytical studies, there are currently few results of full-scale tests of SMA devices for bridge applications. In this study, a full-scale test of an SMA restrainer is presented. A 25.4 mm SMA restrainer bar is developed and tested under cyclical loads in tension. The results of the experimental tests are used to develop an analytical model of the SMA restrainer, which is used to evaluate the effectiveness of the restrainer in multi-span simply supported bridges.

2. Shape memory alloys

Shape memory alloys are a class of alloys that display several unique characteristics, including Young's modulus-temperature relations, shape memory effects, and high damping characteristics. While shape memory alloys have been commercially available since the 1960s, their application has been limited. In most current applications, the temperature-induced phase change characteristic of shape memory alloys is used. For some SMAs, such as Nitinol (NiTi SMA), the phase change can be stress-induced at room temperature if the alloy has the appropriate formulation and treatment. The stress-induced shape memory property (known as superelasticity) is based on a stress-induced martensite formation. The austenitic phase of the material is stable before the application of stress. However, at a critical stress level the martensite becomes stable, causing yielding and a stress plateau, as shown in Fig. 1. Since the martensite is only stable because of the applied stress, the austenite structure again becomes stable during unloading, and the original undeformed shape is recovered.

Nitinol shape memory alloys (NiTi SMAs) possess several characteristics that make them desirable for use as restrainers in bridges, as shown in Table 1. These characteristics include: (1) large elastic strain range; (2) hysteretic damping; (3) highly reliable energy dissipation based on a repeatable solid state phase transformation; (4) strain hardening at strains above 6%; (5) excellent low- and high-cycle fatigue properties; and (6) excellent corrosion resistance [16]. The primary features of the superelastic effects of shape memory alloys are shown in the stress–strain relationship in Fig. 1. The stress–strain relationship is characterized by an elastic region, a long horizontal plateau, followed by a significant increase in stiffness. As evident in Fig. 1, NiTi SMAs demonstrate a high level of energy dissipation and a superelastic hysteresis. Another very useful characteristic of superelastic NiTi SMAs is that they harden after conversion to stress-induced Martensite, at approximately 6–8% strain. This property can be particularly useful for using SMAs as hinge restrainers. The added stiffness at large strains provides additional protection from unseating as the relative hinge opening approaches the critical value.

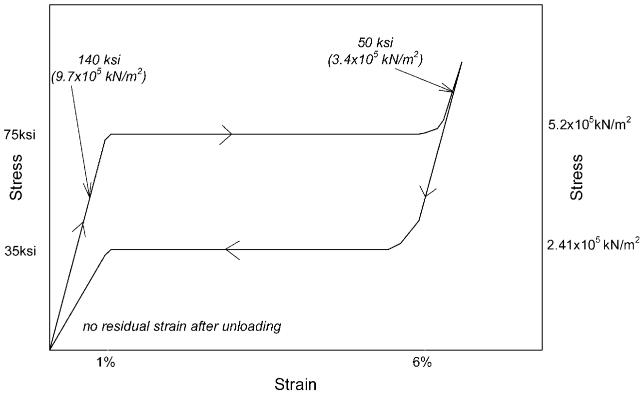

Fig. 1. Idealized stress–strain relationship for superelastic shape memory alloys ($M_d > T > A_f$).

3. Experimental test of shape memory alloy damper

In the first phase of the study, a full-scale SMA restrainer bar is tested. The restrainer consists of a 280 mm long, 25.4 mm diameter Nitinol shape memory alloy bar, as shown in Fig. 2. The SMA bars are fully annealed and 25% cold-worked. The samples are threaded at the ends and vacuum annealed at 450°C for 60 min, followed by water quenching. The testing was performed at room temperature (22°C), at a strain rate of 0.10 mm/mm/s.

The stress–strain curve of the NiTi damper under tension cyclic loading is shown in Fig. 3. The specimens were loaded at increasing strains ranging from 0.5 to 8.0% strain. Several features of the stress–strain diagram can be distinguished. The damper has a loading plateau stress of approximately 450 MPa (65 ksi), with strain

Table 1
Comparison of NiTi shape memory alloy properties with typical structural steel

Property	Ni–Ti shape memory alloy	Steel
Recoverable elongation	8%	0.2%
Young's modulus	8.7E4 MPa (Austenite), 1.4–2.8E4 MPa (Martensite)	2.07×10^5 MPa
Yield strength	200–700 MPa (Austenite), 70–140 MPa (Martensite)	248–517 MPa
Ultimate tensile strength	900 MPa (fully annealed), 2000 MPa (work hardened)	448–827 MPa
Elongation at failure	25–50% (fully annealed), 5–10% (work hardened)	20%
Corrosion performance	Excellent (similar to stainless steel)	Fair

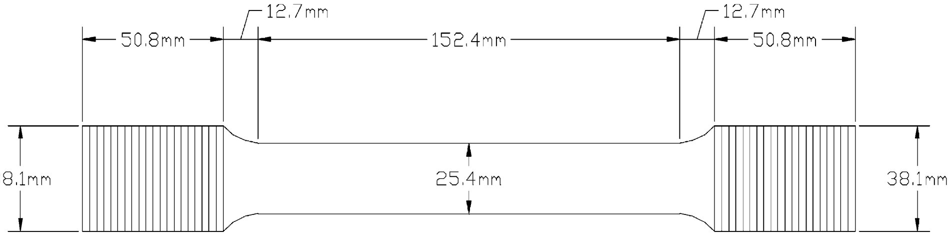

Fig. 2. Nitinol SMA restrainer bar used in experimental test.

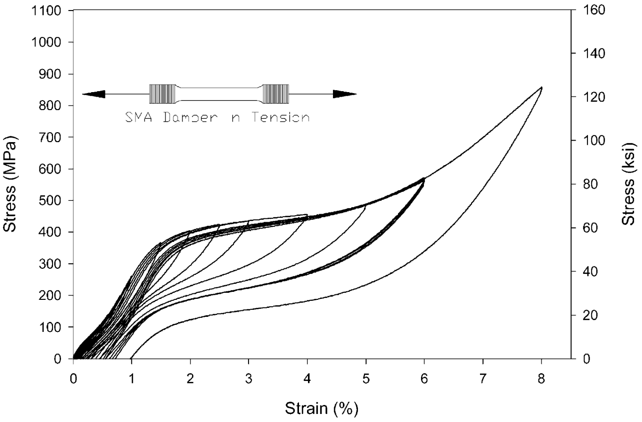

Fig. 3. Stress–strain curve from tension test of SMA restrainer bar.

hardening of approximately 7%. Fig. 3 also illustrates the dependence of the residual strain and unloading plateau on the total strain deformations. The residual strain increases with increasing total stain. For total strains less than 4%, the residual deformation is less than 0.25%. After a total strain of 8%, the bar showed approximately 1% residual strain. The 1% residual strain value indicates that slip began to contribute to the overall deformation. Previous studies of SMA wires show that slip occurs for strain values between 8–10% [16]. Fig. 3 also shows a second important effect of the strain. Although the loading plateau remains constant, the unloading plateau decreased as the total deformation increased. This important effect results in significantly more energy dissipation for larger strain values. For the SMA bar tested in this study, the unloading plateau ranged from 140–200 MPa (20–29 ksi). Finally, the specimen began to significantly strain harden after approximately 5–6% strain, with a stiffness that is approximately 45% of its initial stiffness.

4. Application of SMA restrainer to multi-span bridge

The relative displacement of multi-span simply supported bridges at the hinges and abutments can result in collapse of the bridge if it exceeds the allowable displacement [17]. The use of the SMA restrainers can provide a more effective alternative for limiting relative hinge displacement than conventional restrainer cables or restrainer bars. The SMA restrainers can be designed to provide sufficient stiffness and damping to limit the relative hinge displacement below a pre-determined value. The multi-span bridge considered in this analysis consists of three spans supported on multi-column bents, as shown in Fig. 4. Each bent has four columns and each span has 11 girders. The span lengths are 12.2 m (40 ft), 24.4 m (80 ft), and 12.2 m (40 ft), and the width is 20.4 m (64 ft). The concrete slabs are supported by steel girders resting on elastomeric bearings. The gap between the deck and abutment is 38.1 mm (1.5 in.) and the gap between decks is 25.4 mm (1.0 in.). The SMA restrainers would be connected from pier cap to the bottom flange of the beam in a manner similar to typical cable restrainers, as shown in Fig. 5. Connection to the bottom flange will prevent the possibility of tearing of the web and will provide a relatively simple retrofit. The restrainers would typically be used in a tension-only manner, with a thermal gap provided to limit the engaging of the restrainer during thermal cycles. If adequate lateral bracing could be provided, the restrainers can be made to act in both

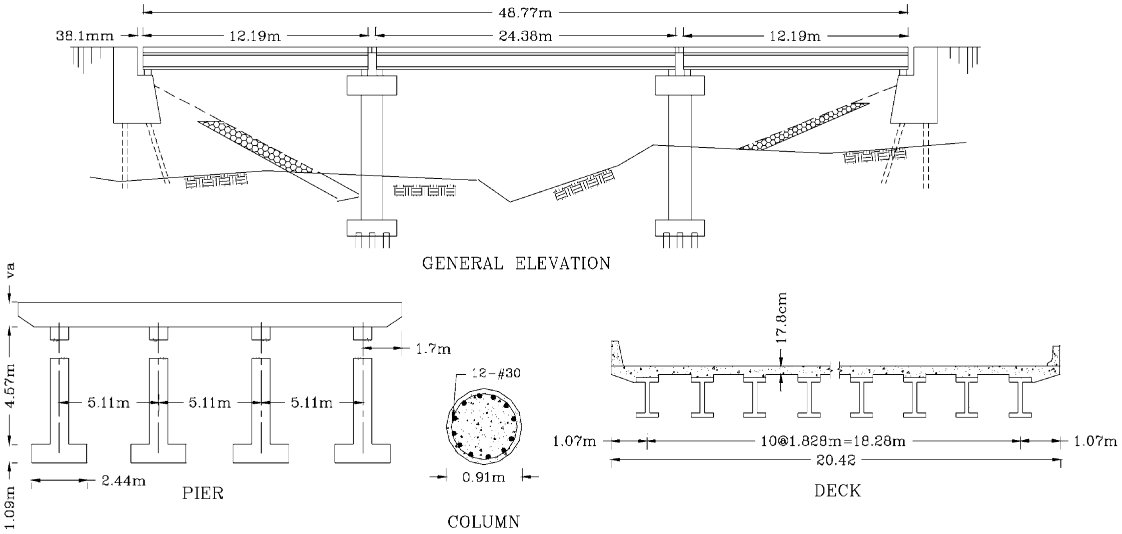

Fig. 4. Typical multi-span simply supported bridge.

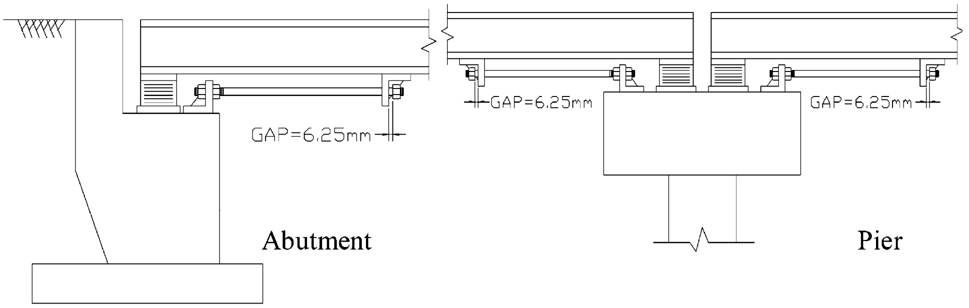

Fig. 5. Configuration of shape memory alloy restrainer bar used in multi-span simply supported bridge at abutments and intermediate piers.

tension and compression. In this study, only tension behavior is considered. Below, a nonlinear analytical model is used to investigate the response of multi-span simply supported bridges retrofitted with the SMA restrainers.

5. Analytical modeling of the multi-span simply supported bridge

A two-dimensional nonlinear numerical model of the three span, simply supported bridge shown in Fig. 4 is developed using the DRAIN-2DX nonlinear analysis program [18]. The superstructure is modeled using linear elastic elements, with properties based on full composite action between the deck-slab and steel girders. The columns are modeled using the DRAIN-2DX fiber element. Each fiber has a stress–strain relationship, which can be specified to represent unconfined concrete, confined concrete, and longitudinal steel reinforcement. The distribution of inelastic deformation and forces is sampled by specifying cross-section slices along the length of the element.

The nonlinear abutment properties used in this model are based on a combination of design recommendations from Caltrans and experimental tests of abutments [19,20]. An impact element is used to model pounding between the decks in the bridge and pounding between the deck and abutment. The compression-only trilinear gap element has springs that penalize closing of the gap. The elastomeric bearings are modeled with a bilinear element with strain hardening.

6. Analytical model of SMA restrainer

Using the results of the experimental tests, an analytical model of the SMA restrainer is developed using a combination of link and connection elements in DRAIN-2DX, as shown in Fig. 6. The SMA restrainers are modeled as tension-only multi-linear elements and represent the force-displacement relationship of the SMAs, including the yield plateau and unloading plateau. The restrainers are modeled with a ‘yield’ strength of approximately 410 kN/mm^2 (60 ksi), and unloading ‘yield’ strength of approximately 140 kN/mm^2 (20 ksi). As previously mentioned, the unloading stress and residual deformation depends on the total deformation. In the

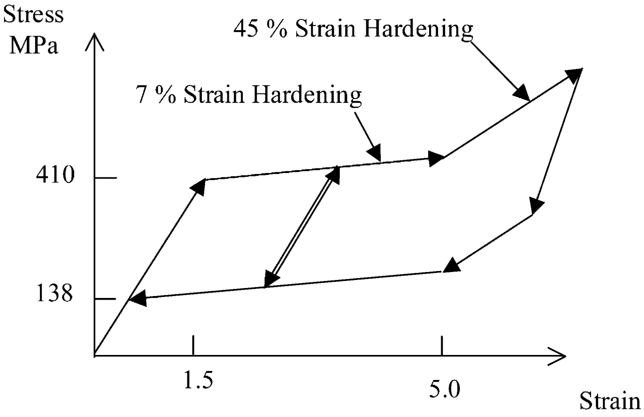

Fig. 6. Analytical model of SMA restrainer used in DRAIN-2DX.

model used in this study, the residual deformation is taken as zero, and the unloading stress is kept constant, based on the average value over the strain range tested. Parametric studies conducted showed that small variations in the parameters used in the analytical model for the residual deformation and the unloading stress have a negligible effect on the response. Seven percent strain hardening is assumed up to 5% strain and 45% strain hardening is assumed for strain beyond 5%, as determined by the experimental tests.

In this study, comparisons will be made between the SMA restrainer and commonly used steel restrainer cables. The steel restrainer cables evaluated are 1.52 m (5 ft) long, 19.1 mm (3/4 in.) diameter cables that stretch approximately 30.5 mm (1.2 in.) at a yield strength of 174 kN (39.1 kips), and 53.3 mm (2.1 in.) at an ultimate strength of 236 kN (53 kips). The conventional restrainer cables are modeled as bilinear springs that only resist tensile forces.

7. Results

To evaluate the effectiveness of the SMA restrainers, an analytical model of the example bridge shown in Fig. 4 is subjected to a set of ground motion records, including the 1940 El Centro (N-S), and the JMA Kobe Record (1995 Kobe Earthquake). The bridge response is evaluated for the case with 1.52 m (5 ft) restrainer cables, and 0.61 m (2 ft) long, 19.1 mm (3/4 in.) diameter SMA restrainer bars, both with a slack of 6.35 mm (1/4 in.).

Fig. 7 shows the response history of relative displacement between the deck and abutment 2 for the bridge subjected to the 1940 El Centro ground motion record, scaled to 0.70 g PGA. The maximum relative displacement of approximately 84.6 mm occurs in the as-built bridge. The use of restrainers at the abutments and piers reduces the maximum relative displacement to 63.8 mm, a reduction of 24% of the original displacement. The SMA restrainers, however, reduce the maximum relative displacement to 49.0 mm, a reduction of 42% of the original displacement. There are several reasons for the effectiveness of the SMA restrainers compared to the restrainer cables. First, since the restrainers are superelastic, they have the ability to maintain their effective stiffness for repeated cycles. Reviewing the response history plot, it is observed that the restrainer cables are effective in limiting the displacement during the first two seconds of loading. However, at approximately two seconds into the response, the restrainers are subjected to their maximum deformation of approximately 57 mm, resulting in yielding of the cable. In subsequent loading cycles, the effectiveness of the restrainers is significantly reduced due to the large residual deformation in the cable. Large deformations of approximately 55 mm occur at 6 s and again at 12 s in the response history. The response history plot shows that, in general, the displacement of the deck with conventional restrainer cables is similar to the case of the as-built bridge for the remainder of the response history. This effect is also observed in the force-deformation plot of the restrainer cable shown in Fig. 8. In contrast to the restrainer cable, the SMA restrainer is effective for repeated cycles, as shown in the response history plot in Fig. 7. Although the SMA restrainers are subjected to a maximum deformation of 40 mm at approximately 2 s in the response, the restrainers remain effective for repeated cycles.

Another reason the SMA restrainers are effective in limiting the relative displacement of the bridge deck is because of the energy dissipated by the restrainers. A comparison of the energy dissipated by the SMA restrainers and the restrainer cables, represented by the area enclosed by the force-deformation relationship, shows the SMA restrainers dissipated only slightly more energy than the steel cable restrainers. This indicates that the effectiveness of the SMA restrainers comes primarily from its ability to remain elastic over repeated loading cycles.

To evaluate the effectiveness of the SMA restrainers to near-field ground motion, the response of the bridge to the 1995 JMA Kobe record is evaluated. The JMA Kobe was recorded within 5 km of the epicenter of the 1995 Kobe earthquake and has a peak ground acceleration of 0.82 g. Near-field ground motions include large pulses that may greatly amplify the dynamic response of long period structures, particularly if structures deform in the inelastic range [21]. The response history of the relative displacement between the deck and abutment 2 for the bridge subjected to the JMA Kobe record is shown in Fig. 9. As expected, the near-field ground motion produced large relative displacements in the as-built structure. The maximum relative displacement at abutment 2 is 134 mm. The analysis with restrainer cables shows that the cables reduce the hinge displacement to 88.4 mm, a reduction of 34%. The SMA restrainers, however, significantly reduced the relative dis-

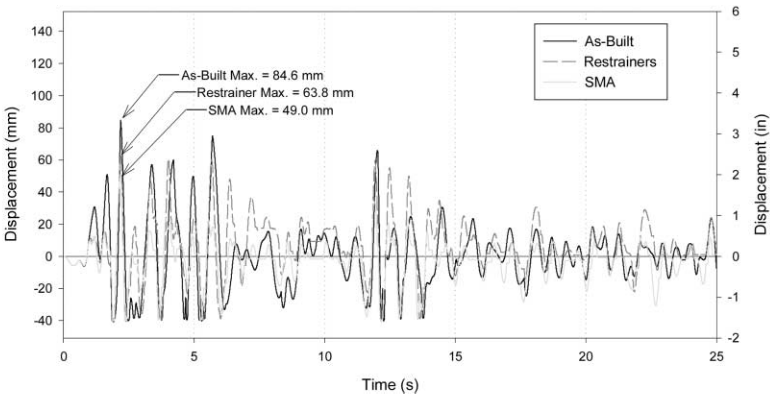

Fig. 7. Comparison of abutment 2 displacement response history for bridge in as-built condition, with cable restrainers, and with SMA restrainers (1940 El Centro record, scaled to 0.70 g PGA).

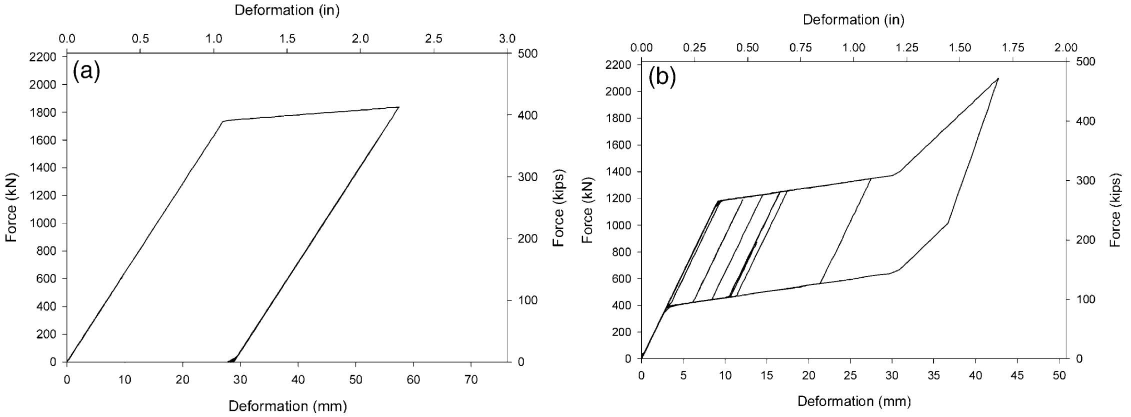

Fig. 8. Force deformation relationship for cable restrainer (left) and shape memory alloy restrainer (right) for bridge subjected to 1940 El Centro record, scaled to 0.70 g PGA.

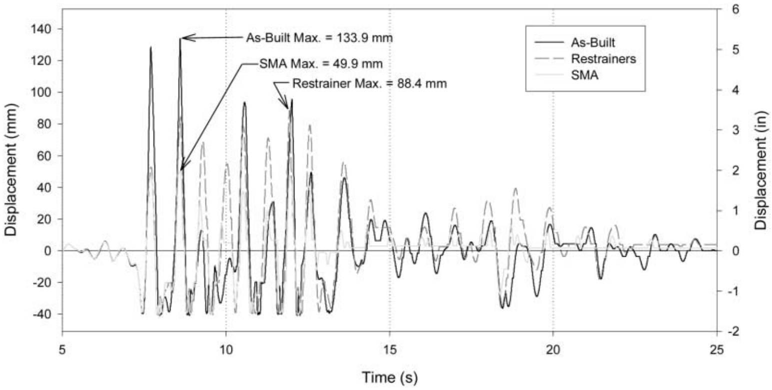

Fig. 9. Comparison of abutment 2 displacement response history for the bridge in as-built condition, with cable restrainers, and with SMA restrainers (JMA Kobe record, 1995 Kobe earthquake).

placement at the abutment. The displacement with the SMA restrainers, 49.9 mm, represents a 63% reduction in the relative displacement at the abutment.

Fig. 10 shows the force displacement relationship for the cable restrainer and SMA restrainer bar in the case of the JMA Kobe record loading. The large pulses from the near-field record produced early yielding in the cable restrainer, which essentially reduced their effectiveness for the remainder of the ground motion record. This resulted in the maximum relative hinge displacement occurring later in the response history. However, the SMA restrainer was able to resist repeated large cycles of deformation while remaining elastic. This resulted in a large effective stiffness and moderate energy dissi-

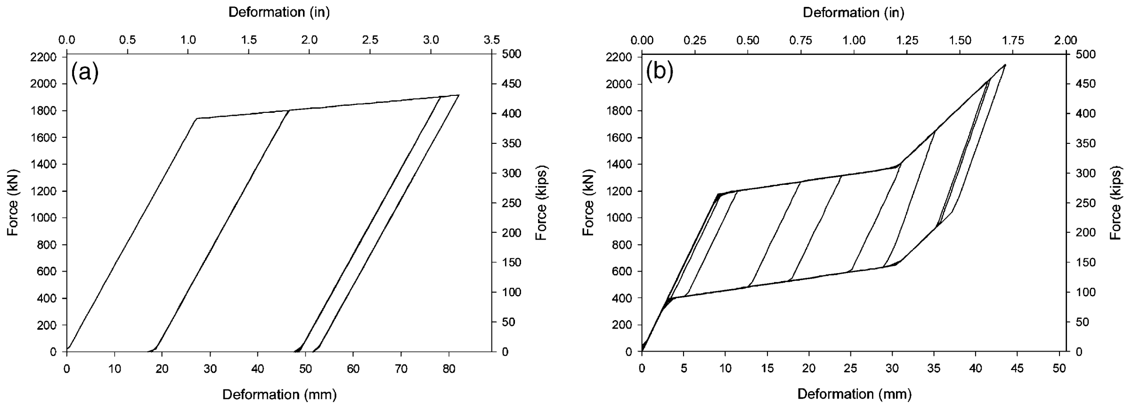

Fig. 10. Force deformation relationship for restrainer cable (left) and SMA restrainer (right) for bridge subjected to JMA Kobe record, 1995 Kobe earthquake.

pation. At the time when the restrainer cables had a maximum hinge displacement of 88.4 mm, the corresponding displacement in the case with the SMA restrainers was only 45 mm, as shown in Fig. 9. In addition, for the large strain values, the SMA restrainer has a significant increase in stiffness, due to strain hardening, which provides additional resistance to the relative opening between the deck and abutment. This analysis illustrates that the SMA restrainers can be extremely effective in limiting the response of bridges subjected to near-field ground motion.

8. Conclusions

This paper presents the results of a study evaluating the efficacy of using SMA restrainers to reduce the response of decks in a multi-span simply supported bridge. Full-scale tests of 25.4 mm diameter SMA restrainer bars subjected to uniaxial tension are conducted. The bars are subjected to cyclical strains up to 8% with minimum residual deformation. The effectiveness of the SMA restrainer bars in bridges is evaluated through an analytical study of a multi-span simply supported bridge. The relative hinge displacement in a bridge is compared for retrofits using conventional steel restrainer cables and SMA restrainer bars. The results show that the SMA restrainers reduce relative hinge displacements at the abutment much more effectively than conventional steel cable restrainers. The large elastic strain range of the SMA restrainers allows them to undergo large deformations while remaining elastic. In addition, the superelastic properties of the SMA restrainers results in energy dissipation at the hinges. Finally, evaluation of the multi-span simply supported bridge subjected to near-field ground motion shows that the SMA restrainer bars are extremely effective for limiting the response of bridge decks to near-field ground motion. The increased stiffness of the SMA restrainers at large strains provides additional restraint to limit the relative openings in a bridge.

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