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Unseating prevention for multiple frame bridges using superelastic devices

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Abstract
Unseating of bridge spans due to excessive relative hinge opening is a common problem for bridges subjected to strong ground motion. Various unseating prevention devices have been developed in both the United States and Japan to try to reduce the likelihood of collapse due to unseating. This paper presents the results of the evaluation of unseating prevention devices using nitinol shape memory alloys (SMAs). Superelastic SMAs have the ability to remain elastic under very large deformations, due to a solid-state martensitic transformation. This unique property leads to enhanced performance of the adaptive superelastic unseating prevention device, compared with conventional devices used in the United States and Japan. To assess the effectiveness of the devices, nonlinear time history analyses are performed on a typical multiple frame reinforced concrete box girder bridge using a suite of representative ground motions. The results show that for multiple frame reinforced concrete box girder bridges the adaptive superelastic devices are very effective in limiting the relative hinge displacement and preventing unseating, compared with the conventional steel cable restrainers.

1. Introduction

Recent earthquakes have highlighted the major problem of unseating due to excessive relative hinge displacements during an earthquake (Schiff 1998). To limit the relative hinge displacements, researchers have used a variety of unseating prevention devices, including steel cable restrainers, steel rods, shock transmission units, and other similar technologies (Kim *et al* 2000, Saiidi *et al* 2001). The traditional steel cable restrainers and rods used have several limitations, including small elastic strain range, and limited ductility capacity. To address some of the limitations of current unseating prevention devices, a new technology using nitinol SMAs as unseating prevention devices is proposed. The study presented in this paper evaluates the effectiveness of these devices in limiting relative hinge displacements in typical multiple frame bridges.

2. Nitinol shape memory alloys

Shape memory alloys are a class of alloys that display unique characteristics, based on a thermoelastic martensitic transformation (Otsuka and Wayman 1998). Unlike for plastically deforming metals, the nonlinear deformation is reversible. Although several alloys exhibit the shape memory property, the most widely used shape memory alloy is nitinol (Nickel Titanium Naval Ordinance Lab.), which consists of an approximately equal composition of nickel and titanium. In the low temperature phase, nitinol exhibits the *shape memory effect*—strain can be recovered by heating the specimen above the transformation temperature, as shown in figure 1. At a slightly higher temperature, nitinol exhibits the superelastic effect, as shown in figure 2. In the superelastic phase, nitinol is initially austenitic. However, upon loading, stress-induced martensite is formed. Upon unloading, the martensite reverts to austenite at a lower stress level, resulting in the hysteresis shown in figure 2. The superelastic behavior of nitinol SMAs possesses several characteristics that make it ideal for use as restrainer cables, including

(1) large elastic strain range, leading to excellent potential as a recentering device,
(2) hysteretic damping, and
(3) strain hardening at large strains.

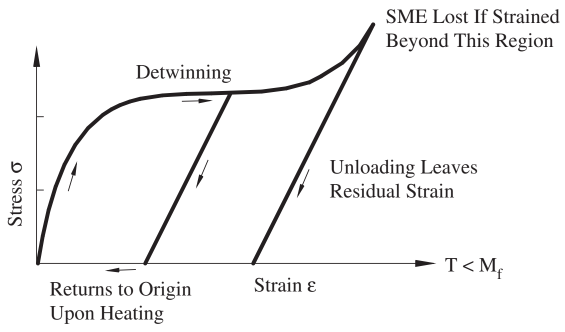


Figure 1. Shape memory effect in nitinol shape memory alloys.

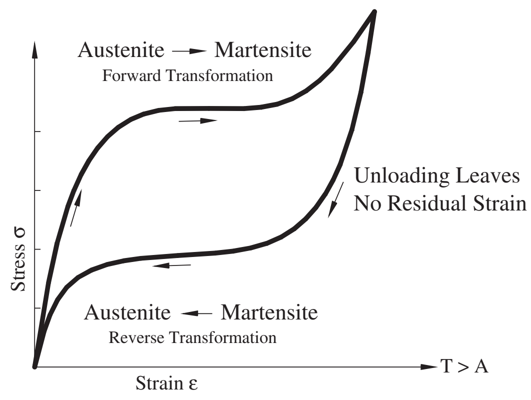


Figure 2. Superelastic effect in nitinol shape memory alloys.

Figure 3. Unseated spans in the 210/5 Interchange during the 1971 San Fernando earthquake (NISEE Collection).

(This figure is in colour only in the electronic version)

3. Unseating prevention devices

Since the 1971 San Fernando earthquake, which resulted in the collapse of more than 60 bridges, a significant number of research studies were conducted in an effort to better understand the problem of unseating in bridges during earthquakes (Cooper *et al* 1994). Figure 3 shows the unseating of several spans of the Route 210/5 Interchange during the 1971 San Fernando earthquake. After the earthquake, the California department of transportation (Caltrans) initiated a state-wide seismic retrofit program to systematically retrofit older and non-ductile bridges. Cables and rods that were made of steel were used to limit relative hinge displacement between spans and reduce the likelihood of unseating. Although the restrainers performed adequately during the 1989 Loma Prieta and the 1994 Northridge earthquakes, there were several instances of failure of the cables and/or connecting elements. The design procedures for the steel restrainers require the restrainers to remain elastic during earthquakes, which causes either the restrainers to break or the diaphragm walls at the two ends of the cable restrainer to suffer punch-through action during a severe earthquake (Feng *et al* 2000). Since the restrainers are designed to remain elastic, they lack the ability to dissipate energy, which is a major drawback during earthquakes. The collapse of the Gavin Canyon Undercrossing and the 14/5 interchange during the 1994 Northridge earthquake has proven the inadequacy of the currently used steel restrainers (Saiidi *et al* 2001).

A number of other devices have been presented in the past two decades as unseating prevention devices for bridges, such as fluid viscous dampers, which are dampers of a velocity-dependent type (Technical Evaluation Report 1999), and metallic dampers, which are considered as force-dependent dampers (Chen *et al* 2001). Although these devices are energy dissipation devices, they lack the capability to recenter, which is important for controlling the hinge opening in bridges. The SMA restrainers in the superelastic phase are characterized by a large elastic strain (6%–8%), which means that the SMA restrainers are capable of recovering the original length even under severe earthquakes. Therefore, SMAs, which show both damping and recentering, offer a unique set of capabilities not seen in current devices. Another advantage of using these devices is the fact that the shape of the SMA hysteresis is controlled by the manufacturing procedures used in developing the alloy; thus a yield-like hysteretic plateau could be developed for the SMA restrainers, limiting the force transferred to adjacent frames. Also, once the SMA restrainers are deformed beyond the elastic range, they strain harden. This behavior induces high level of force, which is required to prevent unseating in the case of strong ground motions.

4. Analytical models

4.1. Bridge as-built model

A multiple frame bridge identical to the type of bridge typically constructed in California was considered in the analysis. Figure 4 shows the elevation of the analyzed bridge. As shown in the figure, the bridge consists of two interior taller frames (Frames 2 and 3) and two exterior shorter frames (Frames 1 and 4). The interior frames have a total length of 183 m (600′) and a total height of 18 m (60′). The exterior frames have a total length of 73 m (240′) and a total height of 12.2 m (40′). The bridge's superstructure consists of a concrete box girder supported on concrete piers. The nonlinear dynamic program DRAIN-2DX was used in analyzing the bridge (Prakash *et al* 1992). The plastic hinge beam–column element (Type 02) was used in modeling the bridge's superstructure and columns. This element consists mainly of an elastic element joining two plastic hinges. The Type 02 element takes into account the inelastic behavior of

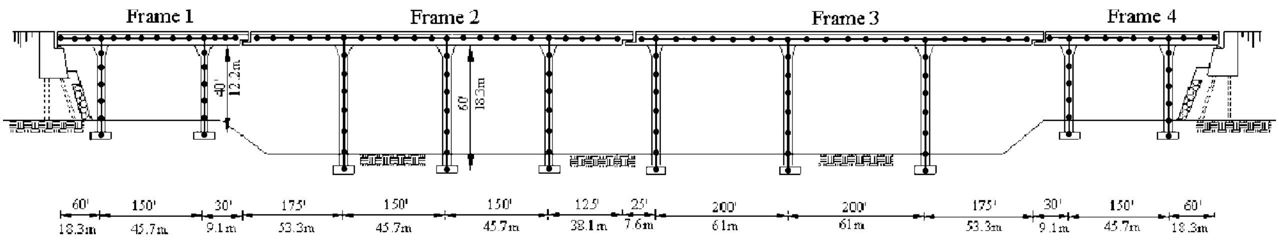


Figure 4. Four-frame box girder bridge considered in the analysis.

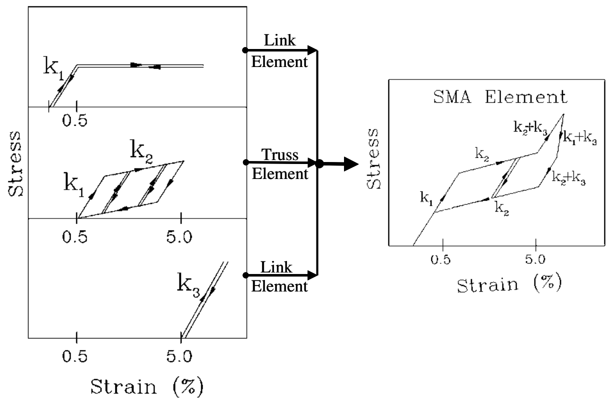


Figure 5. Schematic diagram of the superelastic SMA model developed using two-link elements and a truss element in Drain-2DX.

the element through the formation of plastic hinges at the two end nodes of the element. Under earthquake loadings, the bridge deck is expected to behave elastically. Hence, the superstructure of the bridge was modeled as remaining elastic, while two values of the yield strength were used in modeling the columns, based on the flexibility. The bent caps were modeled using a rigid element connecting the girders with the columns. The nonlinear behavior of the abutments was modeled in Drain-2DX using Type 09 link elements. The Type 09 link element is an inelastic bar which resists only uniaxial loads. The element is used as either tension-only or compression-only with an initial slack or gap. Two link elements with elastic–perfectly plastic behaviors were used in parallel to model the active and passive resistance of each abutment. A compression-only link element was also used to model the impact effect of the bridge components. A 50.8 mm (2 inches) gap and a 12.7 mm (0.5 inches) gap were assumed at the exterior and interior hinges of the bridge, respectively.

4.2. Restrainer modeling

Two types of restrainer were involved in the analysis: the regular steel cable restrainers and the superelastic SMA restrainers. The steel restrainers are modeled as a bilinear element. Once the element yields it unloads inelastically, developing a residual strain. The element was modeled to represent the actual behavior of steel restrainers, which accumulate residual strain upon successive yielding. On the other hand, the constitutive behavior of the superelastic SMA restrainer was modeled through the parallel combination of two Type 09 link elements and a Type 01 truss element, which is a tension–compression bilinear element. However, in this study it was used as tension-only element. Figure 5 shows a schematic diagram of the model that was developed to describe the superelastic behavior in SMAs. As shown in the figure, the initial branch and the strain hardening branch were modeled using the two link elements, while the truss element was utilized in developing the hysteretic behavior of the SMAs. The stiffness of the SMA model was calculated form the superposition of the three element stiffnesses. In this study, the steel and superelastic restrainers were modeled with a 12.7 mm (0.5 inches) slack.

4.3. Design of restrainers

4.3.1. Steel restrainers. Steel restrainers were designed using the AASHTO restrainer design procedure (AASHTO 1992). In this method, the designer calculates the force resisted by the restrainers through multiplying the mass of the lighter frame with a certain acceleration value. In this study, a 3.05 m (10 ft) length steel cable was used, based on a target hinge displacement equal to 63.5 mm (2.5 inches). The length of the restrainers was selected such that it would remain elastic under a target hinge displacement of approximately 63 mm (2.5 inches). A value of 0.7g peak ground acceleration was assumed and used to calculate the force required to restrain each frame. The force required between the outer and inner frames was 16 800 kN (3777 kips), while the force required between the two internal frames was 37 300 kN (8393 kips). The required forces result in approximately 100 restrainers at each of the exterior hinges and 215 restrainers at the interior hinge. These numbers were considered to be extremely large compared to the actual number of restrainers used in bridges. Since the preliminary modal analysis of the bridge indicated that the two interior frames would vibrate in phase while the exterior and interior frames would vibrate out of phase, more restrainers were required at the exterior hinges compared to the interior hinge. This showed that applying the AASHTO design procedure is not appropriate in this study since it depends mainly on the weight of the frames rather than their period ratios. Instead, a practical number of 25 restrainers were used in all of the three hinges. This number is a typical number for the restrainers used by Caltrans in multiple frame bridges. In order to be conservative in this study, the same number of restrainers was used in each of the three hinges.

4.3.2. Superelastic restrainers. The superelastic rods used in the analysis were 12.7 mm (0.5 inches) in diameter, 914 mm

Table 1. The suit of ground motion records selected for the analysis.

Record description	Earthquake magnitude (M_w)	Distance (km)	Duration (s)	PGA (g)	T_g (s)	S_{an} (g)
1994 Northridge, Beverly Hills	6.7	20.8	23.9	0.62	0.26	0.18
1986 N. Palm Springs, North Palm Springs	6.0	8.20	20.0	0.69	0.34	0.12
1979 Imperial Valley, SAHOP Casa Flores	6.5	11.1	15.7	0.51	0.42	0.18
1989 Loma Prieta, Gilroy Array #3	6.9	14.4	39.9	0.56	0.47	0.13
1992 Cape Mendocino, Rio Dell Overpass	7.1	18.5	36.0	0.55	0.48	0.14
1983 Coalinga, Pleasant Valley	5.8	17.4	21.7	0.60	0.69	0.11
1983 Coalinga, Transmitter Hill	5.8	9.20	21.7	0.84	0.72	0.16
1994 Northridge, Tarzana, Cedar Hill	6.7	17.5	40.0	0.99	0.74	0.32
1992 Cape Mendocino, Petrolia	7.1	9.50	36.0	0.66	0.76	0.44
1989 Loma Prieta, WAHO	6.9	16.9	24.9	0.64	0.98	0.17

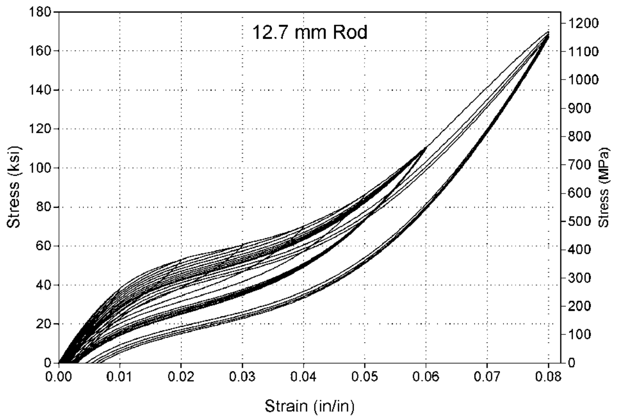


Figure 6. Typical stress–strain curve of the 12.7 mm diameter nitinol superelastic rods considered in the analysis (Delemont 2002).

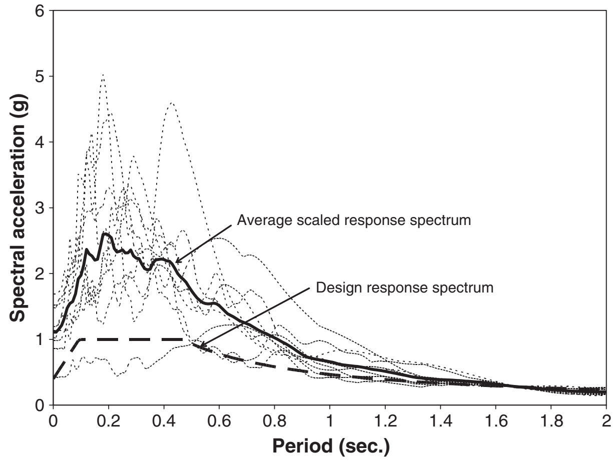


Figure 7. The design response spectrum (dashed) used in the analysis compared to the scaled response spectra of the ground motions suite.

(36 inches) in length. The rods were designed to have a maximum force equal to that in the 25 steel restrainers. The stress–strain curve resulting from the quasi-static test conducted by Delemont (2002) was used in the analysis. Figure 6 shows the superelastic stress–strain curve that was used in the analysis. A value of 5% was assumed for the elastic strain range. The SMA restrainers were designed such that they would reach the same level of force as the steel restrainers at the same elastic strain. At 5% strain in the superelastic restrainers, the force was found to be approximately, 3737 kN (840 kips). Fifty five SMA restrainers were found to be sufficient to produce such force at the 5% strain level.

5. Ground motions

A suite of 10 ground motion records consisting mainly of historical earthquakes that occurred in California in the past 25 years was used in this study. The records were selected to cover a range of ground motion characteristics such as the peak ground acceleration, duration, and frequency content. Table 1 shows a description and characteristics of the ground motions (magnitude, epicentral distance, duration, peak ground acceleration, and predominant period) used in the analysis. Since this study is focusing on the performance of typical California multiple frame bridges, each ground motion record was scaled to a value equal to the design spectral acceleration value of the San Francisco area at the predominant period of the structure (1.67 s). The last column in table 1 shows the spectral acceleration value (S_{an}) for each record at the natural period of the bridge studied. Using the 10% probability of exceedance in 50 years USGS seismic hazard maps with site class B, the code-based design response spectrum was developed. Figure 7 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. As shown in the figure, the two spectra intersect at a value of 0.28g at the predominant period of the structure. Note, however, that for shorter periods the mean response spectrum of the 10 ground motions used in the analysis far exceeds the code-based design spectrum.

6. Analysis results

Figure 8 shows the maximum hinge openings resulting from the analysis of the multiple frame bridge under the suite of ground motions. For each record the analysis was performed without restrainers (as-built), with steel cable restrainers (steel), and with superelastic SMA restrainers (SE). As shown in the figure, the degree of effectiveness of each of the two restrainer types varied from one record to another. However, in all cases the SE restrainers were more effective in reducing the maximum hinge opening.

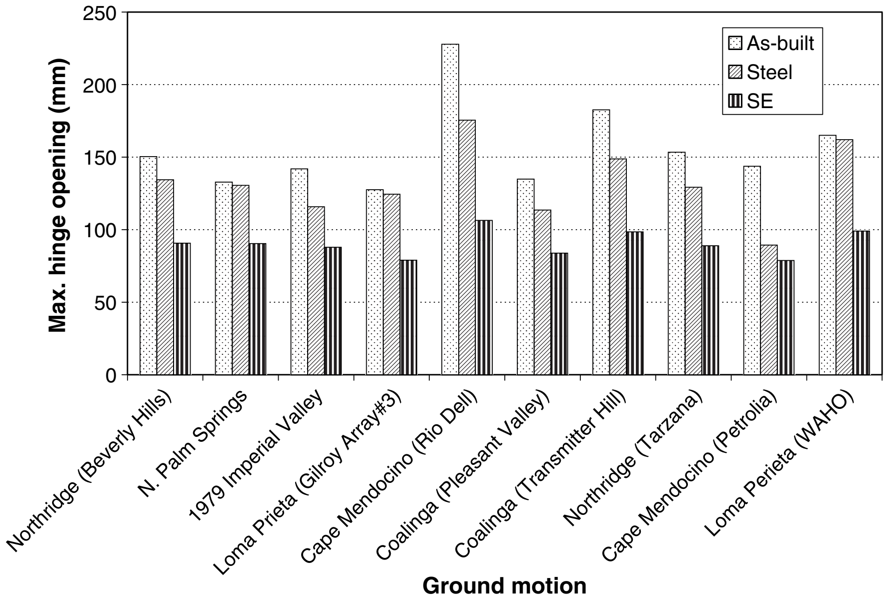


Figure 8. Maximum hinge opening for various ground motions.

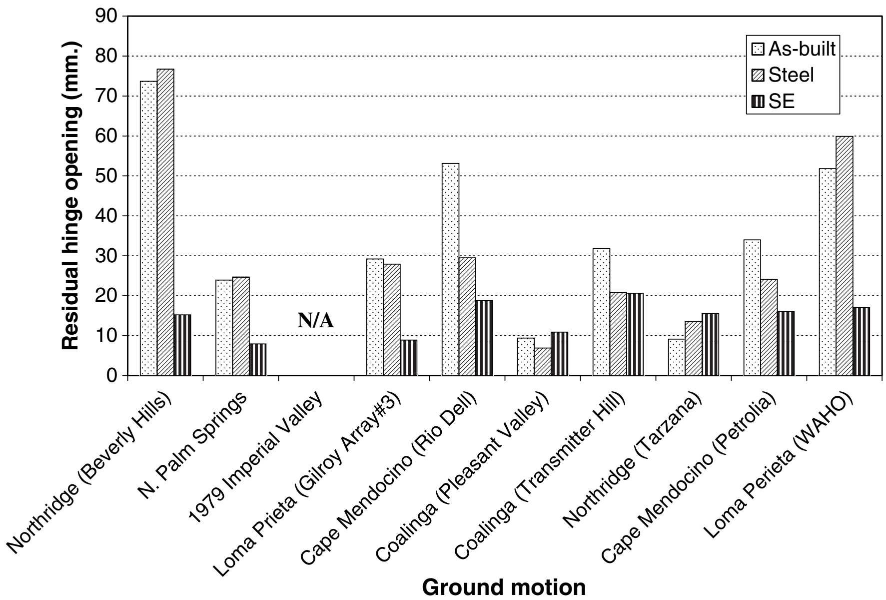


Figure 9. Residual hinge openings for various ground motions.

The maximum effectiveness of steel restrainers was observed in the case of the 1992 Cape Mendocino (Petrolia) ground motion, where the maximum hinge opening was reduced by approximately 37% compared to the as-built case. Three cases showed a poor performance for the steel restrainers, where the restrainers experienced a significant amount of yielding, which reduces the effectiveness of the restrainers and results in a small reduction in the maximum hinge opening (1986 North Palm Springs, the 1989 Loma Prieta (Gilroy Array #3), and the 1989 Loma Prieta (WAHO)). However, the SE restrainers produced a significant amount of reduction in the maximum hinge openings that varied between 31% and 62% approximately. The average amount of reduction resulting from using the SE restrainers was 43%, while the reduction for the steel cable restrainers was approximately 16%.

Figure 9 shows the residual hinge opening resulting at the end of each record for both types of restrainer in addition to the as-built case. The SE restrainers were effective in reducing the residual hinge opening in most cases, particularly for the cases where the bridge frames experienced large residual hinge opening in the case of no restrainers (as-built). However, in the cases where the residual hinge openings in the as-built bridge were relatively small such as in the cases of Coalinga (Pleasant Valley) and Northridge (Tarzana) records the SE restrainers slightly increased the residual hinge openings. This increase

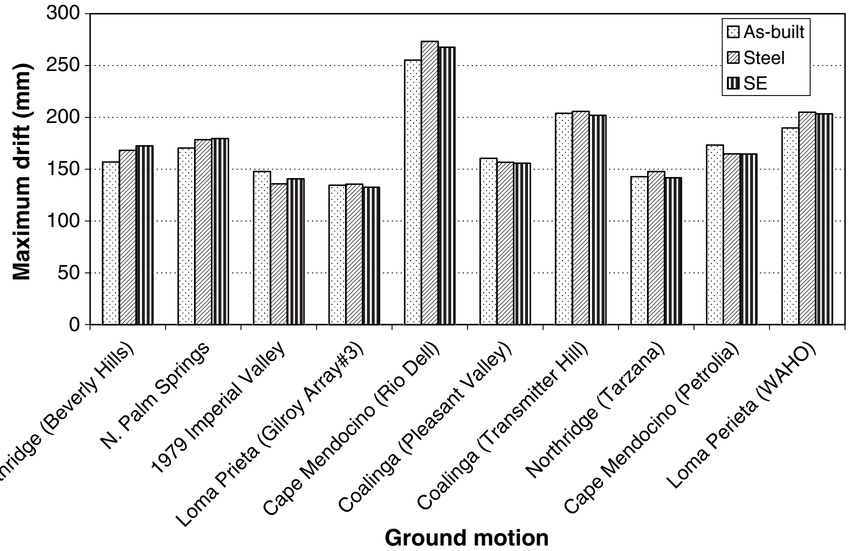


Figure 10. Maximum frame drift for various ground motions.

is most likely due to the large level of force reached during the strain hardening of the SE restrainers. This large force plays an important role in limiting the maximum hinge openings in the case of strong earthquakes where unseating is expected. However, in the case of moderate earthquakes the level of force is significantly reduced, resulting in a reduction in the residual hinge openings. Figure 9 also shows that the 1979 Imperial Valley record did not produce a residual displacement in the hinge. It is also shown that in the cases of the Northridge earthquake (Beverly Hills), the North Palm Springs earthquake (North Palm Springs), and the Loma Prieta earthquake (WAHO) records, the steel restrainers increased the residual hinge openings compared to the as-built case. This behavior is due to the lack of recentering that is associated with the steel cable restrainer type.

Previous studies have shown that one of the drawbacks of using restrainers is that they tie separate spans together, which can increase the force transferred between the two connected frames and thereby increase the lateral drift. Figure 10 shows a comparison between the maximum frame drifts resulting from each record for the SE restrainer case, steel cable restrainer case, and the as-built case. The figure shows that the effect of restrainers on the drifts in the frames is minor. In most of the cases the existence of the restrainers slightly increases the frame drifts. However, for the majority of the cases the frame drifts produced in the case of the SE restrainers is smaller than that produced in the case of steel restrainers.

To provide a better understanding of the effectiveness of SE restrainers versus steel restrainers, the time history response of the 1989 Loma Prieta (Gilroy Array #3) is presented in this section. Figure 11 shows the time history of the relative hinge opening at the hinge between frames 3 and 4. As shown in the figure, the SE restrainers were effective through the entire record and reduced the maximum hinge opening by approximately 38% compared to the as-built case. However, the steel restrainers showed an effective performance in the first cycle (before yielding). Points A and B show the maximum response for steel restrainers and SE restrainers, respectively

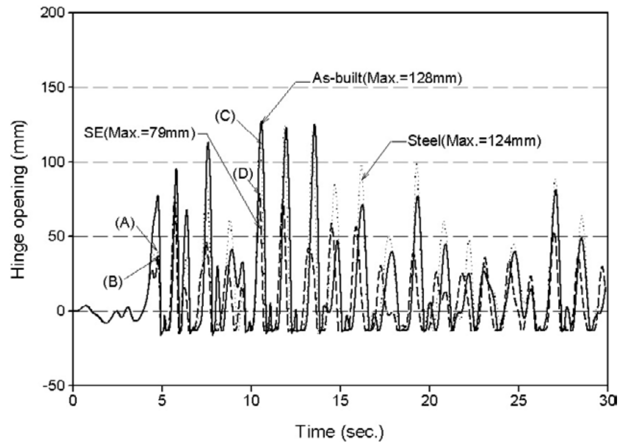
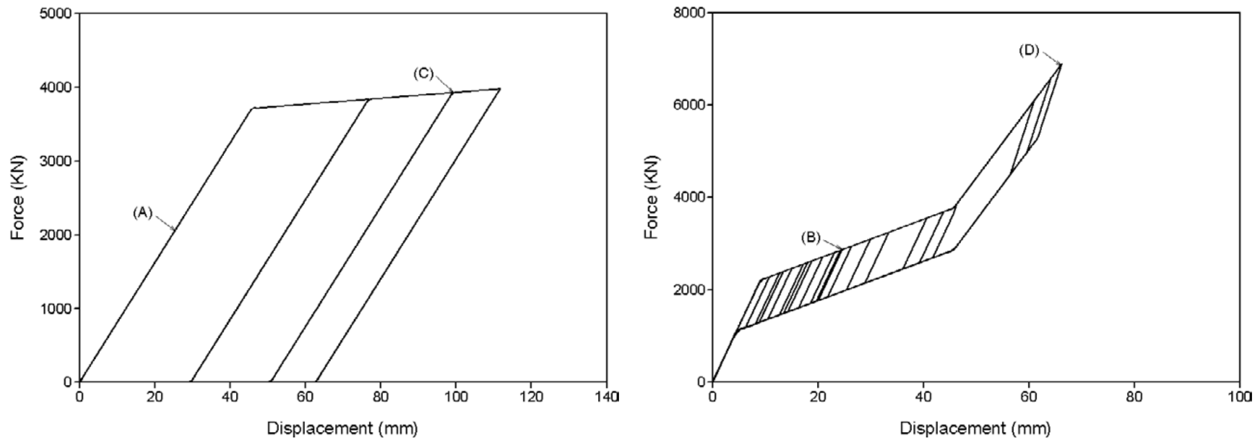


Figure 11. Hinge opening time history for the Loma Prieta (Gilroy Array #3) ground motion record.

during the first major cycle before yielding. The responses of the steel and SE restrainers were similar. However, once the steel restrainers yielded, they began accumulating residual strains and their effectiveness was reduced significantly. This behavior is demonstrated through points C and D on the figure. Point C represents the maximum response in the case of steel restrainers during the seventh major cycle, while point D represents the maximum response in the case of SE restrainers at the same cycle. The difference in performance between the SE and steel restrainers increased significantly in the seventh cycle compared to the first cycle. This is due to the fact that the steel restrainers accumulate strain once yielding is experienced, thus reducing the effectiveness. The maximum hinge opening in the steel restrainer case was approximately equal to that in the as-built case.

Figure 12 shows the force–displacement relationship for the two restrainer types. Points A–D that were previously discussed in relation to figure 11 are shown in the figure.



(a) Steel restrainers

(b) SE restrainers

Figure 12. Force–displacement relationship for the steel restrainers and SE restrainers under the Loma Prieta (Gilroy Array #3) ground motion record.

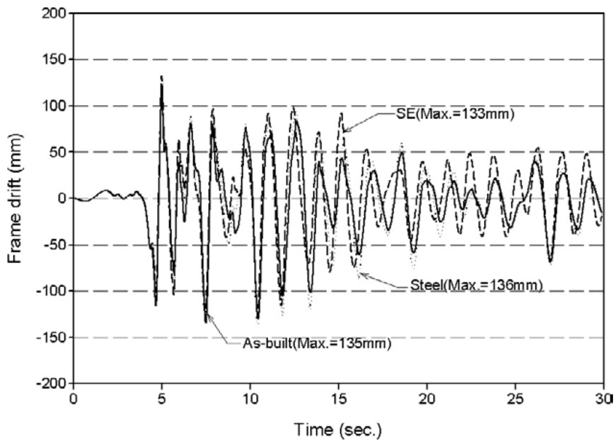


Figure 13. Drift time history of frame (3) for the Loma Prieta (Gilroy Array #3) ground motion record.

The responses at points A and B were close since the steel restrainers were acting in the elastic stage. Once the steel restrainers experience yielding (point C) the efficiency is lost. The figure also illustrates that the recentering behavior of the SE restrainers played an important role in controlling the hinge opening. The strain hardening of the SE restrainers assists in minimizing the possibilities of frame unseating in the case of strong ground motions.

Figure 13 shows the time history of the drift in frame 3. Similar behavior is observed in the three cases (as-built, steel, and SE). This shows that although the SE restrainers transfer larger force to the connected frames compared with the steel cable restrainers, the maximum frame drifts were not affected by this force due to the recentering capability of the SE restrainers. This shows that using the SE restrainer does not increase the ductility demand on the bridge frames.

7. Conclusions

In this paper, a study was conducted to evaluate the efficacy of superelastic nitinol shape memory alloy restrainers in preventing the unseating of multiple frame bridges during strong ground motions. A nonlinear dynamic analysis was conducted using a suite of 10 ground motion records. The performance of a typical California multiple frame reinforced concrete box girder bridge was evaluated using the superelastic restrainers and the traditional steel cable restrainers.

The superelastic elements reduced the relative hinge displacements significantly compared to the steel restrainers. The high elastic strains of the superelastic elements in addition to the damping characteristics were the primary factors behind the effectiveness. The steel restrainer performed poorly in most of the cases due to its low elastic strain limit. The maximum hinge openings for the SE restrainer case, the steel cable restrainer case, and the as-built case were compared and analyzed. The response time history showed that during the first few cycles restrainers of both types perform similarly. Once the steel restrainers yield, residual strain begins accumulating and thus the effectiveness is reduced significantly. However, the SMA superelastic restrainers remain effective during the entire time history due to the capability for recentering and recovering the original length after deformation to a level of strain that can reach 6%–8%.

The analysis of the frame drifts of the multiple frame bridge using the SMA restrainers and the steel cable restrainers showed that the type of restrainer has a minor effect on the maximum drift of the bridge frames. Although the SMA restrainers transfer more force to the connected structural elements, the ductility demand on the frames was not affected. This study showed that the proposed superelastic elements are capable of reducing the relative hinge displacements in multiple frame bridges during strong ground motions without increasing the ductility demand on the bridge frames, and thus of preventing the unseating of the bridge superstructure.

Since the mechanical properties of SMAs are greatly affected by the environmental temperature that the material performs at, future study is required to investigate the effect of temperature variation on the efficacy of SMA restrainers in bridges.

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