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COMPARISON OF DIFFERENT METHODS FOR SEISMIC RETROFIT OF BRIDGES USING SMART MATERIALS

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SUMMARY

Excessive relative displacement between adjacent spans and frames in bridges is a major cause of bridge collapse during earthquakes. This paper evaluates three different technologies to limit the relative hinge opening in bridges during earthquakes. The use of restrainers made of superelastic shape memory alloy, and metallic dampers are compared to the traditionally used steel restrainers to determine their effectiveness in limiting the relative hinge displacement. A simplified 2-DOF analytical model in addition to a multi-frame box girder bridge finite element model is used in the analysis. Using a suite of 8 strong ground motion records, the seismic response of the bridge is evaluated. The results show that superelastic shape memory alloy restrainers with its recentering capability and strain hardening characteristic is more effective than the other two devices in limiting the relative hinge opening for most of the ground motion records.

INTRODUCTION

The vulnerability of bridges unseating during strong earthquakes has been a point of interest for engineers and researchers for the past two decades. A number of earthquakes that occurred recently in the United States and Japan have caused serious damage in bridges due to the unseating of the bridges' superstructure (Schiff [1] and Unjoh [2]). Unseating of the bridge's superstructure occurs when the adjacent frames or spans vibrate out of phase during an earthquake. Different types of retrofit devices have been used in the past to prevent such collapse. The retrofit devices are usually used to limit the relative displacement between adjacent frames or spans. Among these devices are steel restrainer cables and metallic dampers. The main drawback of such devices is that once the device has experienced yielding, its recentering capability is reduced due to the accumulation of residual strain upon unloading. Another problem with these devices is that in some cases it increases the ductility demand of the bridge (Selna [3] and Saiidi [4]). This paper investigates these problems through the usage of Nitinol Shape Memory Alloys (SMAs) cables and rods as bridge retrofit devices. This study compares the efficacy of the

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traditional steel restrainers and metallic dampers and the new SMA restrainers in reducing the relative displacements in bridges.

SHAPE MEMORY ALLOYS

Shape memory alloys are a class of metallic alloys that exhibit unique thermomechanical characteristics that have been used in a number of applications in the past few years (Otsuka [5]). When the alloy is loaded at a temperature below a specific temperature called the martensite finish temperature (M_f), the residual strain formed upon unloading could be recovered by heating the material to a temperature above the austenite finish temperature (A_f). This phenomenon is known by Shape Memory Effect (SME). On the other hand if the material was loaded at a temperature above A_f, upon unloading the material recovers all of its residual strain following an unloading plateau that is degraded from the loading plateau. In other words the material is characterized by high elastic strain (6%-8%). Figure 1 shows the superelastic behavior in SMAs. This study focuses on utilizing the recentering capability of SMAs resulting from its superelastic behavior in controlling the relative displacements in bridges.

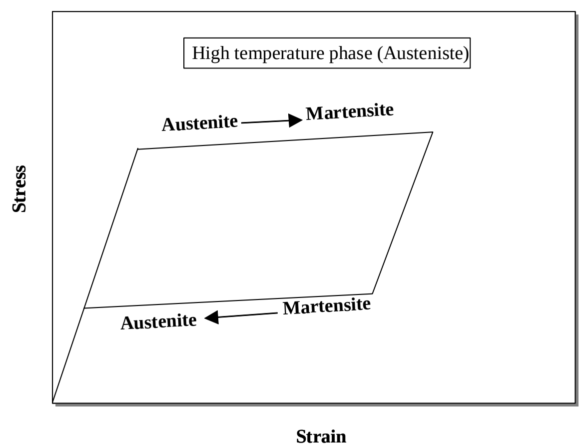


Figure 1. Superelastic phenomenon in shape memory alloys

SIMPLIFIED ANALYTICAL MODEL

A two degree of freedom (DOF) analytical model was developed in MATLAB as a preliminary stage in studying the performance of the Super-Elastic (SE) SMA restrainers compared to other devices in bridges. Figure 2 shows a schematic drawing of the 2-DOF simplified model used in the analysis. As shown in the figure, the model consists of 2 stick-mass elements representing two adjacent frames or spans in a bridge. The mass are connected trough three elements, an element the viscous damping of the system, a friction that represents the friction resistance at the bearings, and a restoring force element that represents the retrofit device used in the system. The pounding effect was included in the model through modifications of the two mass velocities using the coefficient of restitution.

In this study, the two masses were considered identical and equal two 2.27 KN.sec^2/mm. The elements supporting the two masses were assumed to behave linearly with different stiffness (89 KN/mm and 357 KN/mm). The mass and stiffness values were selected based on a typical multi-frame bridges property. The large difference in the stiffness was essential to produce a relatively strong out-of-phase behavior in the system due to the small fundamental period ratio of the system which was taken as 12.7 mm this case study.

Three types of retrofit devices were considered in the analysis, the steel restrainers, the metallic dampers, and the superelastic dampers. The steel restrainers and SE restrainers were modeled as tension-only

elements, while the metallic damper was modeled as a bilinear element in compression and tension. The compression-tension behavior of the metallic dampers would dissipate more energy than the other two devices. In order to compare the effectiveness of the damping capability characterizing the metallic dampers and the recentering capability characterizing the SE restrainers, the initial stiffness and yield strength of the SE restrainers and metallic dampers were assumed to be identical and equal to 429 KN/mm and 3920 KN, respectively. The steel restrainers were designed to experience yielding at the same level of displacement and force where the SE restrainers reach its maximum elastic strain. In this study the maximum elastic strain for SE restrainers was assumed to be 6%. This resulted in an initial stiffness for the steel restrainers equal to 107 KN/mm and yield strength equal to 5880 KN.

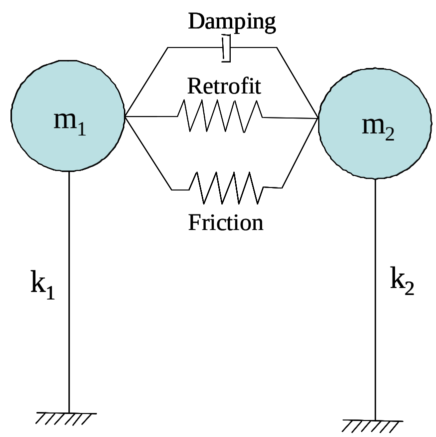


Figure 2. Schematic drawing for the simplified 2-DOF analytical model

RESULTS OF THE SIMPLIFIED ANALYTICAL MODEL

Figure 3 shows the time history results of the relative displacement induced between the two masses using the three retrofit devices under the Loma Perieta (Gilroy array #3), 1989. The ground motion was scaled based on a spectral acceleration equal to 0.6g at the natural period of the structure (1.0 sec). The response of the as-built case with no retrofit device installed is also shown in the figure. As shown in the figure, the maximum relative displacement with no retrofit device installed was 160 mm. All three devices reduced the maximum response. However the SE restrainer was the most effective device among the three used retrofit devices in limiting the maximum relative displacement. It reduces it to 77.7 mm, which corresponds to a reduction of approximately 52% compared to the maximum relative displacement in the as-built case. On the other hand the metallic dampers and steel restrainers reduced the response by approximately 44% and 11%, respectively.

The force displacement relationships for the SE restrainers, steel restrainers, and metallic dampers are shown in Fig. 4. The tension-compression behavior of the metallic dampers allowed the device to dissipate larger amount of energy compared to the other two devices. However, the recentering capability of the SE restrainers was more effective in controlling the relative displacement. The accumulation of residual displacement and lack of recentering was the main reason for the small effectiveness of the steel restrainers.

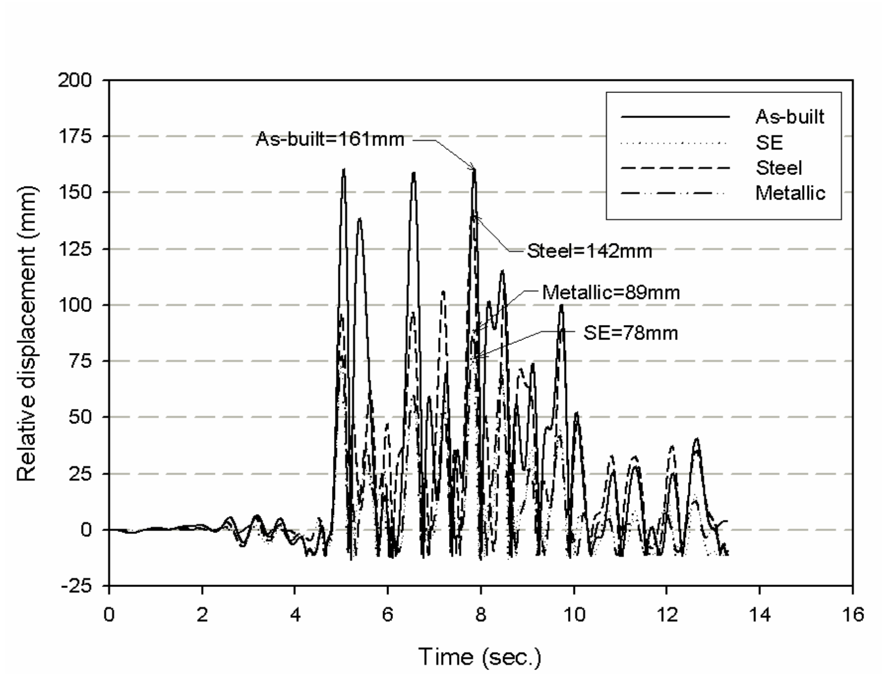
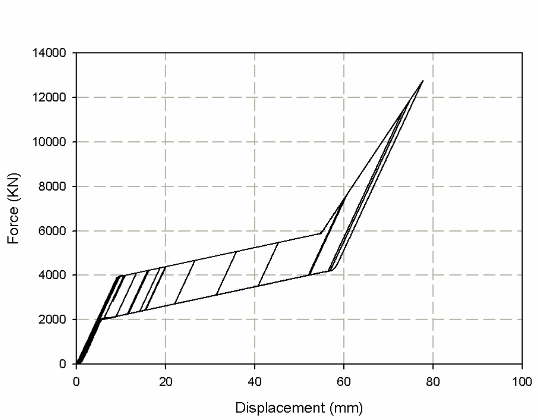
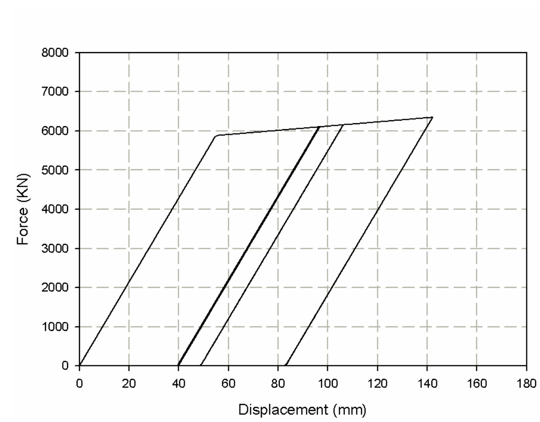


Figure 3. Time history for the relative displacement in the simplified model under Loma Perieta (Gilroy array # 3), 1989 ground motion record

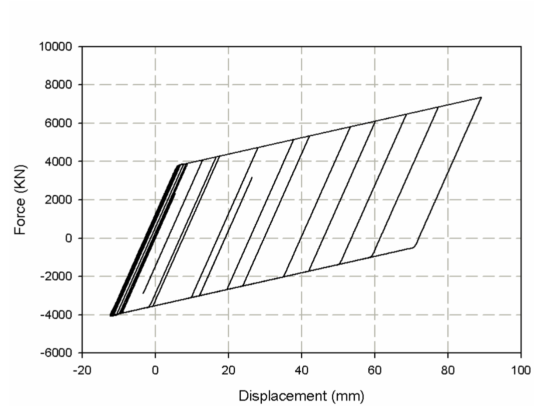


a. SE restrainers



b. Steel restrainers

Figure 4. Continued



c. Metallic dampers

Figure 4. Force-displacement relationship for the three retrofit devices under the Loma Perieta (Gilroy array #3), 1989 ground motion record

FINITE ELEMENT MODEL

Bridge modeling

As shown in the previous section, the results of the preliminary analysis using the simplified model showed a better performance for the SE restrainers compared to the other two devices in limiting the relative displacement in bridges. However, a number of factors were neglected in the simplified analysis that might affect the performance of the retrofit devices. As an example of such factors are the effect of bridge abutments, the nonlinearity of the bridge and the existence of multi-superstructure components such as in multi-span simply supported bridges and multi-frame bridges. In order to consider the effect of such factors, a finite element model was developed for a typical four-frame box girder bridge, which is commonly constructed in California. The model was developed using nonlinear program DRAIN-2DX and is shown in Fig. 5. As shown in the figure, the model consists of two interior long frames (Frames 2 and 3) with a total length of 182.9mm each and a total height of 18.3m, and a two exterior shorter frames (Frames 1and 4) with a total length of 73.2m and a total height of 12.2 m. The bridge box girders and piers were modeled using the plastic hinge beam-column element (Type 02) in DRAIN-2DX. The nonlinearity in the superstructures was only limited to the bridge columns (i.e. the girders were modeled to remain elastic). The properties of the bridge girders and columns were identical to typical multi-frame bridges constructed in California. A nonlinear link element (Type 09) was used in modeling the abutments with a gap between the abutments and the girders of 50.8 mm. The effect of pounding was included in the model through using a rigid link element at the location of the intermediate hinges. The pounding element engages after the gap between the girders, is closed. This gap was assumed to be 12.7 mm.

Modeling of retrofit devices

The same three retrofit devices used with the simplified model previously discussed in section 3 were used for this analysis. Figure 6 shows the model that was developed for the SE restrainers. As shown in the figure, the tension-only model consisted of two link elements (Type 09) and a truss element (Type 01). Fifty five SMA rods with a 12.7 mm diameter and 914 mm length were used in this analysis. The total initial stiffness of the SE restrainers was taken as approximately 242 KN/mm. The connection element (Type 04) in DRAIN 2-DX was used in modeling the tension-compression metallic dampers. The metallic damper was given the same initial stiffness and yield strength of the SE restrainers.

The steel restrainers were modeled using a nonlinear link (Type 09). The same procedure that was described earlier in designing the steel restrainers was used in this analysis. It was found that 25 steel restrainers with a 3.05 m length each would produce the same amount of force as the 55 SE restrainers when the SE restrainers reach its maximum elastic strain, which was assumed to be 5% in this case. Thus the yield strength of the steel restrainers was taken as 3736 KN.

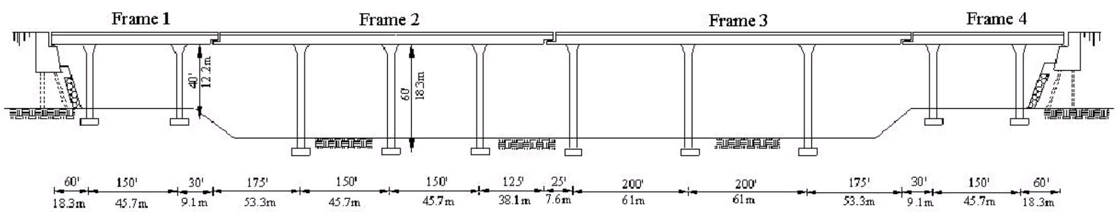


Figure 5. The multi-frame box girder bridge used in the analysis

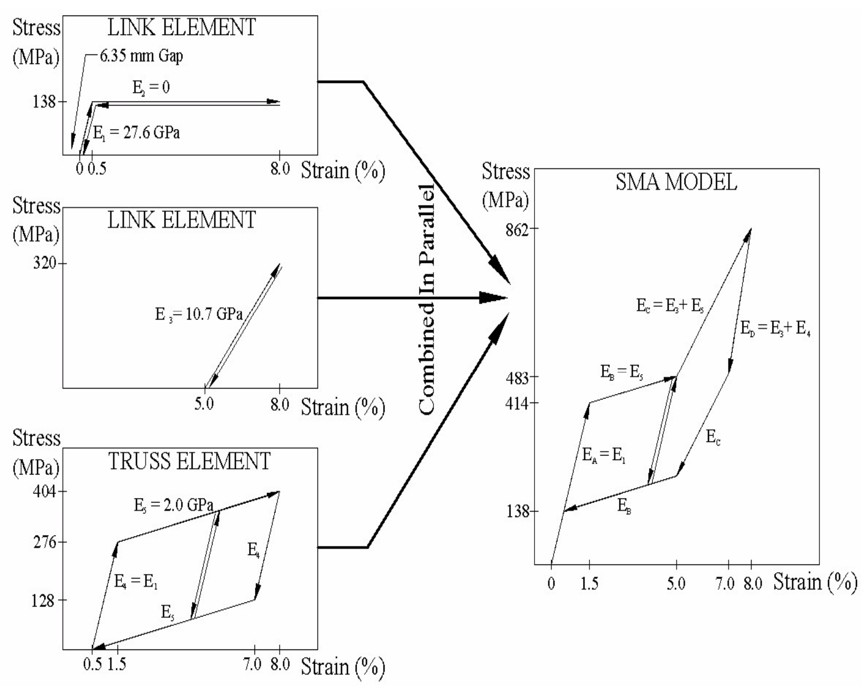


Figure 6. An example of using link and truss element to develop the superelastic restrainer model in DRAIN-2DX

Results of the finite element model

The finite element model that was developed in DRAIN-2DX was tested under a suite of eight ground motions. The ground motion names and properties are shown in Table 1. Since the analyzed bridge is a multi-frame bridge type which is commonly constructed in California, the ground motion records were scaled to the design spectral acceleration value based on the design response spectrum of San Francisco area. At the fundamental period of the structure (1.675 sec), the design spectral acceleration value was found to be 0.28g.

Figure 7 shows the results of the maximum relative hinge displacement for the SE restrainers, Steel restrainer, and metallic dampers in addition to the as-built case. In the majority of the ground motion cases, the SE restrainers are showing more effectiveness in limiting the maximum hinge opening. Although the metallic dampers were modeled as compression-tension element, its performance was less effective compared to the SE restrainers. Figure 8 shows the maximum frame drifts in the case of the three retrofit methods in addition to the as-built case. The retrofit elements did not have a significant effect on limiting the maximum drifts. On the other hand, the high level of force associated with the SE restrainers due to the strain hardening beyond the elastic stage did not impose more drifts on the structures as was expected.

The time history of the relative hinge opening response in the case of Northridge (Cedar Hill), 1994 ground motion is shown in Fig. 9. The SE restrainers reduced the maximum hinge opening by approximately 50% relative to the as-built case. The Metallic dampers and steel restrainers were less effective in limiting the hinge opening. The recentering feature of the SE restrainers helped in eliminating a major part of the residual opening at the end of the record. This is believed to be one of the most important advantages of using SE restrainers as retrofit devices.

Table 1. Ground motion records used in the finite element analysis

Record description	Earthquake magnitude (M_w)	Distance (km)	PGA (g)	Tg (sec)
Northridge, 1994, Baverly Hills	6.7	20.8	0.62	0.26
Whittier Narrows, 1987, Cedar Hill	6.0	43.0	0.64	0.31
N. Palm Springs, 1986 North Palm Springs	6.0	8.20	0.69	0.34
Loma Prieta, 1989, Gilroy Array #3	6.9	14.4	0.56	0.47
Cape Mendocino, 1992, Rio Dell Overpass	7.1	18.5	0.55	0.48
Coalinga, 1983, Transmitter Hill	5.8	9.20	0.84	0.72
Northridge, 1994, Tarzana, Cedar Hill	6.7	17.5	0.99	0.74
Loma Prieta, 1989, WAHO	6.9	16.9	0.64	0.98

The Frame drifts time history is shown in Fig. 10. As previously noticed in Fig. 8, the retrofit elements did not reduce the maximum drifts. This shows that the type of retrofit method used at the intermediate hinges has a small effect on the lateral drifts in bridges. The force displacement relationships for the SE restrainers, steel restrainers, and metallic dampers are shown in Figure 11. As noticed from the figure, the metallic dampers dissipated larger amount of energy compared to the other two cases, however, the recentering capability and the strain hardening behavior of the SE restrainers were more effective in controlling the hinge opening.

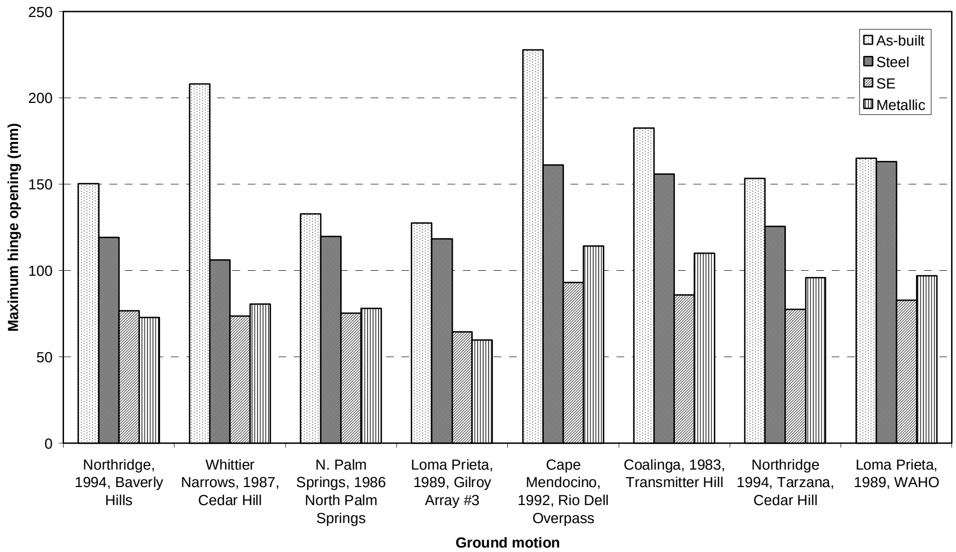


Figure 7. Maximum hinge opening using the three retrofit techniques

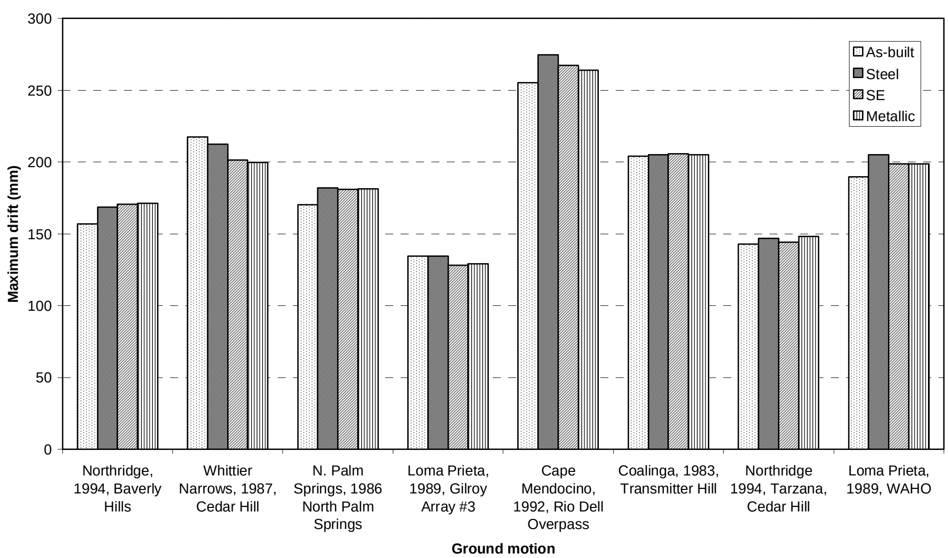


Figure 8. Maximum frame drift using the three retrofit techniques

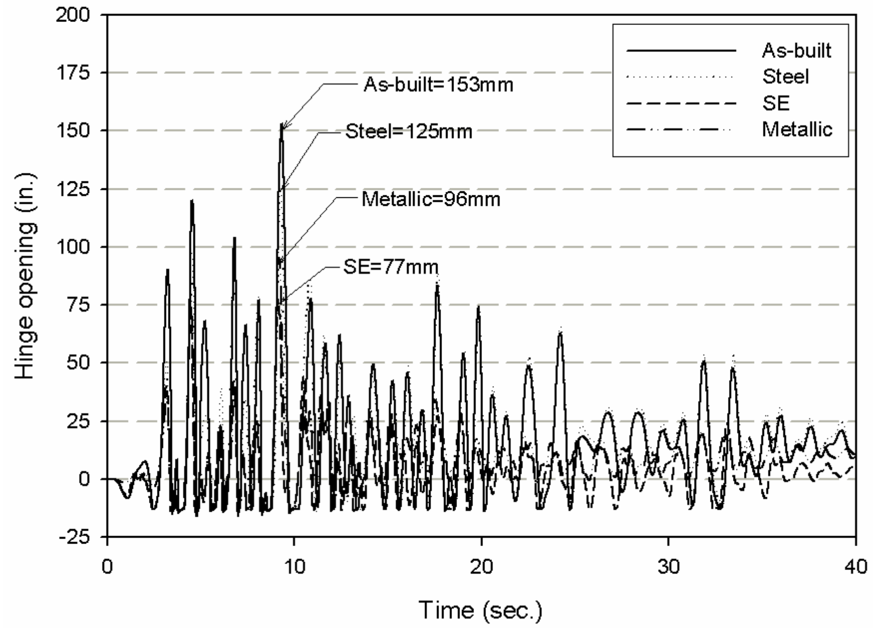


Figure 9. Time history results for the hinge opening under Northridge (Cedar Hill), 1994 ground motion record.

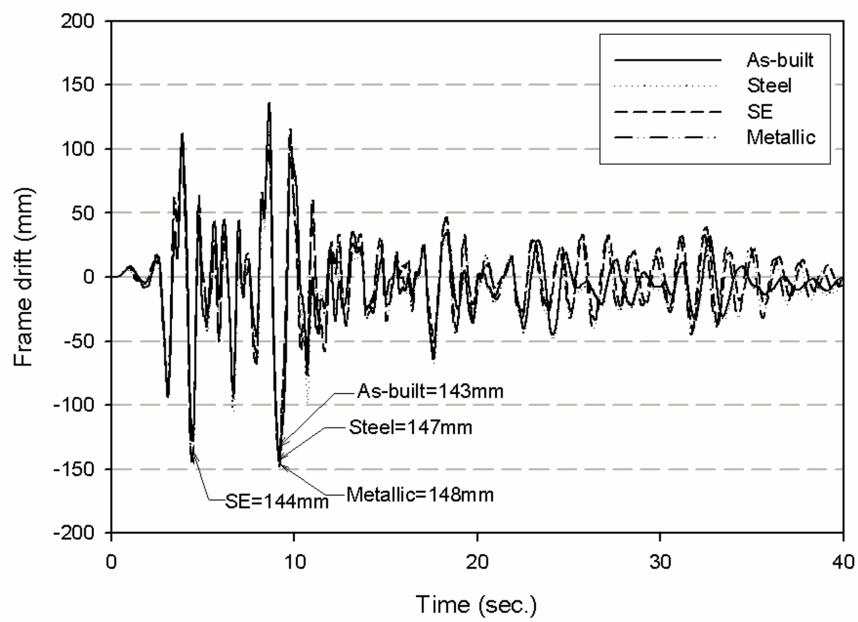
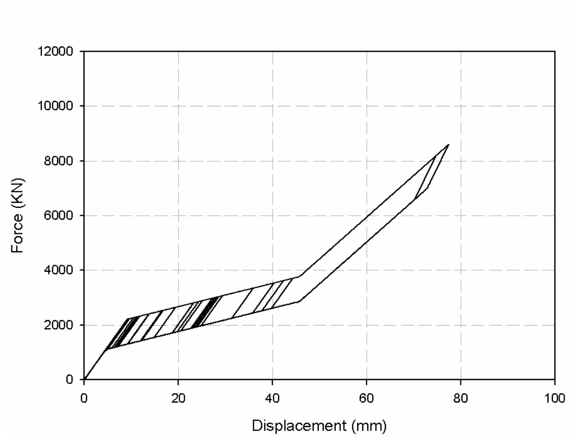
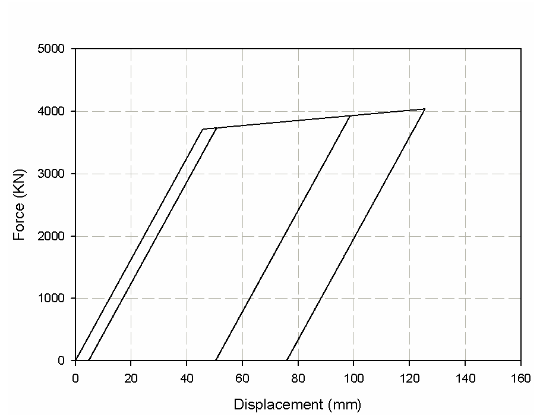


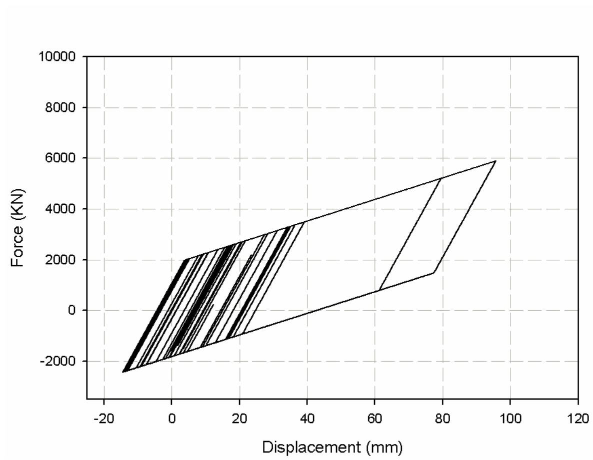
Figure 10. Time history results for the frame drift under Northridge (Cedar Hill), 1994 ground motion record.



a. SE restrainers



b. Steel restrainers



c. Metallic dampers

Figure 11. Force-displacement relationship for the three retrofit devices under Northridge (Cedar Hill), 1994 ground motion record.

CONCLUSION

This paper presented an analytical study that was conducted to compare the efficacy of three seismic retrofit methods in limiting the relative displacement between adjacent spans and frames in bridges. In this study a simplified 2-DOF analytical model and a finite element model of a multi-frame bridge were utilized. The performance of the bridge model using the superleastic restrainers, steel restrainers, and metallic dampers was evaluated under a suite of 8 strong ground motion records.

The superelastic restrainers showed better ability in reducing the relative hinge displacements in most of the ground motion records. The superelastic restrainers were also capable of eliminating the residual hinge displacements at the end of the records. In some records the metallic dampers performance was close to the superelastic restrainers due to the ability of the metallic dampers to carry tension and compression and its high energy dissipation capability. The steel restrainers showed limited capability for reducing the relative displacement due to the accumulation of residual displacement after yielding. The analysis also showed that the type of retrofit device used at the intermediate hinges of bridges has a very minor effect on the lateral drift of the bridge.

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