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Uniform Distribution of Ductility Demand in Irregular Bridges using Shape Memory Alloy

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***Abstract*—**Excessive ductility demand on shorter piers is a common problem for irregular bridges subjected to strong ground motion. Various techniques have been developed to reduce the likelihood of collapse of bridge due to failure of shorter piers. This paper presents the new approach to improve the seismic behavior of such bridges using Nitinol shape memory alloys (SMAs). Superelastic SMAs have the ability to remain elastic under very large deformation due to martensitic transformation. This unique property leads to enhanced performance of controlled bridge compared with the performance of the reference bridge. To evaluate the effectiveness of the devices, nonlinear time history analysis is performed on a RC single column bent highway bridge using a suite of representative ground motions. The results show that this method is very effective in limiting the ductility demand of shorter pier.

***Keywords*—**bridge, ductility demand, irregularity, shape memory alloy

I. Introduction

POOR performance of bridges, especially irregular bridges, in the recent Chi-Chi, Kobe and Northridge earthquakes highlighted the need to devise better methods of reducing the damaging effects of earthquakes. Such damage to bridges can cause significant disruption to the transportation network, posing a threat to emergency response as well as leading to severe direct and indirect economic losses for a region. Due to rough topography of mountain valleys or urban transportation requirements, construction of irregular bridges with unequal height is often inevitable. Main problems with bridges with different column heights are listed below:

- Deformation demands on piers are highly irregular and excessive ductility demands occur in shorter piers.
- Stiffness irregularities cause concentration of seismic shear forces in the shorter columns, so brittle shear failure is possible.
- Sequential yielding of ductile members may cause significant deviations of the results from linear analyses performed with assumption of a global response modification factor in force based seismic design procedures.
- Irregular bridges are highly sensitive to excitation above design earthquake. That is, while regular bridges are able to withstand twice the design loads, the increase of 20 percent in the intensity of input action can significantly increase the displacement ductility demand of shorter pier in irregular bridges and cause them to collapse [1]-[5].

However, designers sometimes do use some techniques for balancing the stiffness of adjacent bents such as 'pre-shafts' (upward extensions of the foundation shaft) that increase the effective height of shorter piers, combination of monolithic and bearing deck to pier connections or adjusting stiffness characteristics of bearings placed at different bents. Although these techniques lead to more balanced stiffness of adjacent bents, but often tend to increase the overall cost of the bridge and require regular maintenance [6]-[7].

This paper examines a new approach for balancing the ductility demand in irregular bridges using Nitinol shape memory alloy. The proposed method is new and innovative in which the susceptibility to collapse is limited and also it improves the seismic behavior of bridges.

II. Shape memory alloy

Shape Memory Alloys (SMA's) are class of alloys that display unique characteristics, based on thermoelastic martensitic transformation [8]. Among them Nitinol shape memory alloy posses several characteristics that make them ideal for retrofit application in structures and particularly in bridges. Table I provides mechanical properties of SMA and steel for comparison [1]. SMA characteristics comprise: (1) large elastic strain range; (2) hysteretic damping; (3) proper energy dissipation through repeated solid state phase transformation; (4) strain hardening at strain above 6%; (5) excellent low- and high-cycle fatigue properties; (6) excellent corrosion resistance; and (7) the formation of stress plateau during phase transformation which controls the forces transmitted to the structure [1],[9].

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TABLE I
MECHANICAL PROPERTIES OF SMA AND 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)	2.07E5 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

SMA could be categorized as either superelastic austenite (the high temperature phase) which can recover its original shape when unloaded or martensite (the low temperature phase) which recover its original shape when heated [10]. This study will concentrate on the former SMA type.

Fig. 1 shows a schematic of the stress-strain relation typically observed in superelastic SMAs. 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 [9]. The loading and unloading paths do not coincide, with the loading path being a lower stress plateau. As a result, there is an area enclosed under the "flag shape" stress-strain diagram which represents the energy dissipated.

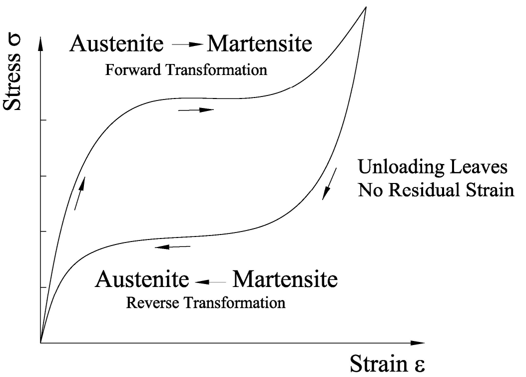

Fig. 1 stress-strain relationship for superelastic SMA

III. Application of SMAs in Bridges

A. Application of SMA bars as restrainers or dampers

Several studies have been conducted to examine the effectiveness of SMA restrainers as unseating prevention devices or dampers. Reference [1] evaluated the efficiency of using SMA restrainers to reduce the response of decks in a multi span simply supported bridge. The results show that the SMA restrainers reduce relative hinge displacements at the abutment much more effectively than conventional steel cable restrainers. Subsequently, many researchers studied different aspects of SMA restrainers as unseating prevention devices [8], [11], [12]. Reference [9], studied the application of SMAs as seismic passive damper devices for vibration mitigation of cable stayed bridges. It was concluded that SMA dampers can significantly reduce the maximum bridge displacement, tower base shear and tower base moment compared to response of reference bridge.

B. Application of SMAs in innovative bridge bearings

A proper isolator must have: (1) stability in large deformation, (2) power of recentering (3) adequate energy dissipation capacity, and (4) no need for replacement of the deformed bearing even after a strong earthquake. Having all these characteristics, SMAs are considered to be used in seismic isolation devices. Reference [13] proposed a new SMA-rubber bearing which is composed of a conventional elastomeric bearing and SMA wires wrapping the bearing in longitudinal direction. The study showed that the SMA-rubber bearing restrained the deck displacement and controlled the relative displacement between deck and pier satisfactory in strong ground motions. However, they increase pier demand compared to lead-rubber bearing. Other researchers examine the applicability of SMA in isolation devices in different ways [14].

C. Application of SMAs in bridge columns

Reference [15] presented the application of SMA bars instead of steel bars in plastic hinge zone on reinforced concrete bridge. The feasibility of superelasticity in increasing ductility and decreasing residual displacement of concrete bridge column was investigated in [16]. Also SMA spirals were used with shape memory effect in order to apply active confining pressure on bridge columns [17].

IV. Analytical Model

A. Reference Bridge

The particular RC single column bent highway viaduct investigated here has been used widely as a reference bridge in several published research works. The bridge piers are of unequal height with the shortest pier in the middle, resulting in an irregular configuration of the structure, with an increased possibility for concentration of ductility demands in the short intermediate pier [5].

The bridge has four equal spans with a total length of 200 m. The boxed section deck has the width of 14 m and it rests on the abutments as well as on the three intermediate piers of unequal heights (21 m, 7 m and 14 m) with hollow rectangular section. Fig. 2 show details regarding the deck and pier cross sections.

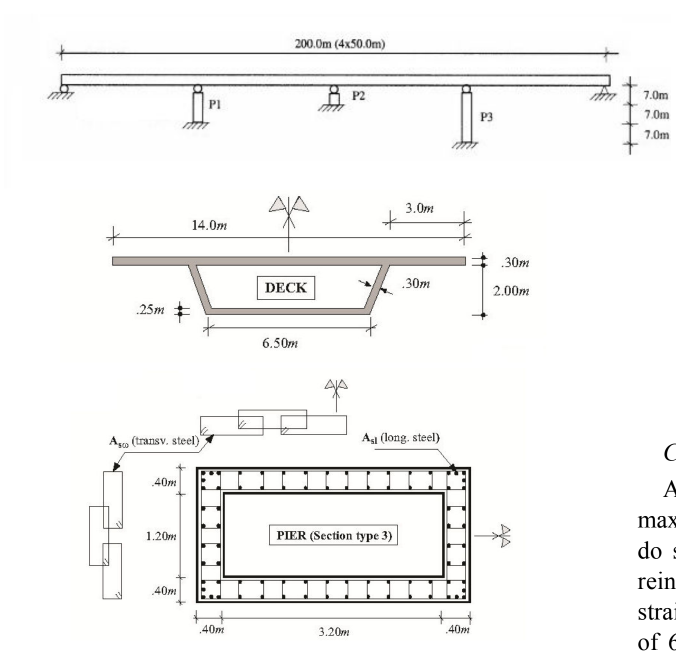

Fig. 2 bridge configuration

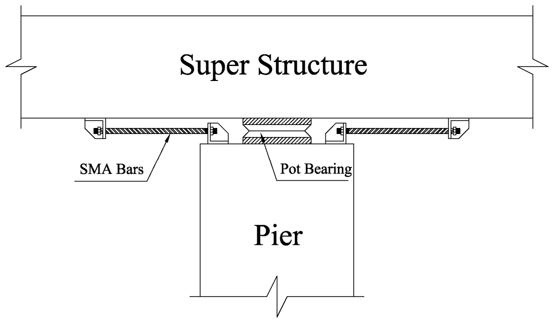

Fig. 3 schematic of the setup proppposed for SMA restrianer

B. SMA Restrainer

To improve the seismic behavior of reference bridge, fixed bearing above the short pier are replaced by pot bearing and two groups of SMA bars that would be connected from pier cap to the bottom of the girder, as shown in Fig. 3. Connecting bars to the bottom of the girder provides a relatively simple retrofitting strategy for existing bridges or designing strategy for new bridges. Two groups of SMA bars work alternatively in positive and negative longitudinal direction and act typically in tension only manner. In this study, area of SMA bars would be designed and their length would be iterated among 4 values of 150, 200, 250, and 300 cm.

Mechanical properties of shape memory alloy are quite sensitive to its chemical components. The yield strength of SMA bars is assumed to be 500 MPa with unloading yield strength of 140 Mpa. Five percent strain hardening is assumed up to the level of 6 percent strain and recoverable elongation was set to 8 percent. It is also assumed that the yielding occurs at 0.6% strain.

C. Design of SMA Restrainer

Area of SMA restrainers was designed to keep the maximum strain of SMA bars within the recoverable range. To do so, shear strength of column with different percentage of reinforcement was put equal to axial strength of SMA bars at strain of 6%. In other words, when SMA bars reach the strain of 6%, shorter column would yield and therefore control the forces to be developed in SMA bars. This philosophy of design would guarantee the superelasticity feature of SMA to take place.

D. OpenSees Modeling

The 2-D finite element model of the reference bridge as well as bridge equipped with SMA bars was developed and analyzed using the open-source finite element program, OpenSees [18]. The bridge deck was modeled using 40 elastic beam column elements with 41 nodes. The columns, in the plastic hinge zone, were modeled using nonlinear beam column element which was separated into both steel and concrete fibers. Each fiber had a uniaxial stress-strain relationship representing confined and unconfined concrete or longitudinal reinforcing steel. Out of plastic hinge zone, elastic beam column elements with appropriate crack coefficient were modeled according to their reinforcment. SMA bars were modeled by a one dimensional tension only SMA material model which was developed and implemented in the OpenSees material library. The mass of the deck and piers were lumped at nodes. Fixed and pot bearings were modeled by zero length element. In addition, rigid arms were used to level the centre of mass in the reference bridge and analytical model. Deck was free longitudinally at abutments. According to an eigen value analysis, the predominant period of structure in longitudinal direction was approximately 1.0 second. Fig. 4 illustrates the schematic of model in OpenSees.

TABLE II
THE SET OF GROUND MOTIONS SELECTED FOR ANALYSIS

NO	Earthquake	Station	Year	Magnitude	Duration (s)	PGA (g)	PGV (cm/s)
1	Northridge	Beverly Hills - Mulhol	1994	6.7	30	0.517	63
2	Duzce	Bolu	1999	7.1	56	0.822	62
3	Imperiall Valley	El Centro Array #11	1979	6.5	39	0.380	42
4	Kobe	Nishi-Akashi	1995	6.9	41	0.509	37
5	Kocaeli	Arcelik	1999	7.5	30	0.218	40
6	Landers	Yermo Fire Station	1992	7.3	44	0.245	52
7	Loma Prieta	Gilroy Array #3	1989	6.9	40	0.555	45
8	Superstition Hills	El Centro Imp. Co	1987	6.5	40	0.358	46
9	Chi-Chi	CHY036	1999	7.6	90	0.294	39
10	San Fernando	LA - Hollywood Stor	1971	6.6	28	0.210	19

V. GROUND MOTIONS

A set of 10 Far-Field ground motion records selected from the PEER NGA database. Records are selected to have magnitude, PGA, and PGV greater than 6.5, 0.2g, and 15 cm/s, respectively. Table II shows a description and characteristics of the ground motions (year, magnitude, duration, PGA, and PGV) used in the analysis. Using code procedure, records are scaled to AASHTO design response spectrum between periods of 0.2T to 1.5T; in which T is fundamental period of bridge.

Using the 10% probability of exceedance in 50 years seismic hazard maps with soil profile type 2 and acceleration coefficient equals 0.35g, the AASHTO design response spectrum was developed. Fig. 5 shows a comparison between the code based design response spectrum and the average response spectrum of the 10 ground motion records after they were scaled. However, for shorter periods, the mean response spectrum of the 10 ground motions used in the analysis far exceeds the code-based design spectrum.

VI. ANALYSIS RESULTS

For all records, analysis was performed without restrainers (as-built) and with superelastic SMA restrainers. Then average of shorter pier ductility improvement was calculated. Ductility improvement indicates the effectiveness of the proposed innovative system in reducing the ductility demand of shorter pier and it is calculated; as follows:

$$I = \frac{\mu_{s,asbuilt} - \mu_{s,controlled}}{\mu_{s,asbuilt}} \quad (1)$$

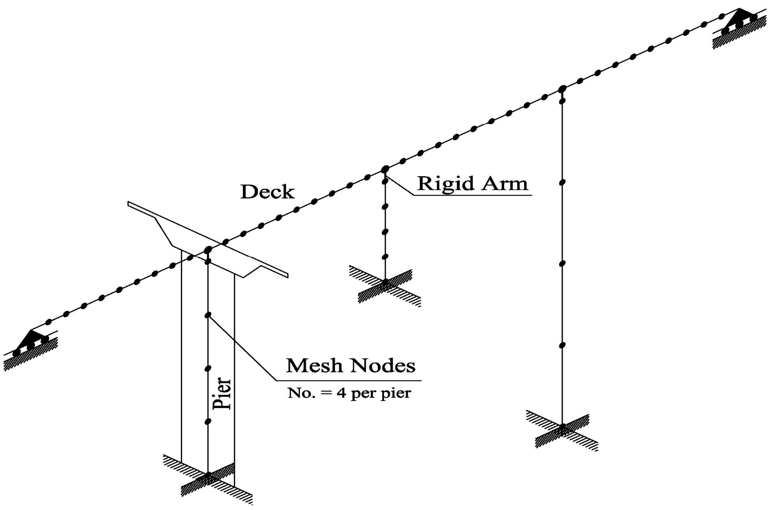

Fig. 4 Analytical model of bridge in OpenSees

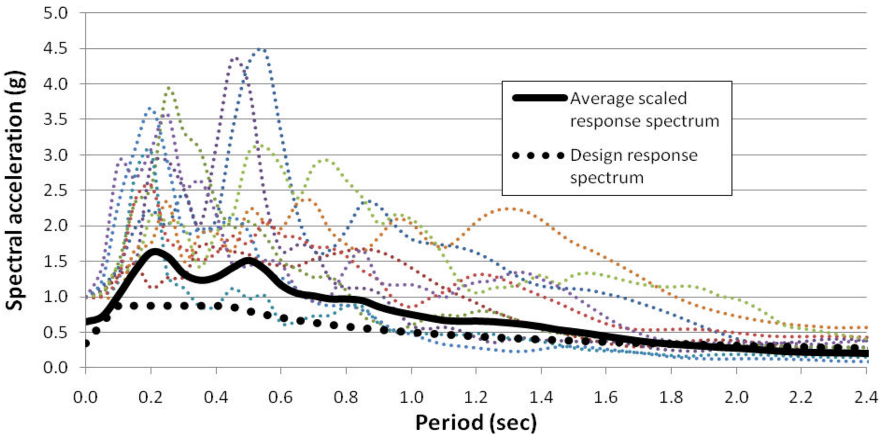

Fig. 5 Design response spectrum used in the analysis compared to the scaled spectra of the ground motions set

Where $\mu_{s,asbuilt}$ and $\mu_{s,controlled}$ are shorter pier ductility demand in as-built and controlled bridge, respectively, and I is improvement of ductility demand. The average and standard deviation of this index, I_{avg} and I_{dev} respectively, are illustrated in Figs. 6 and 7.

As Fig. 6 shows, the degree of effectiveness of SMA restrainers is function of length of the restrainer and reinforcement percentage of the pier (ρ). As length of SMA restrainer increases, the ductility demand of shorter pier decreases and bridge behave appropriately. The maximum effectiveness of restrainers was observed in the case of ρ=2%.

Fig. 7 illustrates the standard deviation of parameter I. In the case of ρ=1% high deviation of analysis results left the reliability of effectiveness in doubt. However for the cases of ρ=2% and ρ=3% standard deviations became reasonable with decreasing trend by increasing the restrainer lengths.

Fig. 8 shows the average ductility demand (μ_{avg}) of different piers for both as-built and controlled bridge for ρ=2% and 200 cm length of SMA restrainer. In as-built bridge, concentration of ductility demand on shorter pier may cause bridge to collapse, but in controlled bridge displacement capacity provided by SMA restrainers in the place of shorter pier was quite effective in improving seismic behavior and regularizing the bridge.

To provide a better understanding of effectiveness of SMA restrainers, the time history response of the 1987 Superstition Hills earthquake for ρ=2% and 200 cm length of SMA restrainer is presented in this section. Fig. 9 illustrates the short pier displacement. As shown in the figure, SMA restrainers can significantly (50%) limit the displacement demand of the pier but cannot eliminate residual displacement.

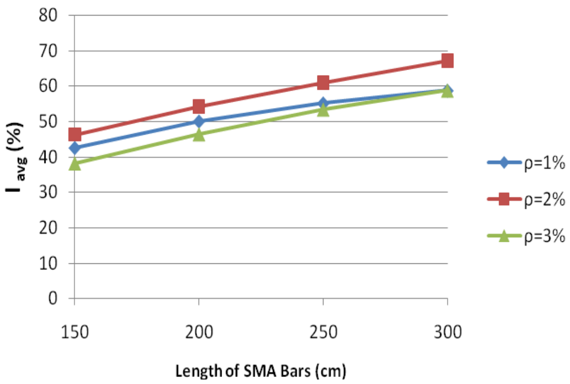

Fig. 6 Average of improvement of ductility demand

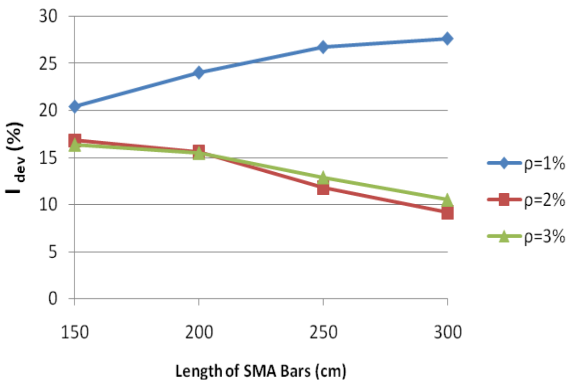

Fig. 7 Standard deviation of improvement of ductility demand

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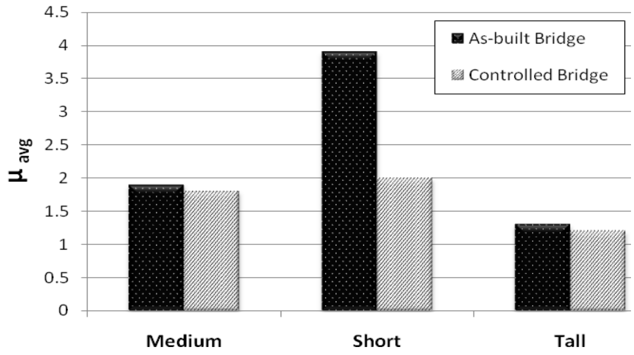

Fig. 8 ductility demand on piers

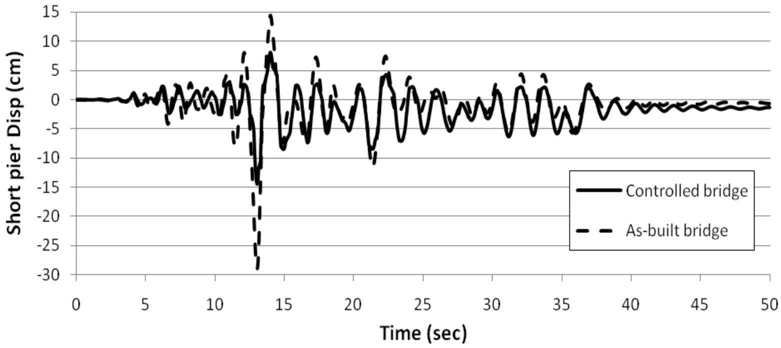

Fig. 9 Time history of short pier displacement

VII. CONCLUSION

SMAs are a unique class of materials that have the ability to undergo large deformations, while reverting back to their undeformed shape through the removal of stress (superelastic effect). In this paper, a study was conducted to evaluate the efficiency of the superelastic Nitinol shape memory alloy restrainers in standardizing the behavior of the highly irregular reference bridge. To improve the seismic behavior of bridge, fixed bearing above the short pier replaced by pot bearing and two groups of SMA bars that would be implemented at the deck to pier connection. A nonlinear dynamic analysis was conducted using a suite of 10 ground motion records with different length of restrainers and various reinforcement ratios of shorter pier. Areas of SMA restrainers are designed with a philosophy to keep the maximum strain of SMA bars within the recoverable range. The performance of irregular reference bridge was evaluated with and without SMA restrainers.

The results showed that superelastic elements significantly reduced the ductility demand on shorter pier in controlled bridge compared to as-built bridge up to 70%. The high elastic strains of SMA restrainers in addition to the damping characteristics were the primary factors behind the effectiveness. It was also found that the increasing the length of SMA restrainers would improve the seismic behavior of bridge with an extent that depends on the reinforcement percentage of shorter pier.

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