Georgia Tech Sponsored Research

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Project	E-20-F51
Project director	Desroches Reginald
Research unit	CEE
Title	Application of Shape Memory Alloys in Seismic Rehabilitation of Bridges
Project date	6/20/2001

E-20-F51

Application of Shape Memory Alloys in Seismic Rehabilitation of Bridges

IDEA Program **Final** Report
for the period October 1/2000 through April 1/2000
N637

Prepared for the IDEA Program

Transportation Research Board
National Research Council

Reginald DesRoches

Georgia Institute of Technology
School of Civil & Environmental Engineering
October 1, 2000

Acknowledgements

I would like to acknowledge Dr. Subhash Gupta and Dr. Frank Scerzine at Special Metals Corporation for their generous donations of material and their advice in regards to the material processes and properties of Nitinol used in the study.

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bridges. This audience is ideal for the innovative use of SMA devices in bridges. Currently, several states, including South Carolina, North Carolina, Tennessee, and Arkansas have begun retrofit programs which consist of adding steel cable restrainers. Encouraging research results would provide impetus for the consideration of the new technologies discussed above.

IDEA Product

The proposed research will develop seismic damping devices made of shape memory alloys that can be applied to retrofit of bridges. By concentrating energy dissipation in controlled locations, these devices can be used to reduce the demand on individual frames in a multiple-frame bridge, thereby enhancing the performance of these structures. Restrainer devices will be tested in full-scale. Analytical models will be developed to determined the effect of these devices in structures.

Background on SMA

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. Unlike plastically deforming metals, the nonlinear deformation is reversible, as shown in Figure 1. This unique "shape memory" characteristic is a result of a martensitic phase-change that can be temperature induced or stress-induced. Stress-induced transformation leads to a superelastic (or pseudo-elastic) property, as shown in Figure 1. Superelastic shape memory alloys possess several characteristics that make them desirable for use as restrainers and passive energy dissipation devices in bridges. These characteristics include: (1) hysteretic damping; (2) highly reliable energy dissipation based on a repeatable solid state phase transformation; (3) excellent low- and high-cycle fatigue properties; and (4) excellent corrosion resistance. The stress-strain relationship is characterized by an elastic region, a long horizontal plateau, followed by a significant increase in

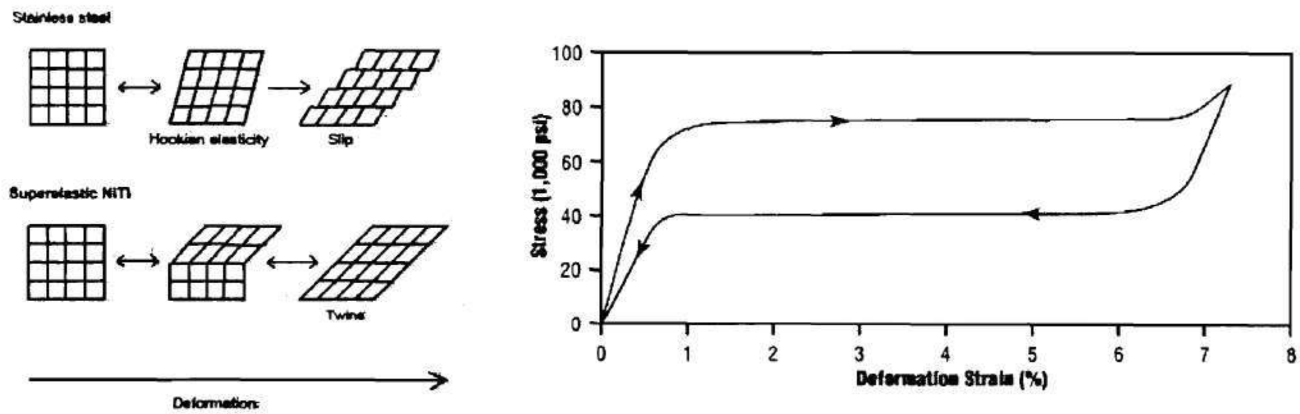


Figure 1 - (Left) Schematic of lattice structure changes in steel vs. superelastic Nitinol. In steel, deformation takes place via slip, which is irreversible. In superelastic Nitinol, stress causes a twinning type of accommodation, which is recovered when stress is removed. (Right) Typical unloading and loading behavior of superelastic shape memory alloy.

stiffness. ***This increase in stiffness at high strains is an ideal property for limiting displacements at hinges due to very large excitation, such as that from near field motions.*** Upon unloading, the material returns to the origin with little permanent offset. Table 1 shows a comparison of the properties of shape memory alloys and structural steel.

While SMA's have been commercially available since the 1960s, their application has been limited. It is only in the past 20 or so years that the material has found functional applications in aerospace, marine, and biomedical fields (Van Humbeeck, 1992; Van Humbeeck, 1999). The growth in materials research revealed the potentials as well as the limitations of SMA's. An improvement in quality and reliability combined with a significant decrease in prices has led to new potential applications for the material and the redressing of applications that were previously deemed unfeasible.

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	12E3 ksi (Austenite)	*4-6E3 ksi (Martensite)*	30E3 ksi
Yield Strength	28-100 ksi (Austenite)	*10-20 ksi (Martensite)*	36-75 ksi
Ultimate Tensile Strength	130 ksi fully annealed	*275 work hardened*	65-120 ksi
Elongation at Failure	25-50% (fully annealed)	*5-10 % (work hardened)*	20 %
Corrosion Performance	Excellent (similar to stainless steel)		Fair

Many current applications take advantage of the temperature-induced phase change characteristic of shape memory alloys. For some SMA's, such as Nitinol (NiTi SMA), the phase change can be stress-induced at room temperature if the alloy has the appropriate formulation and treatment, as shown in Figure 2 below. Figure 3 shows the phase change process at a molecular level. Passive energy dissipation devices using shape-memory alloys have taken advantage of the high damping characteristics of these devices. There have been several studies of applications for NiTi SMA's to seismic resistant design.

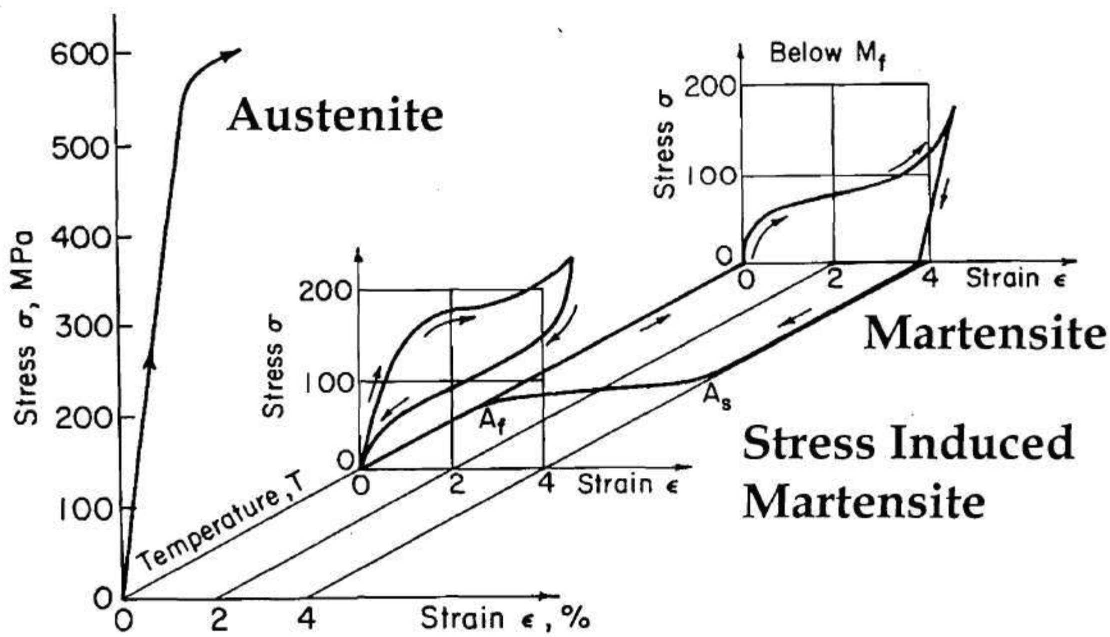


Figure 2 - Phase change in Nitinol (Stress-Strain Plots).

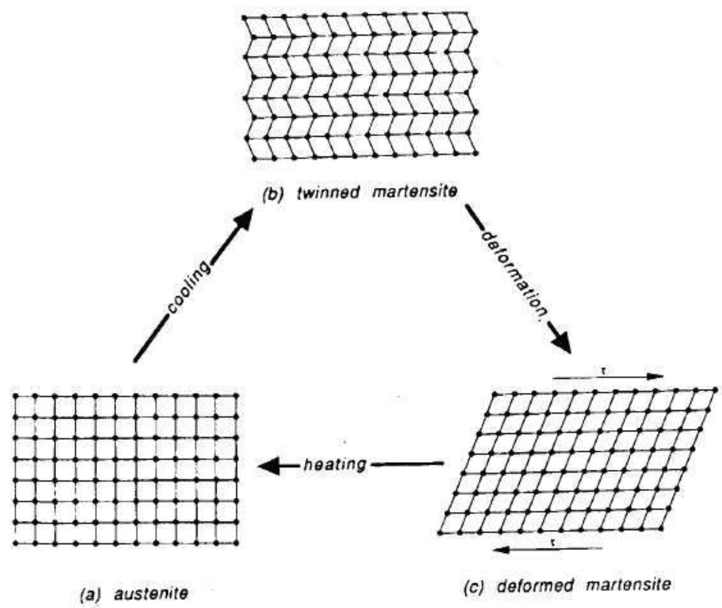


Figure 3 - Phase change in Nitinol (Molecular Arrangement).

The shortcomings of traditional unseating prevention devices can potentially be addressed with the use of shape memory alloy – based restrainers. They 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 7-9%, which provides very high energy dissipation per unit mass of material. The material has excellent low and high cycle fatigue properties, and excellent corrosion resistance. The damping properties are largely amplitude and frequency independent, which is particularly useful for response to multi-frequency, variable amplitude earthquake ground motion records. The proposed research will evaluate the efficacy of SMA-based restrainers in bridges. The restrainers will serve multiple roles. First, they can limit the relative displacement between frames, thereby reducing the risk of collapse due to unseating of frames at the hinges. Second, by concentrating energy dissipation in controlled locations, these "restrainers" will serve as dampers, which will reduce the demand on individual frames in a multiple frame bridge. Finally, they provide a fail-safe mechanism during response to large near-field ground motion.

Optimization of SMA Properties

The goals of stage 1 of the project are to evaluate the effects of thermo-mechanical processing on the characteristics of Nitinol bars and the evaluate the effect of bar diameter, loading frequency and temperature on the characteristics of Nitinol bars undergoing tension compression cycles. Initial studies show that the effect of loading frequency, within the range expected for seismic applications, is minimal. This has been also shown in previous studies (Tobushi et al, 1998; Otsuka, K. and Wayman, C. M., 1977). In addition, the effect of ambient temperature on the response is well understood from previous studies and has little effect on the damping characteristics (Aboudi, 1997; Rengarajan et al., 1998; Whittaker et al., 1995). Therefore, the effort in stage one is focused on optimizing the superelastic properties of SMA's through heat treatment and evaluating the effect of bar diameter on the response of SMA rods in tension/compression. In addition, the efficacy of using SMA bars that display the shape memory effect is evaluated.

Background Information

Preliminary research on SMA wires has shown that there is a relationship between the thermomechanical processing and the monotonic tensile properties of the wire (Duerig et al., 1990; Goldstein et al, 1987; Kaufman et al., 1975; Rozner and Buehler, 1966). More recent work has focused on the effect of thermo-mechanical processing on the stabilization of pseudoelastic stress-strain loops during pure tensile cycling (Miyazaki, 1986; Gall, 1999-a). In general, cold work introduces a high density of dislocations, and thus strengthens the matrix phase. Without annealing, however, the shape memory properties are poor due to extreme dislocation densities. Annealing will restore the memory effect by annihilating dislocations and possibly precipitating out second phases in Ni rich compositions (Gall, 1999-b,c). The optimal density of dislocations and precipitates is achieved when the martensitic transformation occurs readily over dislocation motion, thus creating a cyclically stable transformation response. Figure 4 shows an example of an optimal response in small section single crystals deformed under tension from previous research efforts (Gall, 1999-a).

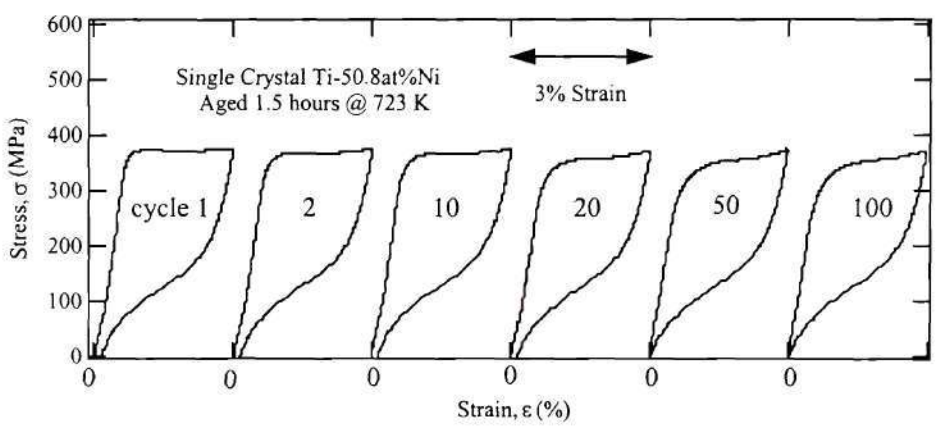


Figure 4 - Cyclic stress-strain response of a NiTi SMA single crystal given the optimal heat treatment for repeated damping characteristics at room temperature (Gall, 1999).

While processing-property relationships have been investigated in wires and small specimens deformed under tension, *they are significantly less understood in larger section SMA bars*. Large section SMA bars will have different spatial crystallographic texture distributions, and will see considerably more compressive stresses in applications compared to thin wires. Both texture and stress-state effects have a *first order* influence on the stress induced transformation (damping characteristics) of NiTi shape memory alloys (Gall and Sehitoglu, 1999). In stage 1, the thermomechanical processing is varied to optimize the properties of the SMA's that are most applicable for seismic resistant design and retrofit applications. Small and large diameter sections are processed under various levels of cold work and annealing time/temperature. The bars are tested in tension and compression cycles to determine the effects of the thermomechanical processing on yield strength (tension and compression), energy dissipation, and residual strain as a function of loading cycles.

Experimental Tests of SMA Bars

Several experimental tests were performed on SMA bars of varying sizes and properties. Table 2 below shows a list of all bar specimen tested.

Table 2: Bar Specimens Tested.

Specimen Name	Gauge Diameter	Gauge Length
CE_1	0.1”	1.0”
CE_2	0.1”	1.0”
CE_3	0.1”	1.0”
MR_1	0.1”	1.0”
MR_2	0.1”	1.0”
MR_3	0.1”	1.0”
ED_1	0.1”	1.0”
ED_2	0.1”	1.0”
ED_3	0.1”	1.0”
EE_2	0.1”	1.0”
EE_3	0.1”	1.0”
Ad1	1.0”	6.0”
Bd2	1.0”	6.0”
Cd3	1.0”	6.0”
M-1	1.375”	9.0”
M-2	1.375”	9.0”
M-3	1.375”	9.0”
M-4	1.375”	9.0”

Note: CE_1 through Cd3 are Superelastic Nitinol
M-1 through M-3 are Martensitic Nitinol

Small Diameter Bars

In this series of tests four sets of small diameter bars were obtained from a 2 ¼ inch diameter bar. The bars were taken from the center, mid-radius, marked edge and ear edge, and had a diameter of 0.1” and gauge length of 1.0”. The specimen shown in Figure 5 has been elongated due to testing. The goal was to determine what the effect of location and annealing temperature had on the characteristics of the bar. For each location, three heat treatment temperatures were evaluated: 450 °C, 400 °C, and 350 °C. In each case the bar was treated in an oven for 1 hour and was cooled in open air. The samples were subjected to cyclical strain at strain values ranging from 1% to 6%. The stress-strain results for the 16 samples are shown in Figure 6.

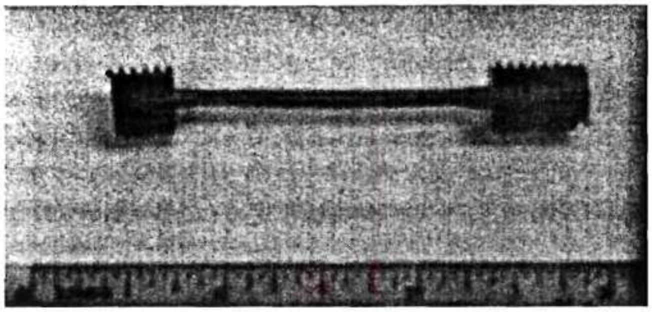


Figure 5 – Small Superelastic Nitinol SMA Bar.

Discussion of Results

Comparing the energy dissipated and the residual strain in the samples, it is found that annealing temperature of 350 °C was the optimal temperature for all 4 locations. The energy dissipated per unit mass of material was greatest for the samples at 350 °C, followed by the samples heat treated at 400 °C. The samples treated at 450 °C had by far the worst performance in terms of energy dissipation, as shown in Table 3.

Another parameter which is important for applications in seismic mitigation is the residual strain in the SMA bar. Ideally, the sample should have very small residual strains after repeated cycles. Large residual strains lead to large displacement in the structure as well as reduced energy dissipation capacity. Once again, the samples heat-treated at 350 °C have the smallest residual strain, as shown in Table 3. Figure 6 shows residual strain after every cycle for the 4 sets of samples.

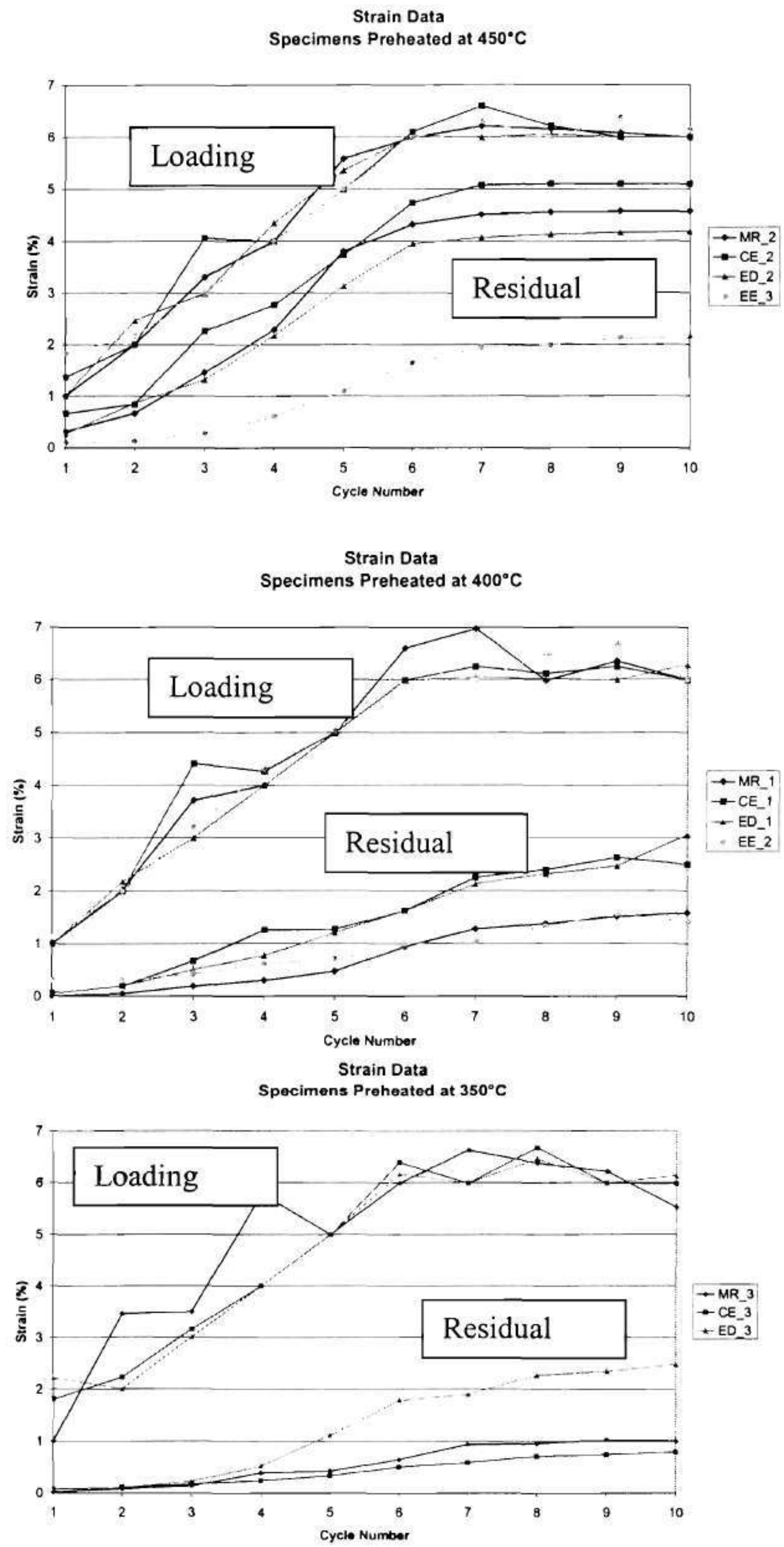


Figure 6 - Loading and Residual Strain as a Function of Number of Cycles.

Table 3: Effect of Temperature on the Energy Dissipated, Ultimate Strain, and Residual Strain of Small Diameter SMA Bar.

Center Specimens

Preheat Temperature	Dissipated Energy	Normalized By Volume	Normalized By Mass	Ultimate Strain	Residual Strain
350°C	0.1398 k-in	1053 k-in/in^3	4519 k-in/lb	22.45%	0.79%
400°C	0.0936 k-in	731 k-in/in^3	3137 k-in/lb	29.82%	2.52%
450°C	0.0279 k-in	208 k-in/in^3	893 k-in/lb	18.41%	5.10%

Mid-Radius Specimens

Preheat Temperature	Dissipated Energy	Normalized By Volume	Normalized By Mass	Ultimate Strain	Residual Strain
350°C	0.1478 k-in	1127 k-in/in^3	4837 k-in/lb	27.57%	1.01%
400°C	0.1313 k-in	972 k-in/in^3	4172 k-in/lb	21.16%	1.58%
450°C	0.0444 k-in	321 k-in/in^3	1378 k-in/lb	18.07%	4.57%

Marked Edge Specimens

Preheat Temperature	Dissipated Energy	Normalized By Volume	Normalized By Mass	Ultimate Strain	Residual Strain
350°C	0.1158 k-in	888 k-in/in^3	3811 k-in/lb	28.80%	2.48%
400°C	0.1023 k-in	736 k-in/in^3	3159 k-in/lb	20.44%	3.06%
450°C	0.0541 k-in	357 k-in/in^3	1532 k-in/lb	12.15%	4.18%

Ear-Edge Specimens

Preheat Temperature	Dissipated Energy	Normalized By Volume	Normalized By Mass	Ultimate Strain	Residual Strain
400°C	0.1103 k-in	826 k-in/in^3	3545 k-in/lb	17.62%	1.42%
450°C	0.1179 k-in	883 k-in/in^3	3790 k-in/lb	13.24%	2.14%

Large Diameter Bars

The lack of information on large section behavior of SMA's is a fundamental reason that SMA's have not been implemented as seismic dampers in structures. In this section three 1-inch diameter bars are tested to determine their energy dissipating characteristics. Similar to the study of the small diameter bars, these bars are tested as a function of three different heat treatment temperatures. Most of the research to date on SMA's has been in the biomedical and aerospace industry, with SMA sizes ranging from 0.05-1.0 mm in diameter. It is generally thought that large section rods do not exhibit the same energy dissipating characteristics as smaller sections, although few studies exists to quantify this assumption.

A full-scale SMA restrainer bar is tested. The restrainer consists of a 305 mm long, 25.4 mm diameter Nitinol shape memory alloy bar, as shown in Figure 7. The SMA bars are fully annealed and 25% cold-worked. The samples are threaded at the ends and vacuum annealed at 450 degrees C for 60 minutes, followed by water quenching. The testing was performed at room temperature (22 degrees C), at a strain rate of 0.10 mm/mm/s.

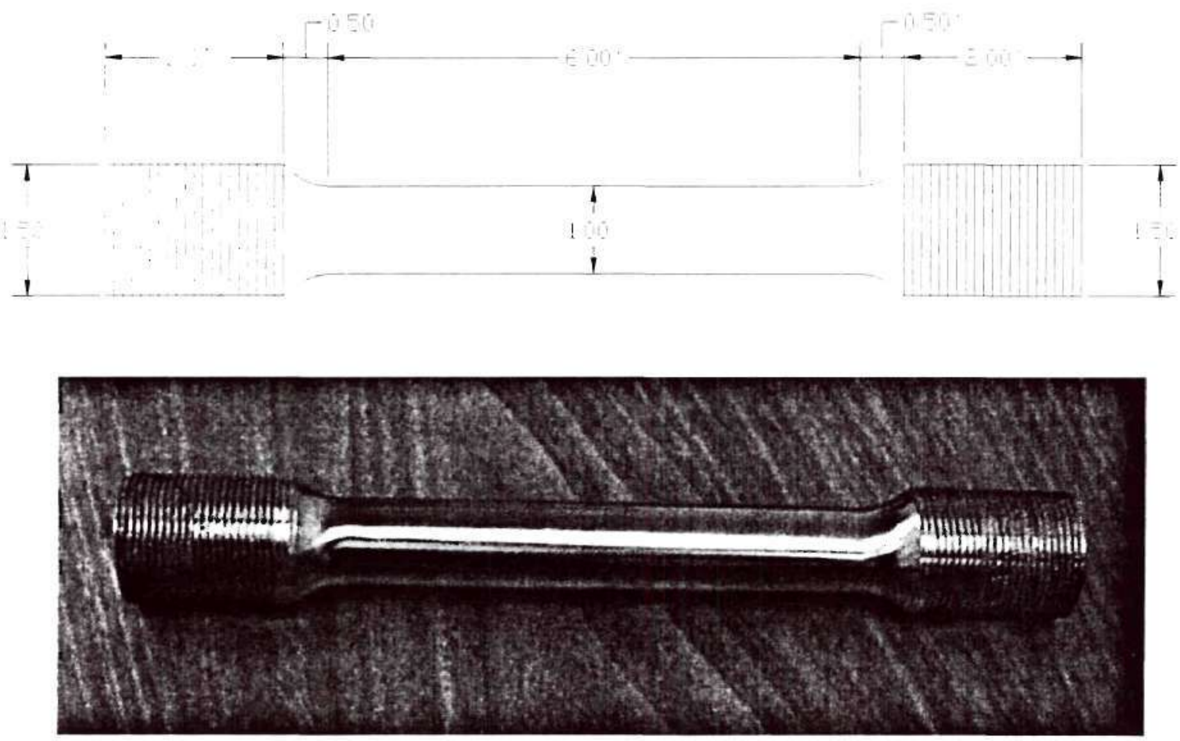


Figure 7 – Large Superelastic Nitinol SMA Bar (Top: Schematic, Bottom: Photo).

The idealized stress-strain curve of a NiTi damper under tension cyclic loading is shown in Figure 8. The specimens were loaded at increasing strains ranging from 0.5% to 8.0% strain. A stress-strain curve from this test is shown in Figure 9. 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 hardening of approximately 7%. Figure 9 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. Figure 9 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. The bars failed at approximately 10% strain, due to stress concentrations at the connections.

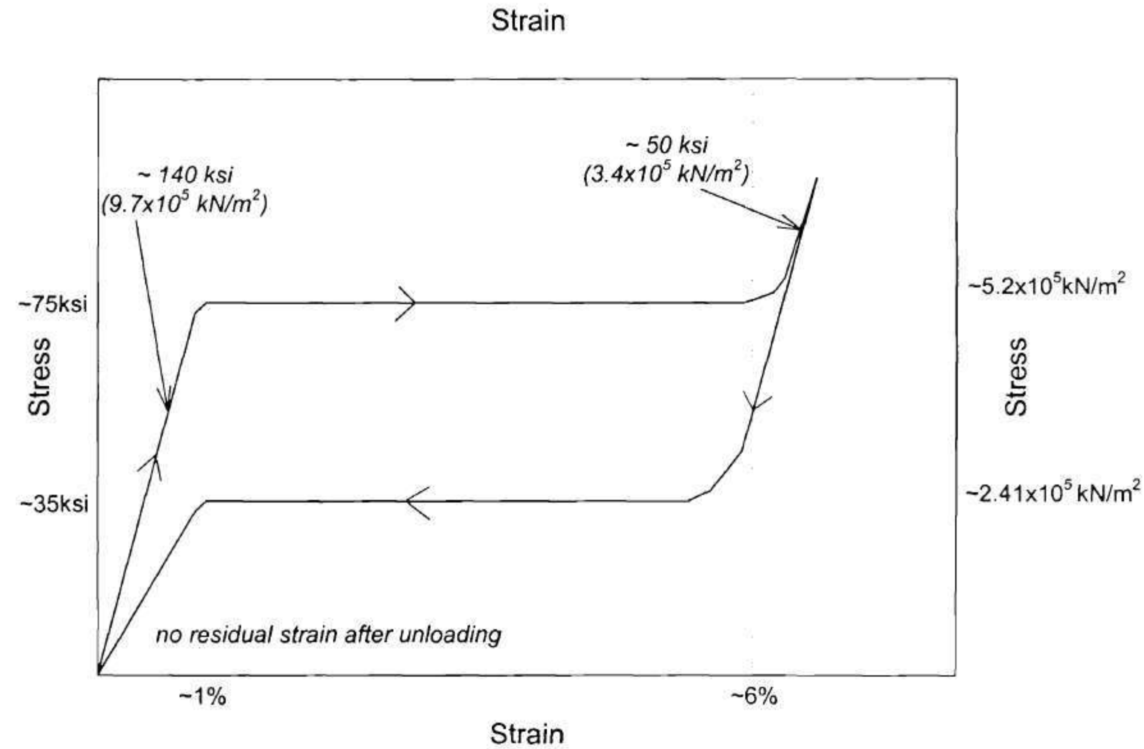


Figure 8 – Idealized Behavior of Superelastic SMA.

Discussion of Results

The results of the tests of the 1-inch diameter SMA bars show that, in fact, nearly perfect superelastic behavior can be obtained when bars are properly heat treated. This leads to the potential application of using SMA as dampers in large-scale structures, such as bridges. Table 4 below compares the energy dissipating characteristics of the large bars for different preheating temperatures.

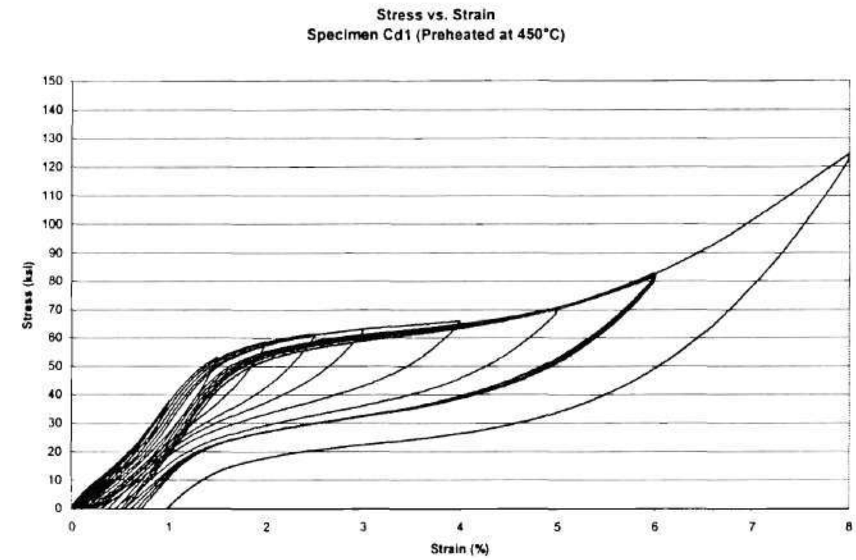


Figure 9 - Stress vs. Strain Diagram for Bar Diameter = 1 inch in Tension.

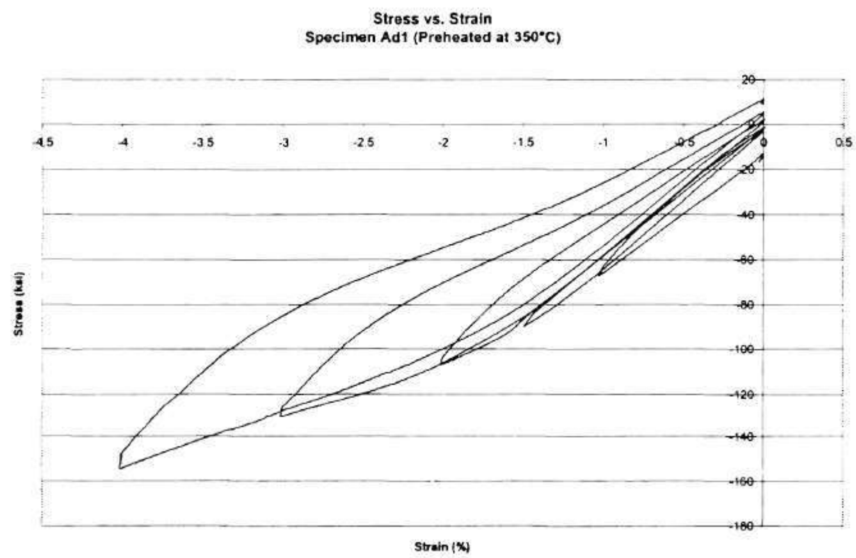


Figure 10 - Stress vs. Strain Diagram for Bar Diameter = 1 inch in Compression.

Table 4: Energy Dissipation for Different Preheat Temperatures.

Bars Tested at University of Illinois

Preheat Temperature	Dissipated Energy	Normalized By Volume	Normalized By Mass
350°C	2498 k-in	530 k-in/in^3	2275 k-in/lb
400°C	3515 k-in	746 k-in/in^3	3202 k-in/lb
450°C	7761 k-in	1647 k-in/in^3	7069 k-in/lb

Martensitic SMA

Another form of shape memory alloy worth investigation is martensitic SMA, shown in Figure 11. As previously shown in Table 1, the martensitic form of SMA has a lower modulus of elasticity and a lower yield stress than superelastic SMA, which makes it slightly less effective as a restraining device, but quite effective as an energy dissipation device. Figure 12 shows the idealized behavior of martensitic SMA. Previous experimental data has shown that martensite is extremely effective as an energy dissipation device. Figures 13 and 14 show the stress-strain histories of these experiments. Both before and after heating, it can be seen that it exhibits a very repeatable and wide hysteretic behavior.

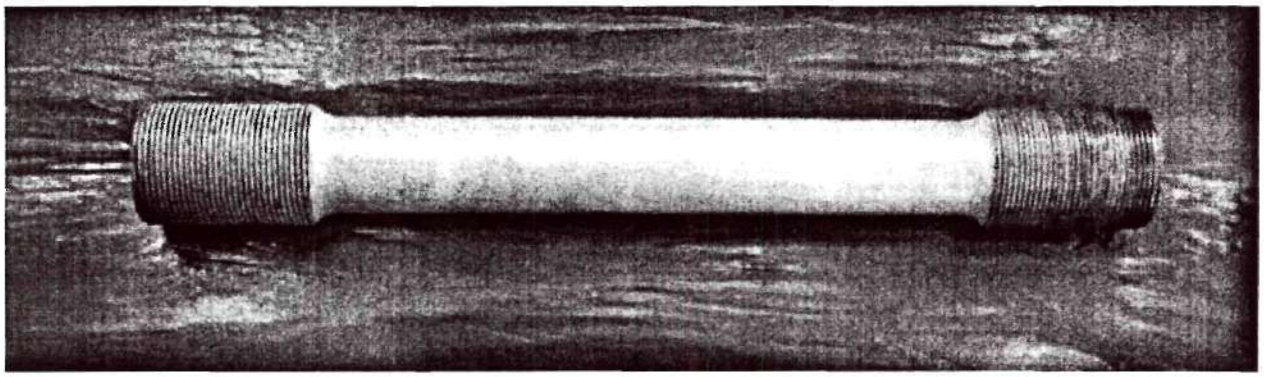


Figure 11 - Martensitic Nitinol SMA.

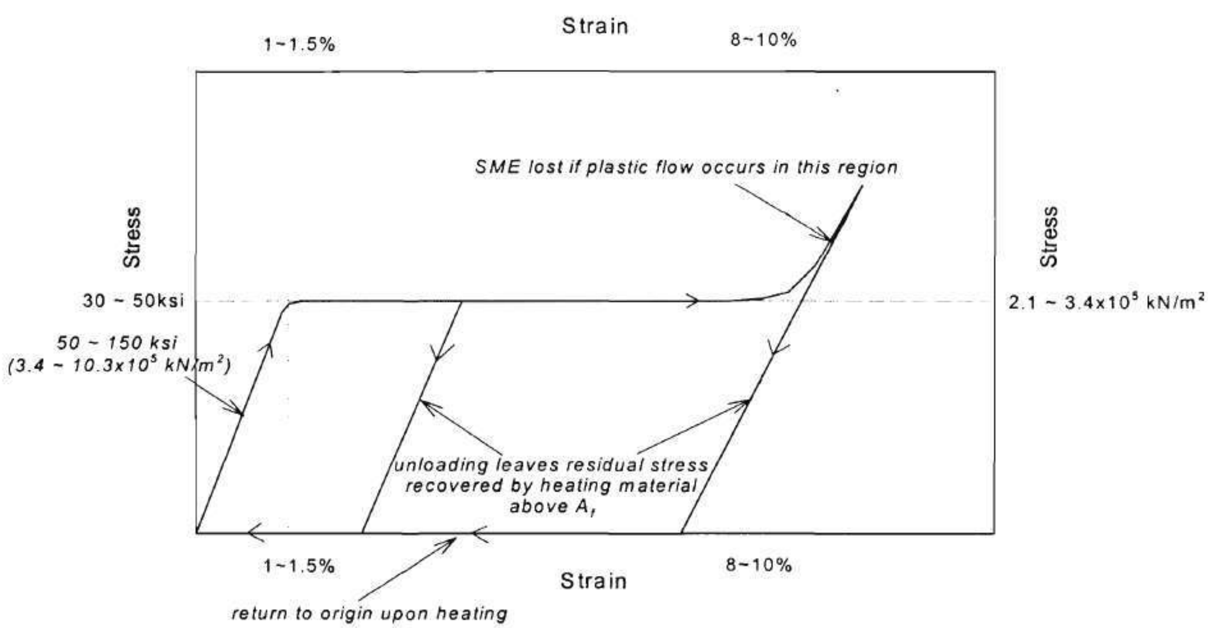
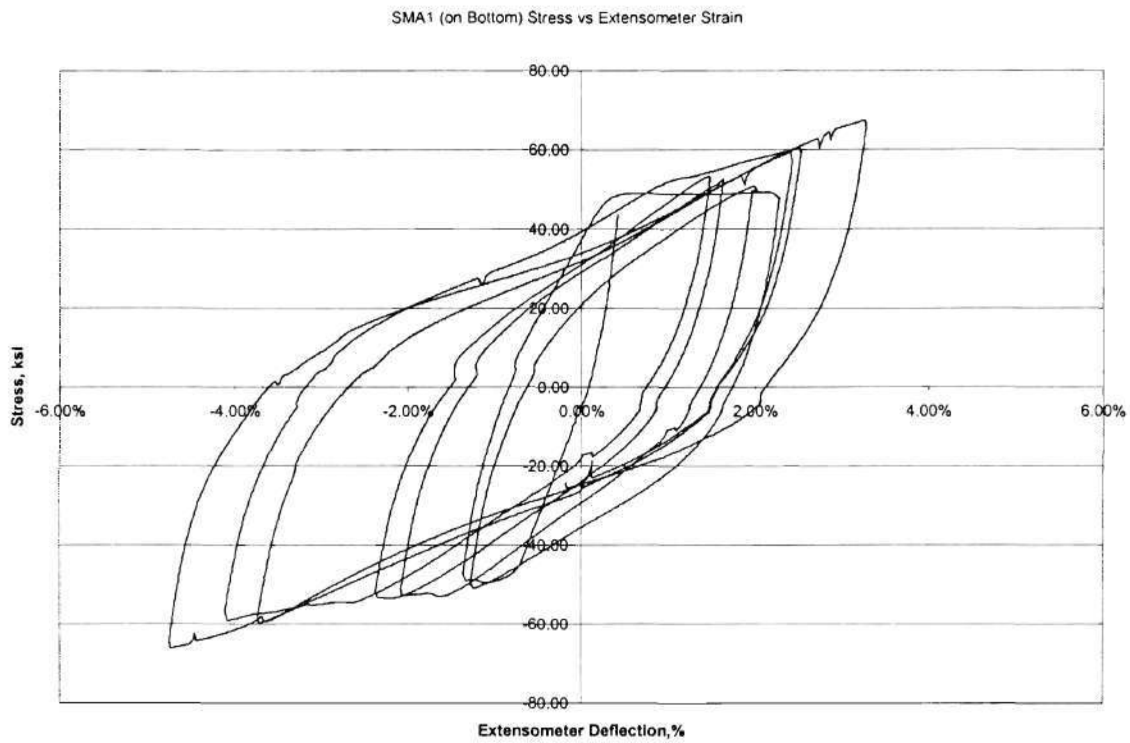


Figure 12 - Idealized Behavior of Martensitic SMA.



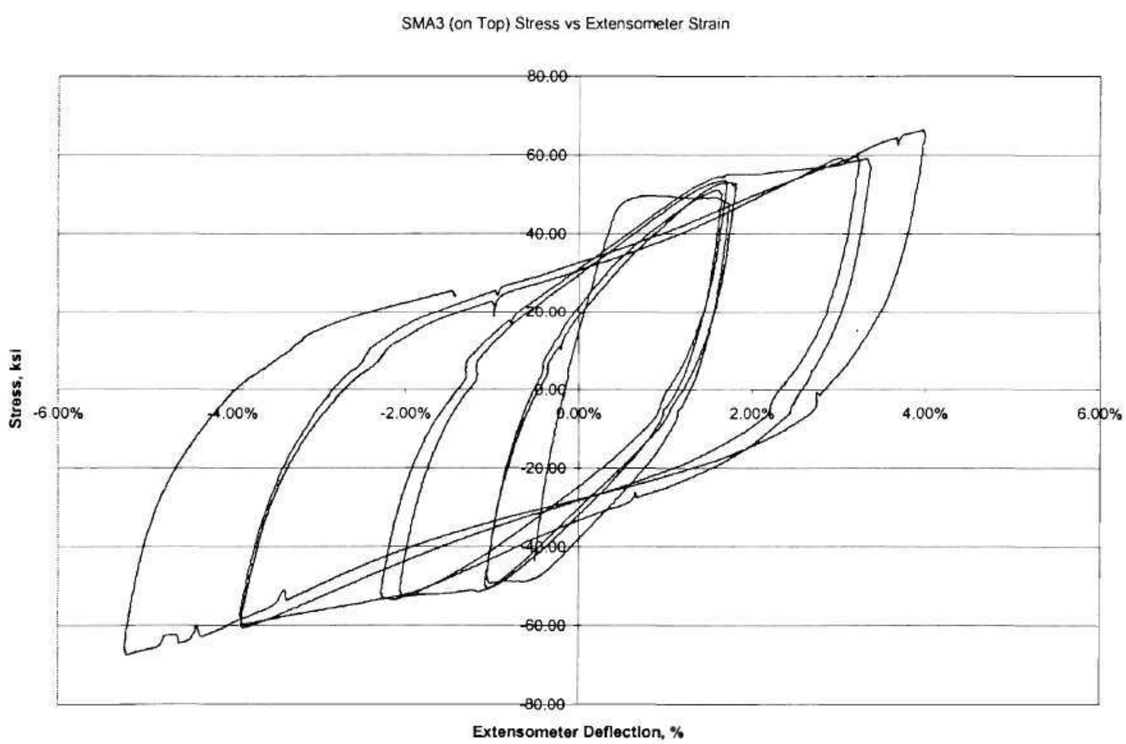
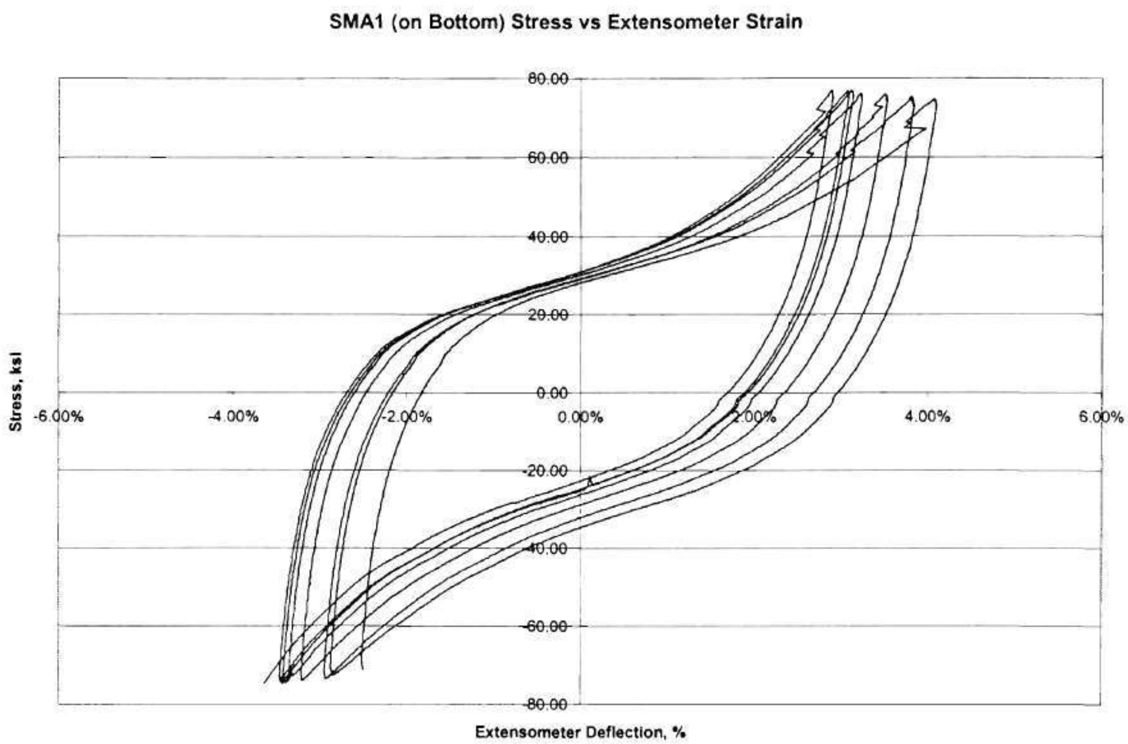


Figure 13 - Stress-Strain Curve for Martensitic SMA before Heating.



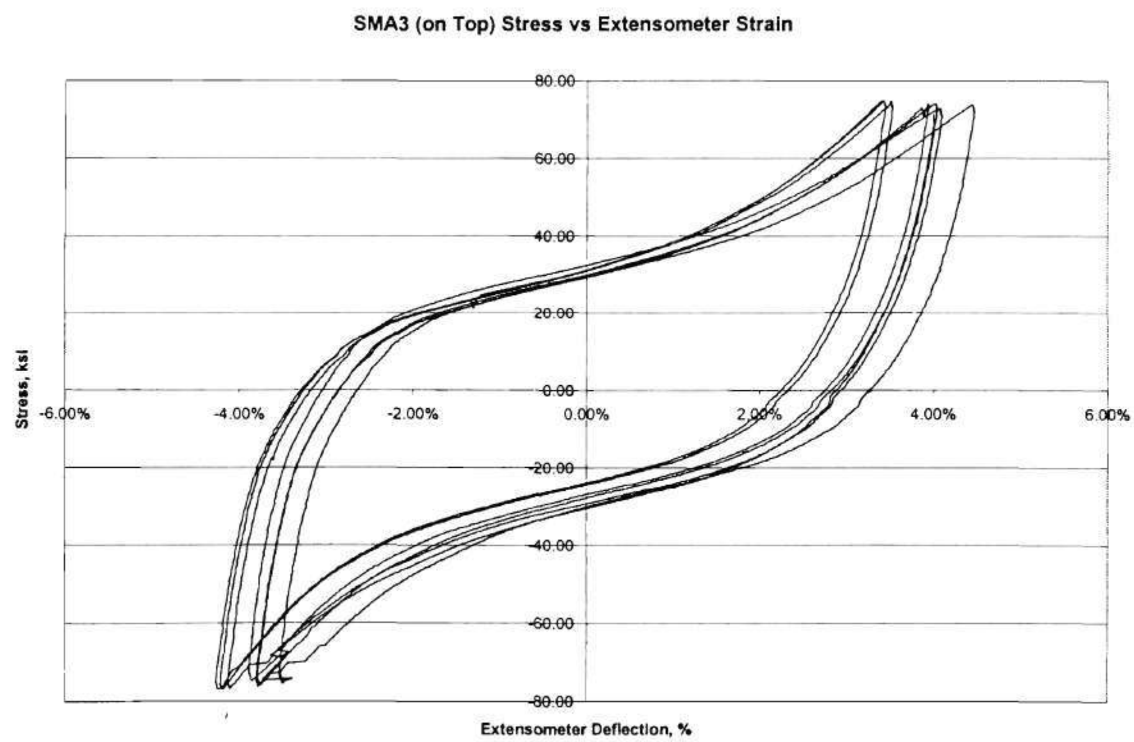


Figure 14 - Stress-Strain Curve for Martensitic SMA after Heating.

Performance of Conventional Hinge Restrainers in Bridges

Unseating of simple spans and frames has been a major problem in recent earthquakes, such as the 1989 Loma Prieta, 1994 Northridge, 1995 Kobe, and 1999 Taiwan earthquakes.

The Caltrans Maintenance Division reported that 23 bridges that had hinge restrainers suffered damage during the 1989 Loma Prieta earthquake and in two instances the restrainers failed (Saiidi et al., 1993). The Richardson Bay Bridge and Separation is a 21-span bridge built in 1957 and retrofitted with cable restrainers in 1973. Failure of the restrainer and the connection devices was observed at the hinges. In addition the diaphragm cracked where the restrainers were connected. The Oakland Overcrossing (West Grand Avenue Viaduct) is a steel girder bridge built in 1937 and retrofitted in 1976. The retrofit consisted of longitudinal restrainers at each joint connected by steel brackets to the bottom girder flange or web. Failure of the restrainers and connection devices was also observed at the hinges. Yielding of restrainers occurred in the China Basin Viaduct and the Route 92/101 Separation. In addition, excessive crack opening in the soffit of the superstructure was observed. It is believed that the restrainer forces in the superstructure reduced the flexural strength and helped open the flexural cracks that were developed by the gravity loads. There were several other bridges in which restrainers were engaged but did not yield or sustain damage.

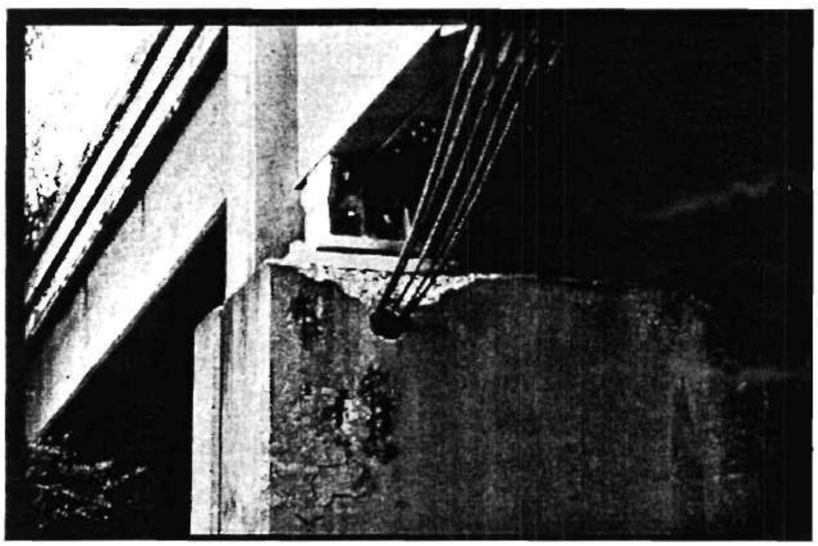


Figure 15 - Damage due to Restrainers from the 1989 Loma Prieta Earthquake.

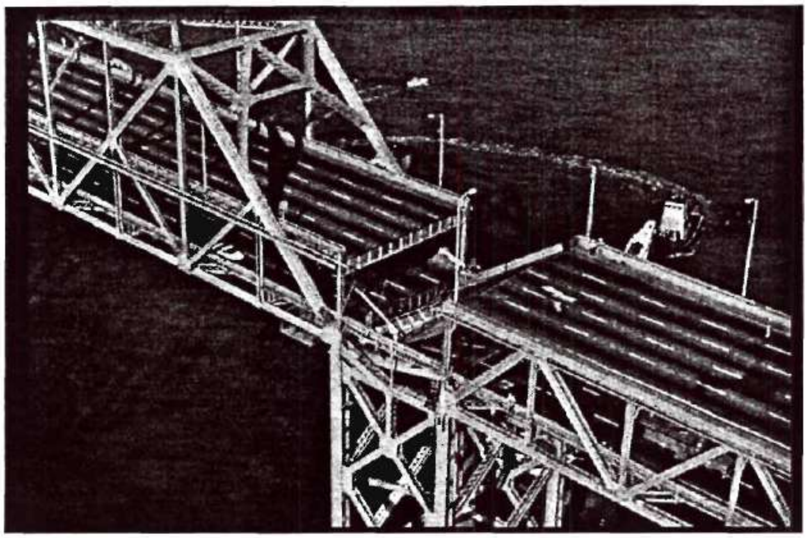


Figure 16 - Span Unseating due to the 1989 Loma Prieta Earthquake.

The epicentral region of the 1994 Northridge Earthquake contained several bridges which had been retrofitted with hinge restrainers, and most of the bridges performed well. However, in some cases, hinge restrainers did not perform adequately. The Gavin Canyon Undercrossing is a concrete box-girder bridge which had been retrofitted in 1974 with restrainer cables and diaphragm bolsters across the in-span hinges. The heavily skewed bridge collapsed due to unseating. The end frames in the bridge were vulnerable to in-plane torsional response because of the eccentricity of the centers of mass and stiffness. The restrainer cables provided minimal restraint to transverse displacement at the hinge. Based on the observed damage, it is difficult to determine whether restrainers failed before or after loss of seat support. (Moehle, 1995: Priestley et al., 1994). The Interstate 5/State Road 14 Interchange and the South Connector Overcrossing are concrete box-girder bridges located approximately 12 km from the epicenter. It had also been retrofitted with cable restrainers following the 1971 San Fernando earthquake. Although the collapse of a frame was caused by shear failure in columns, spans in other frames that did not collapse were barely supported on hinge seats. Other structures in the interchange showed evidence of hinge and restrainer damage. The older C-1-type restrainers had been grouted during installation. The grouting led to large strains in the cable outside the grouted segment and premature fracture. Several bridges had evidence of pounding at the hinges.

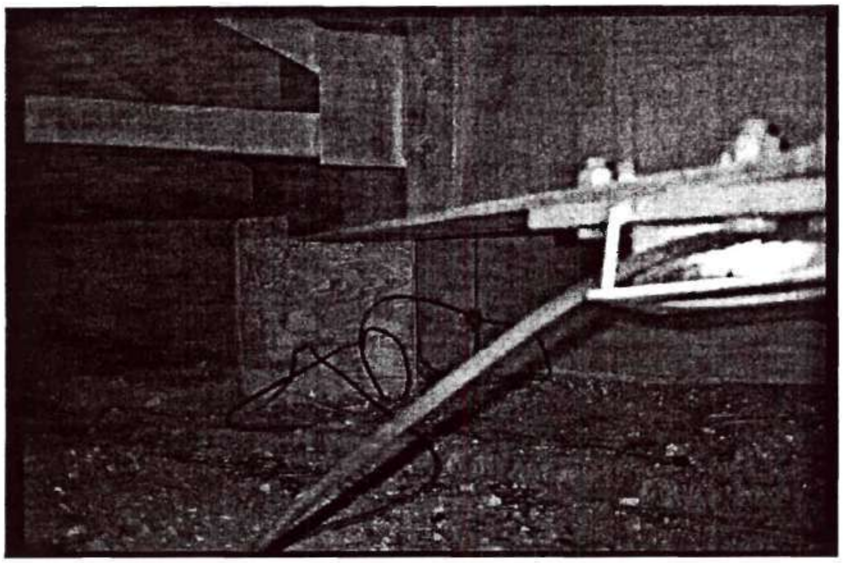


Figure 17 - Restrainer Failure due to the 1994 Northridge Earthquake.

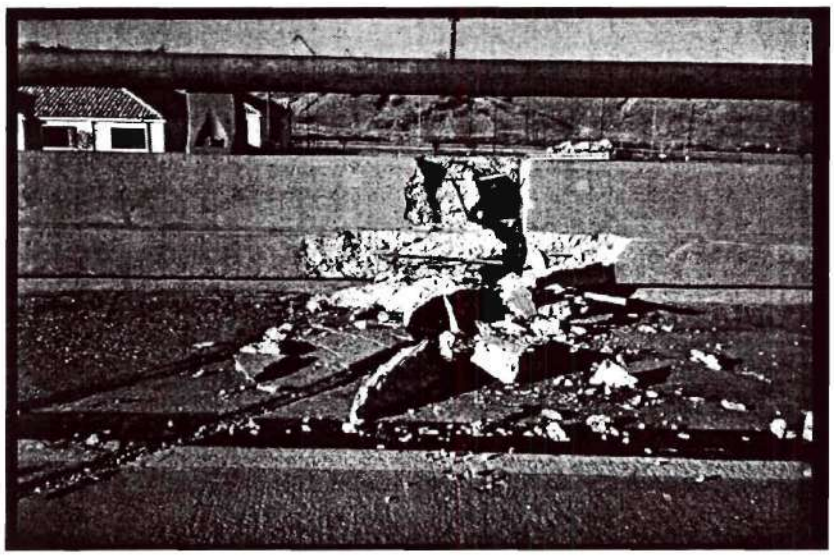


Figure 18 - Pounding Damage due to the 1994 Northridge Earthquake.

The Hanshin Expressway, which is the major traffic artery through the city of Kobe, sustained extensive damage in the 1995 Hyogo-Ken Nanbu (Kobe) earthquake. Inadequate seat widths and insufficient restrainers ("falling-off prevention devices") caused many spans to fall off their bearings and bents (Comartin et al., 1995). The eastern portion of the Hanshin Expressway is nearly normal to the strike-slip fault which produced primarily longitudinal movement due to the fault normal near source effect of the earthquake. The Harbor Freeway also sustained significant damage. In particular, almost every expansion joint along the freeway was damaged. Many hinge restrainers sustained damage and failure.

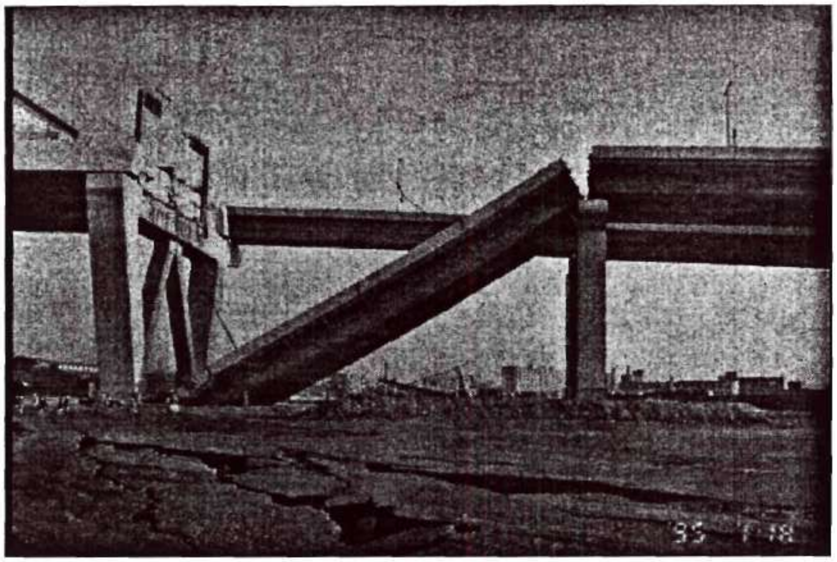


Figure 19 - Span Unseating due to the 1995 Kobe Earthquake.

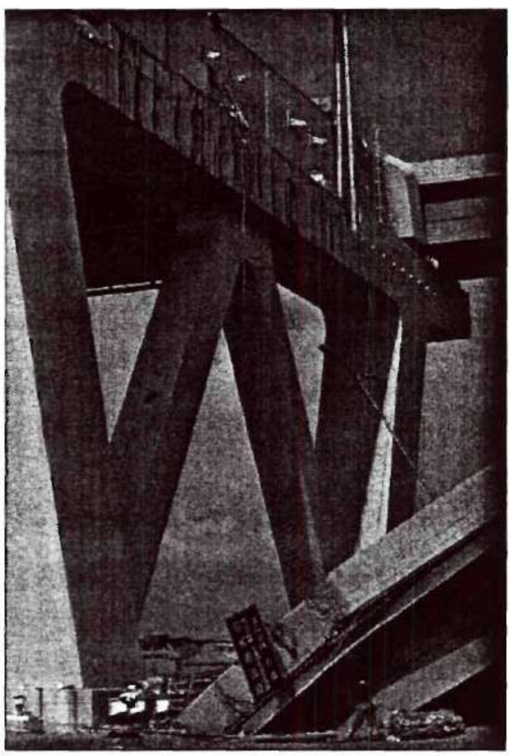


Figure 20 - Closer View of Span Unseating due to the 1995 Kobe Earthquake.

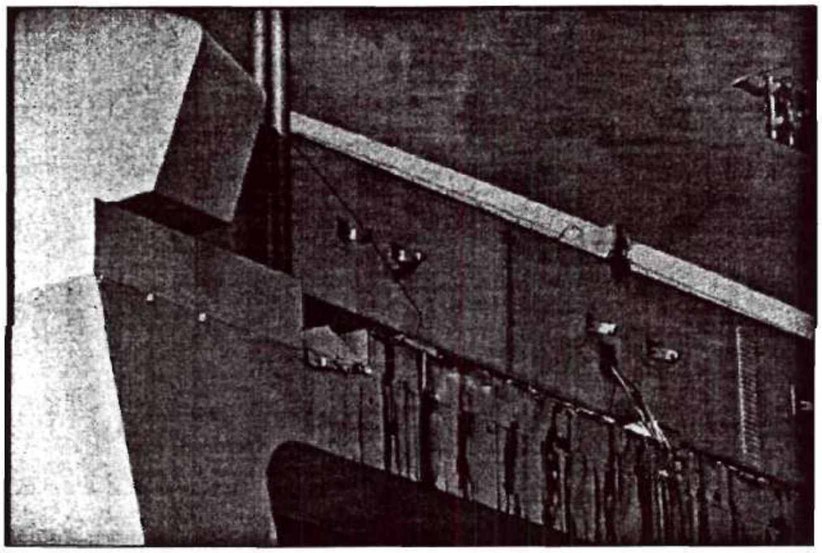


Figure 21 - Restrainer Failure due to the 1995 Kobe Earthquake.

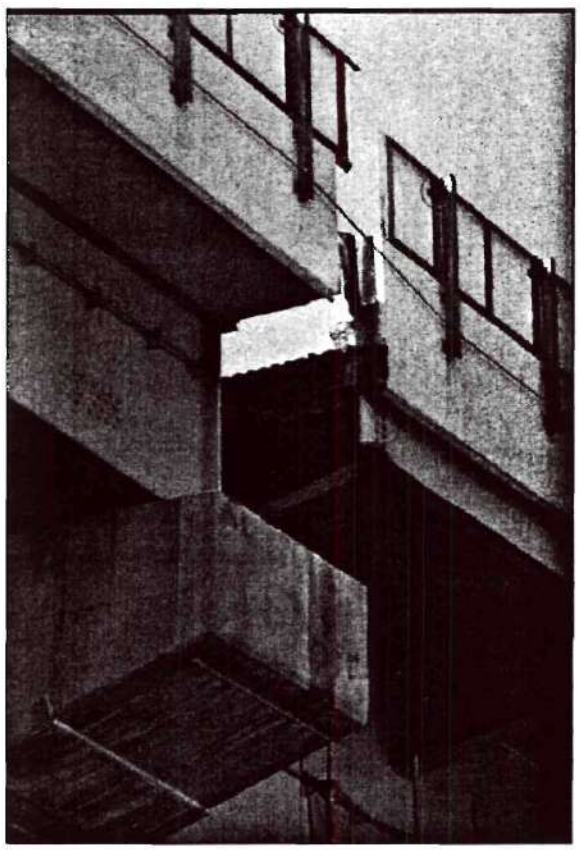


Figure 22 - Permanent Hinge Opening due to the 1995 Kobe Earthquake.

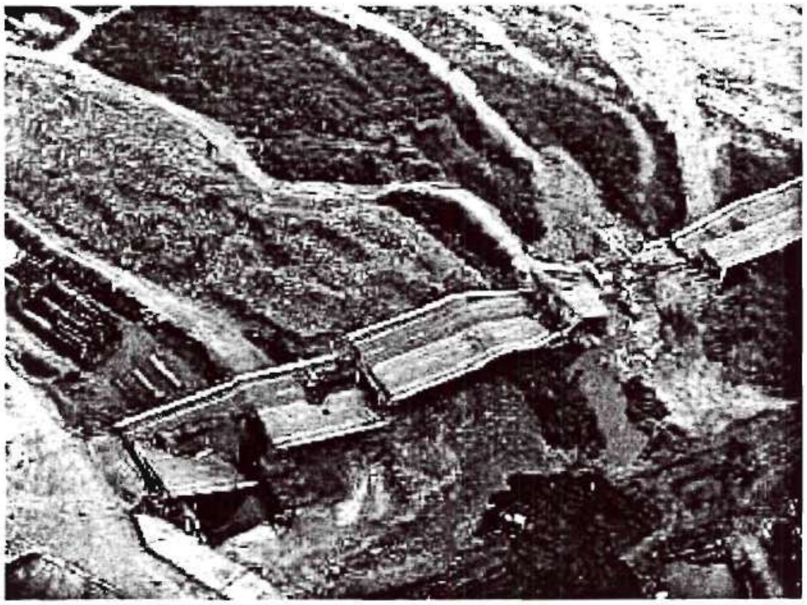


Figure 23 - Span Unseating due to the 1999 Taiwan Earthquake.

Figure 24 - Span Unseating due to the 1999 Taiwan Earthquake.

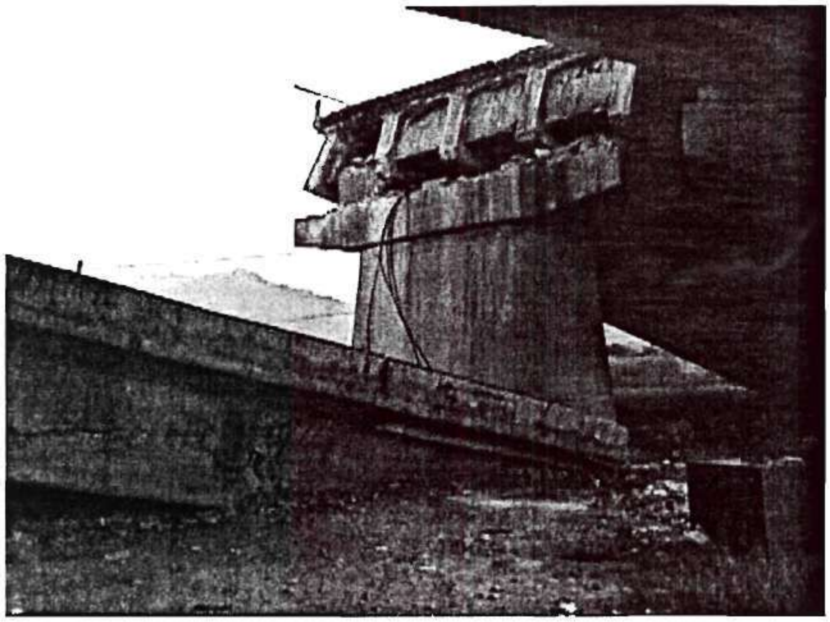


Figure 25 - Span Unseating due to the 1999 Taiwan Earthquake.

Application of SMA Restrainers to Multi-Span Bridges

In phase 2, analytical studies of typical bridges with the SMA restrainers were conducted to determine the effectives of the SMA restrainers in limiting the relative hinge displacement at the hinge in bridge decks. Using the results of the experimental tests from phase 1, nonlinear analytical models of the bridges are developed. A suite of strong ground motion is used to simulate the effects of the SMA restrainers on the response of the bridge.

The relative displacement of multiple-span simply supported bridges at the hinges and abutments can result in collapse of the bridge if it exceeds the allowable displacement. 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 3 spans supported on multi-column bents, as shown in Figure 26. Each bent has 4 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 Figure 27. 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 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.

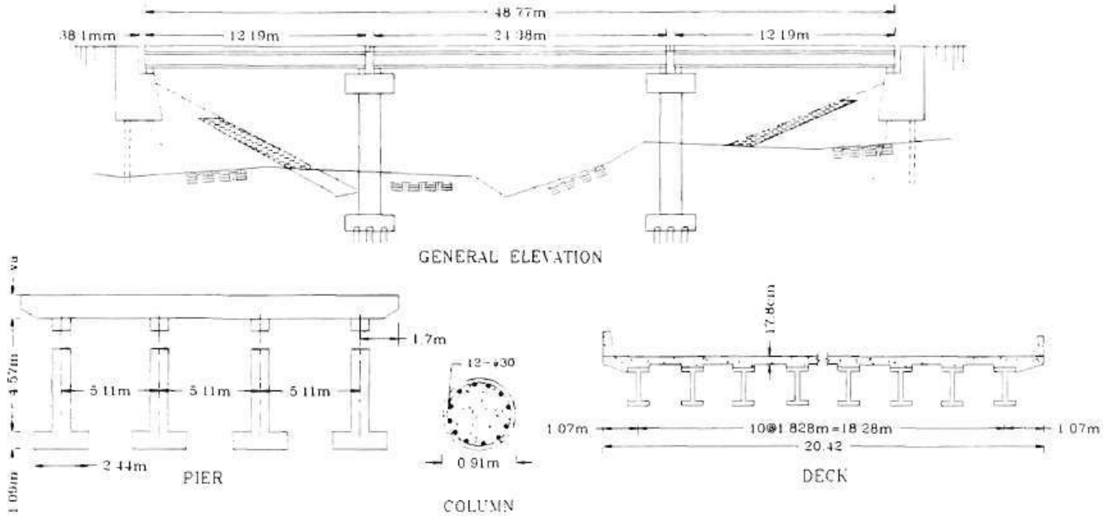


Figure 26 – Typical Multi-Span Simply Supported Bridge.

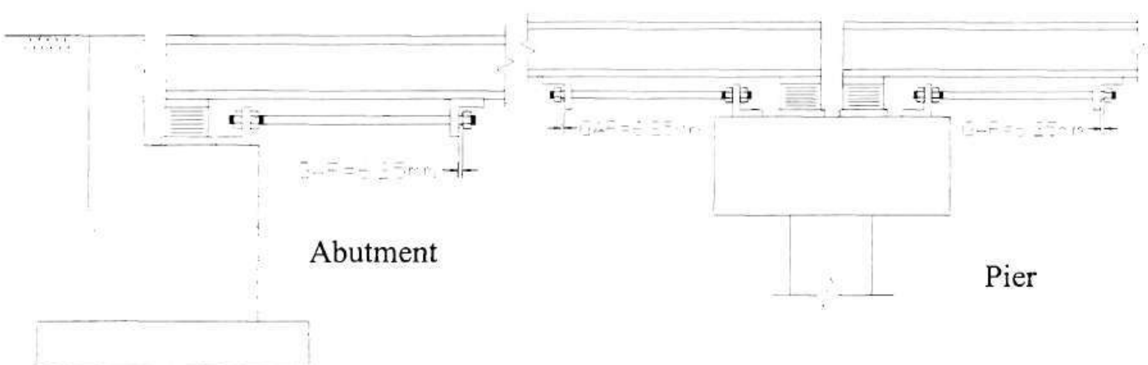


Figure 27 – Configuration of Shape Memory Alloy Restrainer Bar Used in Multi-Span Simply Supported Bridge at Abutments and Intermediate Piers.

Analytical Modeling of the Multi-Span Simply Supported Bridge

A 2-dimensional nonlinear numerical model of the 3 span, simply supported bridge is developed using the DRAIN-2DX nonlinear analysis program. 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. 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.

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 Figure 28. The SMA restrainers are modeled as tension-only multi-linear elements and represent the force-displacement relationship of the SMA's, 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 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 small 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 restrainer cables evaluated are 1.52 m (5 ft.) long, 19.1 mm (¾") diameter cables that stretch approximately 30.5 mm (1.2 inches) at a yield strength of 174 kN (39.1 kips), and 53.3 mm (2.1 inches) at an ultimate strength of 236 kN (53 kips). The conventional restrainer cables are modeled as bilinear springs that only resist tensile forces.

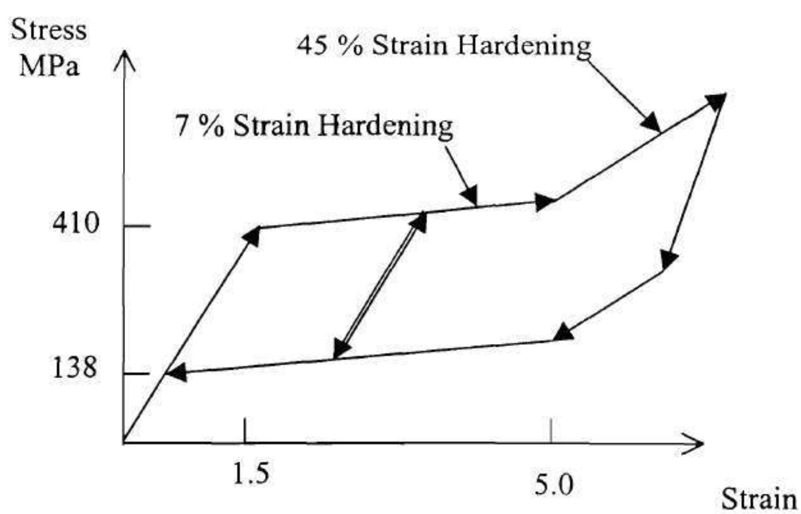


Figure 28 – Analytical Model of SMA Restrainer Used in DRAIN-2DX.

Results

To evaluate the effectiveness of the SMA restrainers, the analytical model of the example bridge shown in Figure 26 is subjected to a set of ground motion records, including the 1940 El Centro (N-S), and the Kobe City 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).

Figure 29 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 0.70g 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 2 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 seconds and again at 12 seconds 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 Figure 30. In contrast to the restrainer cable, the SMA restrainer is effective for repeated cycles, as shown in the response history plot in Figure 31. Although the SMA restrainers are subjected to a maximum deformation of 40 mm at approximately 2 seconds 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 15% more energy.

To evaluate the effectiveness of the SMA restrainers to near field ground motion, the response of the bridge to the 1995 Kobe City record is evaluated. The 1995 Kobe City record was recorded within 5 km of the epicenter of the earthquake and has a peak ground acceleration of 0.85g. 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 Kobe City earthquake is shown in Figure 31. 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 displacement at the abutment. The displacement with the SMA restrainers, 49.9 mm, represents a 63% reduction in the relative displacement at the abutment.

Figure 32 shows the force displacement relationship for the cable restrainer and SMA restrainer bar in the case of the Kobe City earthquake 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 dissipation. 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 Figure 31. 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.

An analytical model was also created and computer analyses were performed using martensitic SMA to examine its efficacy as a bridge restrainer. The results shown in Figures 33 and 34 show that the martensitic SMA reduced the hinge displacement over the entire time history, but did not have considerable effect on the maximum hinge displacement. Therefore it was determined that the effectiveness of using a hybrid configuration of SMA should also be investigated. Several analyses were performed with a combination of superelastic SMA in parallel with martensitic SMA. As shown in Figures 35 and 36, this hybrid was effective in reducing the maximum hinge displacement as well as reducing the hinge displacement over the entire time history.

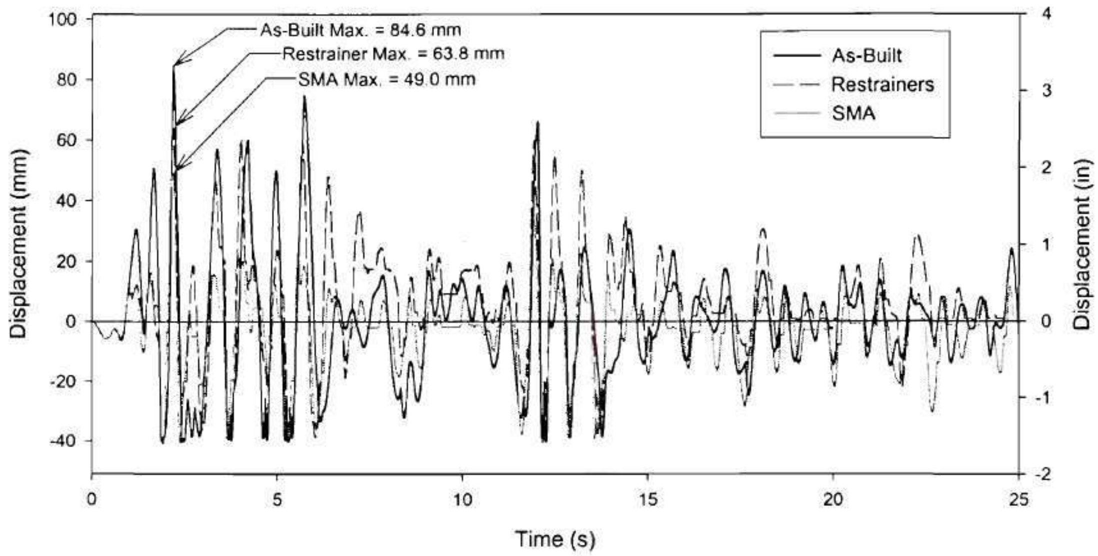


Figure 29 – Comparison of Abutment 2 Displacement Response History for Bridge in As-Built Condition, with Cable Restrainers, and with SMA Restrainers (1940 El Centro Record, Scaled to 0.70g PGA).

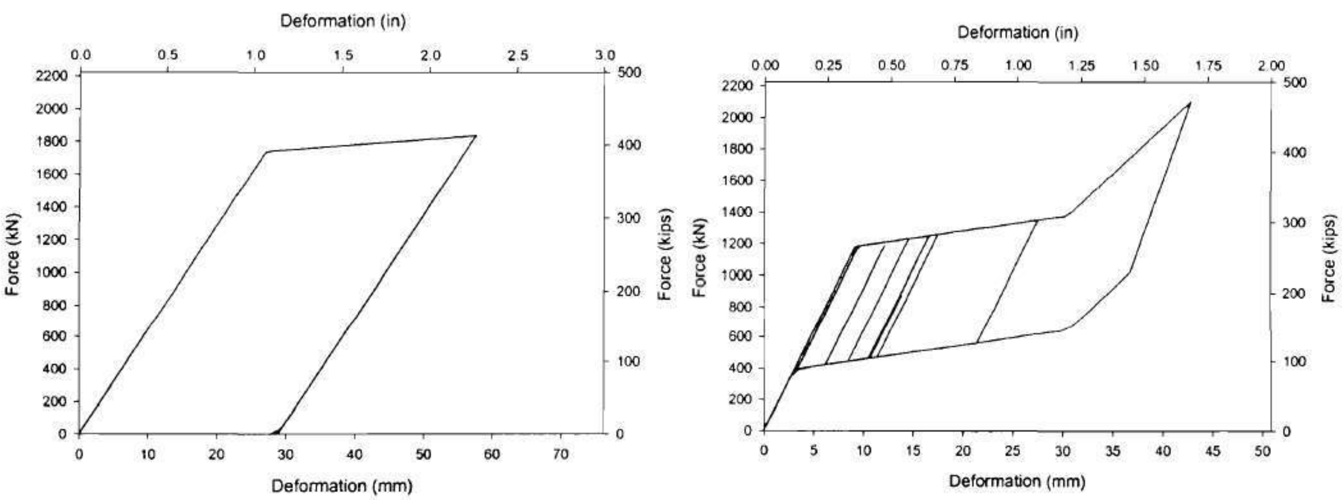


Figure 30 – Force Deformation Relationship for Cable Restrainer (left) and Shape Memory Alloy Restrainer (right) for Bridge Subjected to 1940 El Centro Record, Scaled to 0.70g PGA.

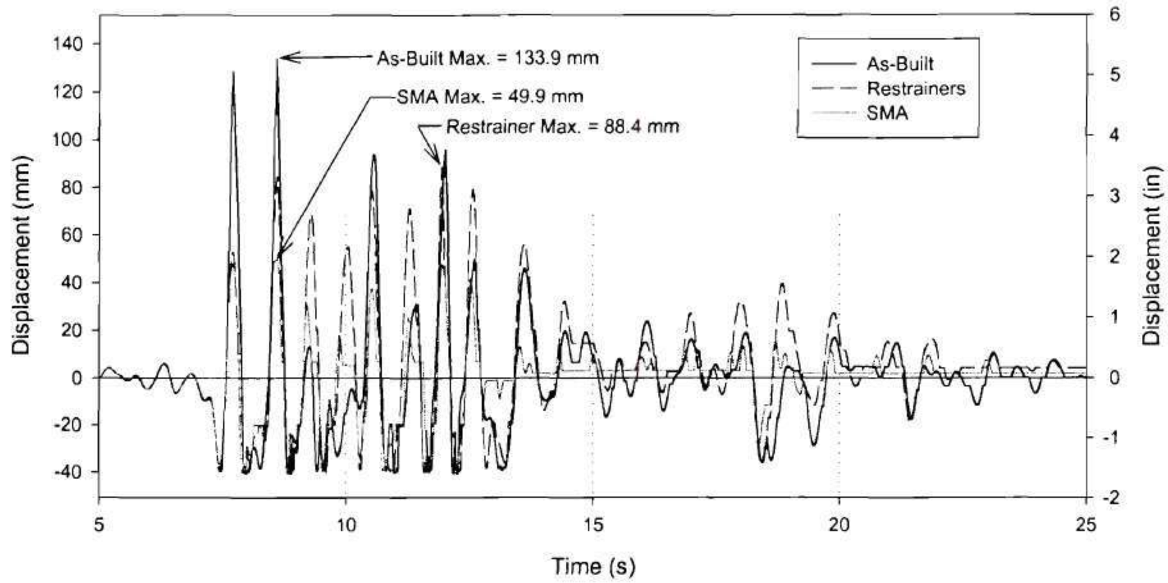


Figure 31 – Comparison of Abutment 2 Displacement Response History for the Bridge in As-Built Condition, with Cable Restrainers, and with SMA Restrainers (Kobe City Record, 1995 Kobe Earthquake).

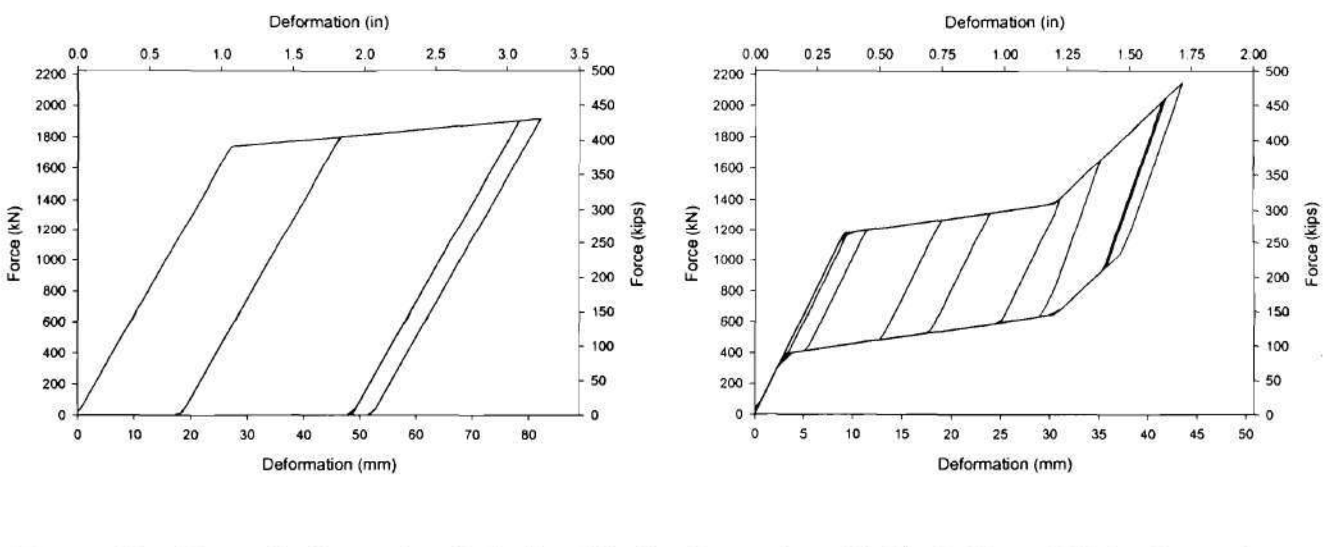


Figure 32 – Force Deformation Relationship for Restrainer Cable (left) and SMA Restrainer (right) for Bridge Subjected to Kobe City Record, 1995 Kobe Earthquake.

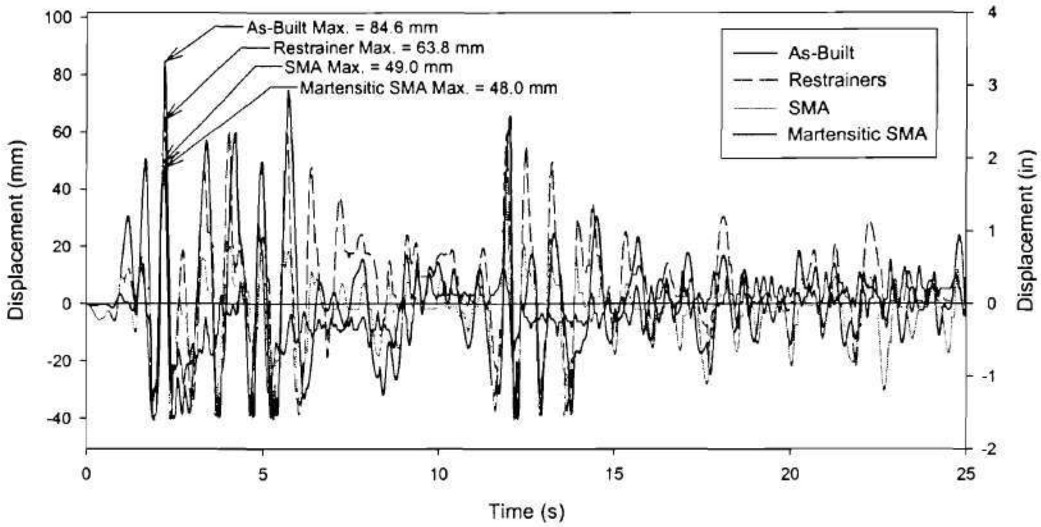


Figure 33 – Comparison of Abutment 2 Displacement Response History for Martensitic SMA (1940 El Centro Record, Scaled to 0.70g PGA).

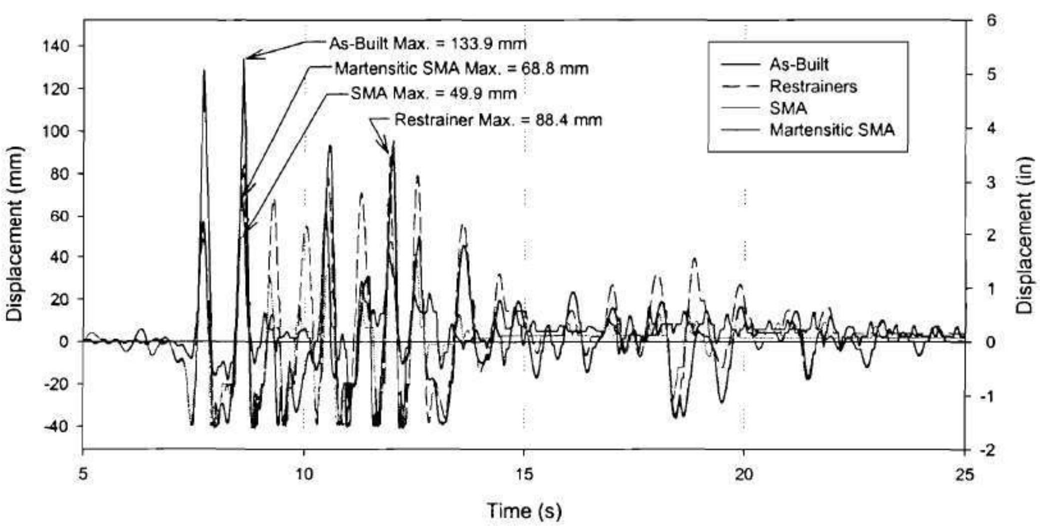


Figure 34 – Comparison of Abutment 2 Displacement Response History for Martensitic SMA (Kobe City Record, 1995 Kobe Earthquake).

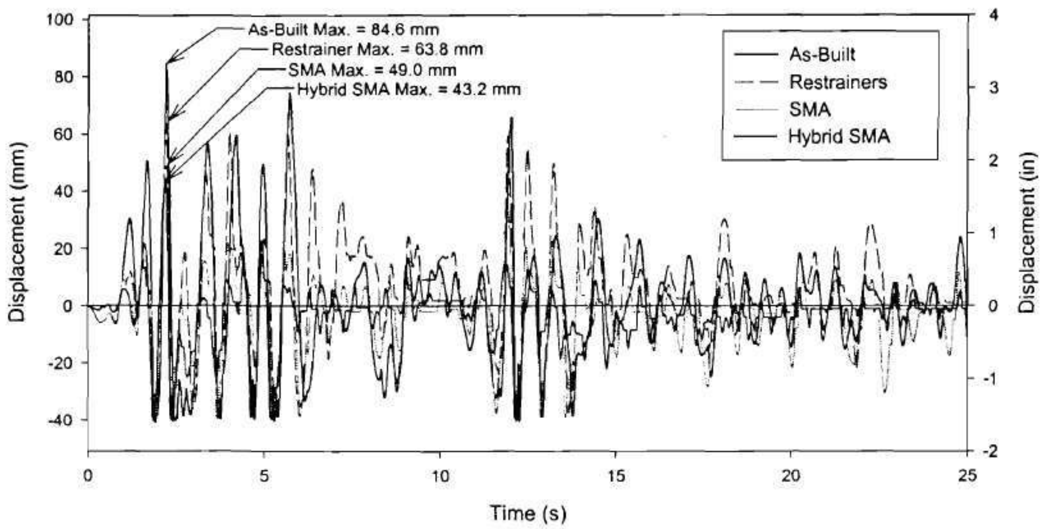


Figure 35 – Comparison of Abutment 2 Displacement Response History for Hybrid SMA (1940 El Centro Record, Scaled to 0.70g PGA).

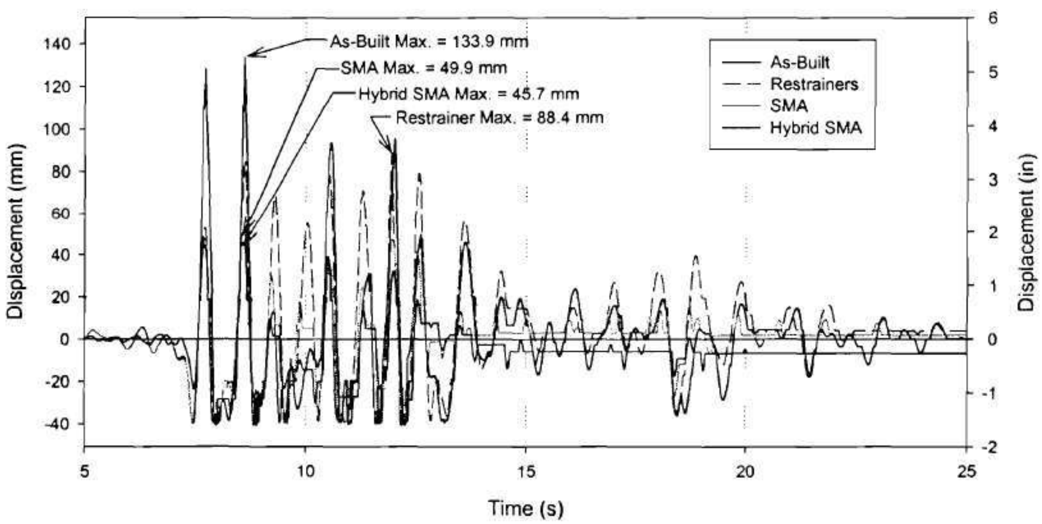


Figure 36 – Comparison of Abutment 2 Displacement Response History for Hybrid SMA (Kobe City Record, 1995 Kobe Earthquake).

Application of SMA Restrainer to Multi-Frame Bridges

SMA restrainers can also improve the seismic response of multiple-frame bridges. They can be designed in the same way as for simply supported bridges to limit the relative displacement below a pre-determined value. The multi-frame bridge considered for this analysis consists of four frames as shown in Figure 37. The SMA restrainers would be connected similar to the way cable restrainers in multi-frame bridges are currently designed, shown in Figure 38. The SMA restrainer would be connected from the end of one frame to the start of the next as shown in Figure 39. Since the SMA restrainers will typically have a length shorter that that of cables, an extension device such as the steel tube shown would be required to reach the entire distance of the connection.

An analytical model similar to that for the simply supported bridge was created in Drain 2D-X for the multi-frame bridge in Figure 37. It was subjected to the same suite of ground motions as the previous model. The response was compared for the as-built model, 30-20 foot restrainer cables, and for 15-1.25"D 60" long SMA restrainers. The responses to the Kobe City and Sylmar ground motion records are shown in Figures 40 and 42, respectively. The force-displacement relationships for the steel cables and SMA restrainers are shown in Figures 41 and 43. The summary shown in Table 5 shows how the SMA restrainers allowed much less relative hinge displacement without significantly increasing pier drifts.

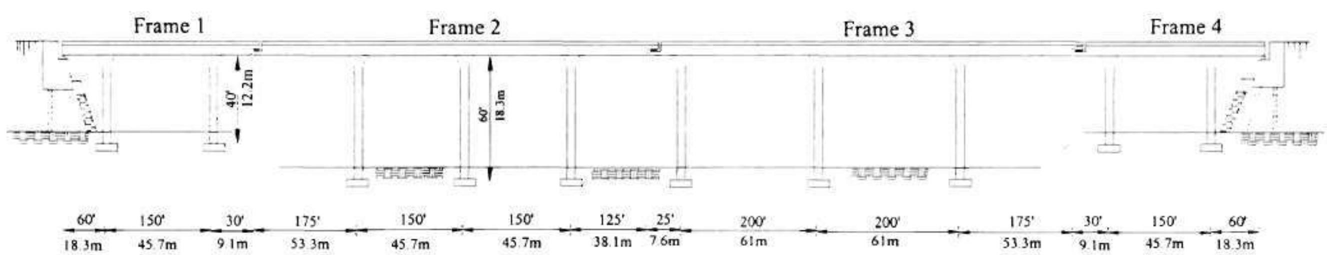


Figure 37 – Typical Multi-Frame Bridge

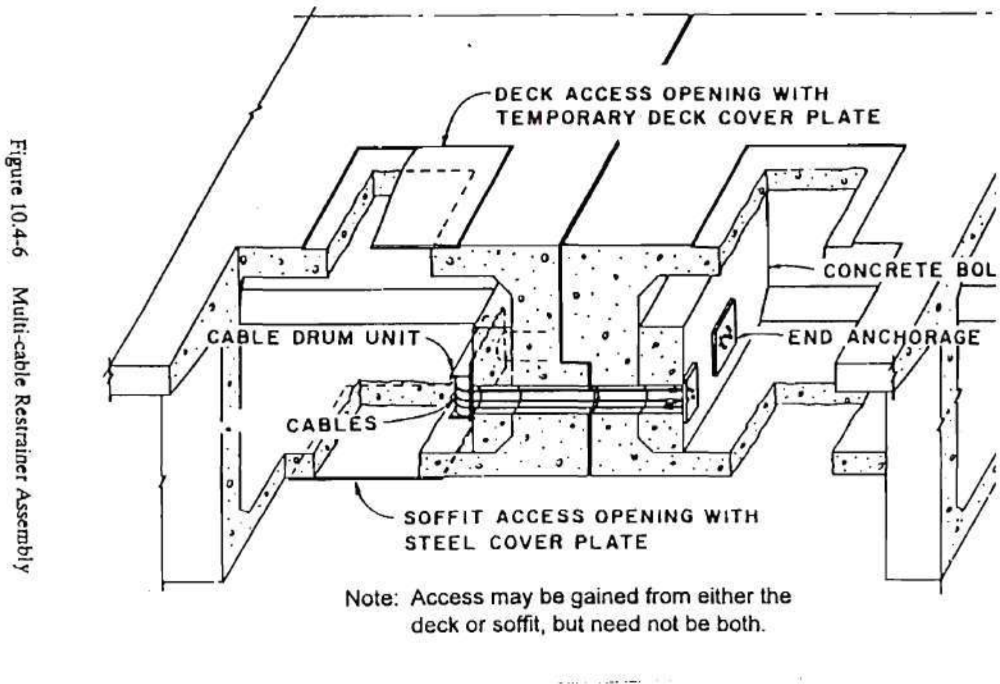


Figure 38 – Typical Steel Restrainer Cable Connection on a Multi-Frame Bridge

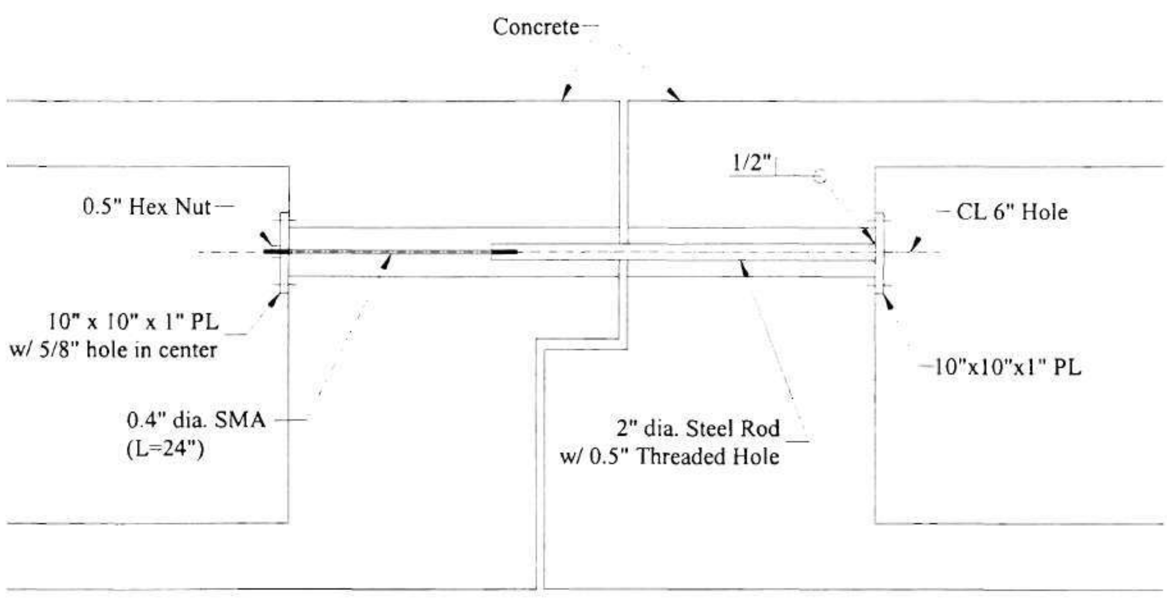


Figure 39 – SMA Restrainer Connection on a Multi-Frame Bridge

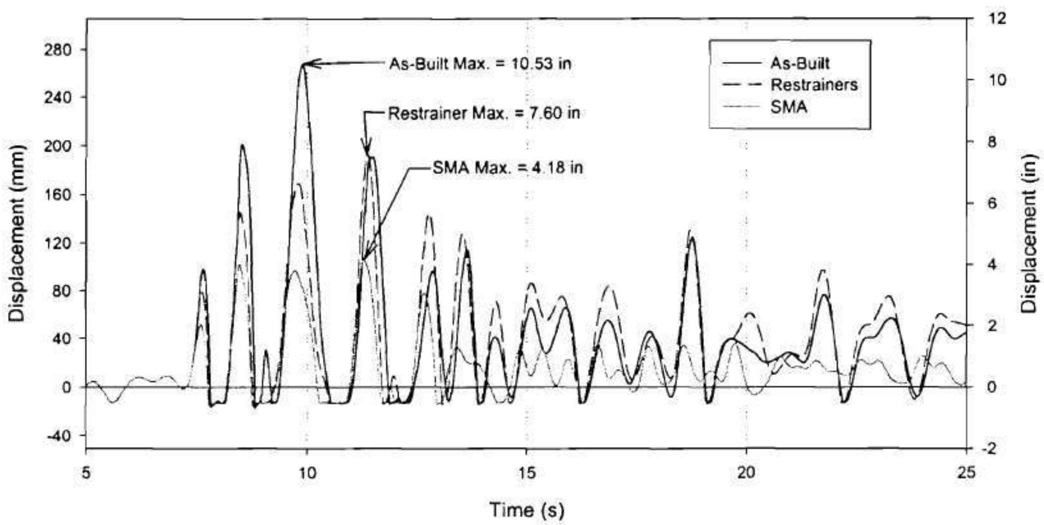


Figure 40 – Comparison of Joint 1 Displacement Response History for the Multi-Frame Bridge (Kobe City Record, 1995 Kobe Earthquake).

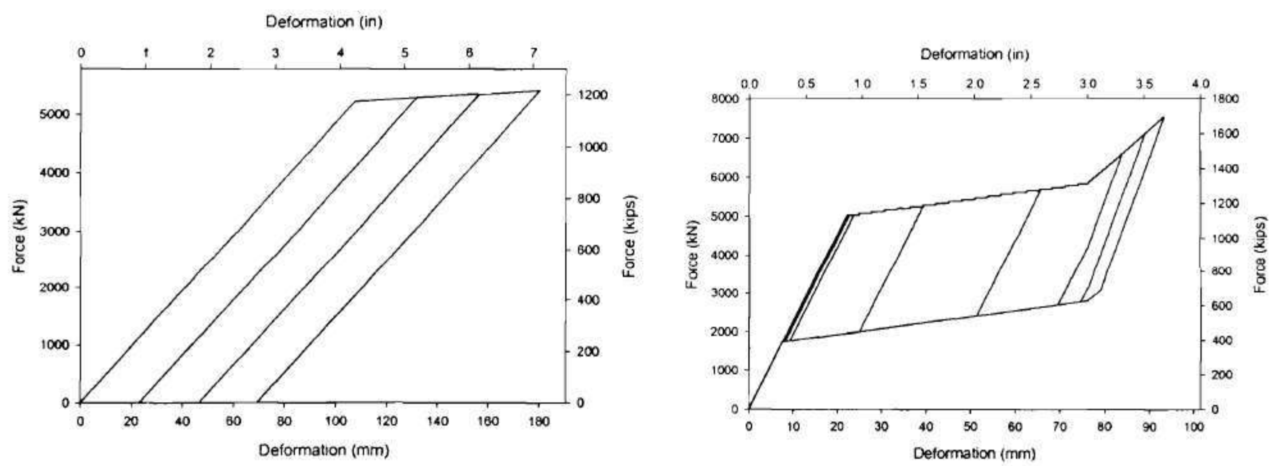


Figure 41 – Force Deformation Relationship for Restrainer Cable (left) and SMA Restrainer (right) for Multi-Frame Bridge subjected to Kobe City Record, 1995 Kobe Earthquake.

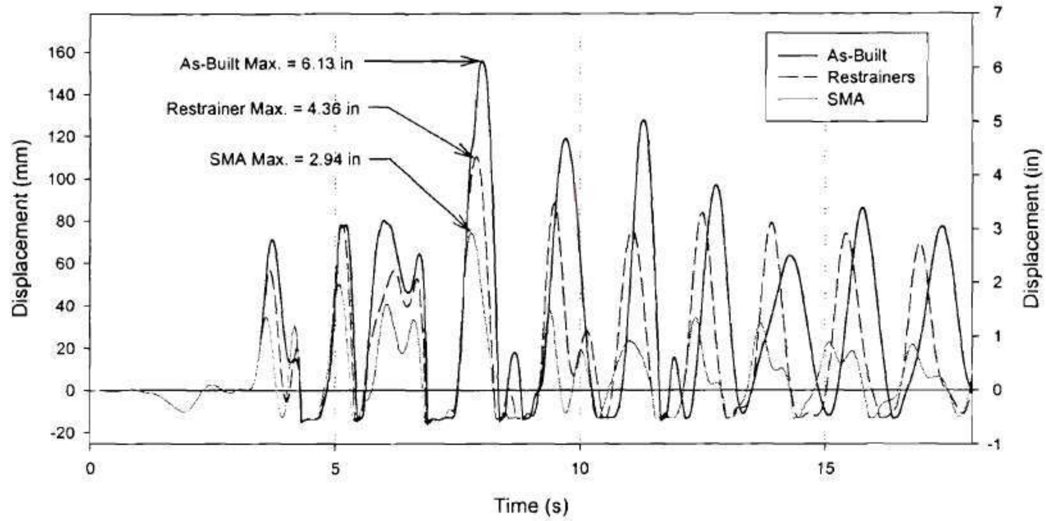
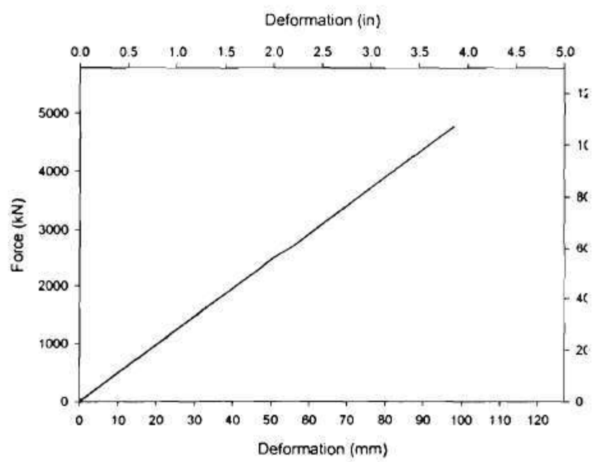


Figure 42 – Comparison of Joint 1 Displacement Response History for the Multi-Frame Bridge (Sylmar Earthquake).



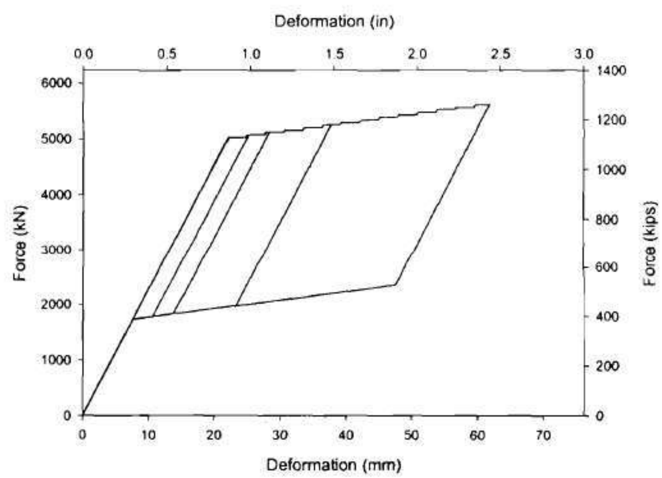


Figure 43 – Force Deformation Relationship for Restrainer Cable (left) and SMA Restrainer (right) for Multi-Frame Bridge subjected to Sylmar Earthquake.

Table 5 – Comparison of Results of Multi-Frame Analysis

30-20 foot Restrainer Cables vs. 15-1.25"D 60" long SMA (0.5 inches of slack)

	Pier Drift (%)				Relative Hinge Opening (in)		
	Piers in Frame 1	Piers in Frame 2	Piers in Frame 3	Piers in Frame 4	d1	d2	d3
Kobe							
As Built	1.65	1.20	1.33	1.29	10.53	2.14	10.33
Cables	1.40	1.25	1.08	1.49	7.60	1.69	7.22
SMA	1.33	1.22	1.11	1.50	**4.18**	**1.05**	**4.62**
Sylmar							
As Built	1.49	1.19	1.38	1.17	6.13	1.60	6.93
Cables	1.66	1.27	1.41	1.27	4.36	0.69	4.72
SMA	1.53	1.18	1.33	1.26	**2.94**	**0.83**	**3.59**

Similar to what was done for multi-span bridge, an analytical model was also created and computer analyses were performed using martensitic SMA. The results in Figures 44 and 45 show that the martensitic SMA reduced the hinge displacement over the entire time history. The results for the Kobe earthquake did not show as much reduction in the maximum hinge displacement as did the results for the Sylmar earthquake. The effectiveness of using a hybrid configuration of SMA was also investigated for the multi-frame bridge. Several analyses were performed with a combination of superelastic SMA in parallel with martensitic SMA. As shown in Figures 46 and 47, this hybrid was effective in reducing the hinge displacement over the entire time history, but once again the results for the Kobe earthquake did not show as much reduction in the maximum hinge displacement as did the results for the Sylmar earthquake.

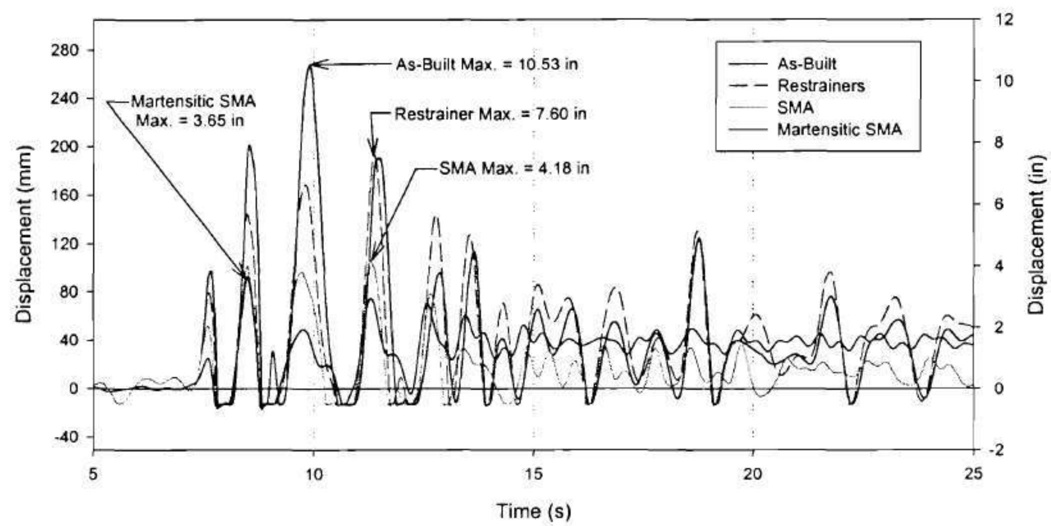


Figure 44 – Comparison of Joint 1 Displacement Response History for Martensitic SMA (Kobe City Record, 1995 Kobe Earthquake).

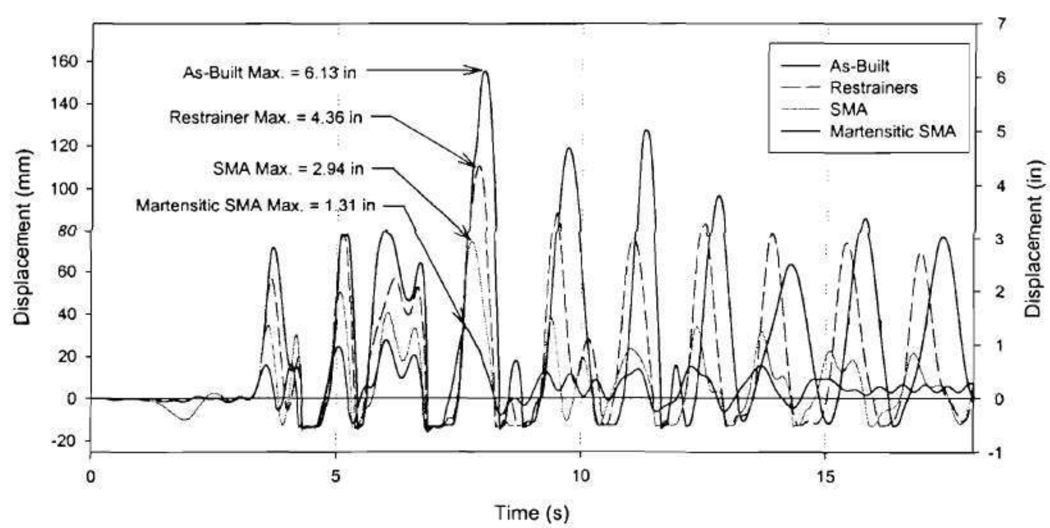


Figure 45 – Comparison of Joint 1 Displacement Response History for Martensitic SMA (Sylmar Earthquake).

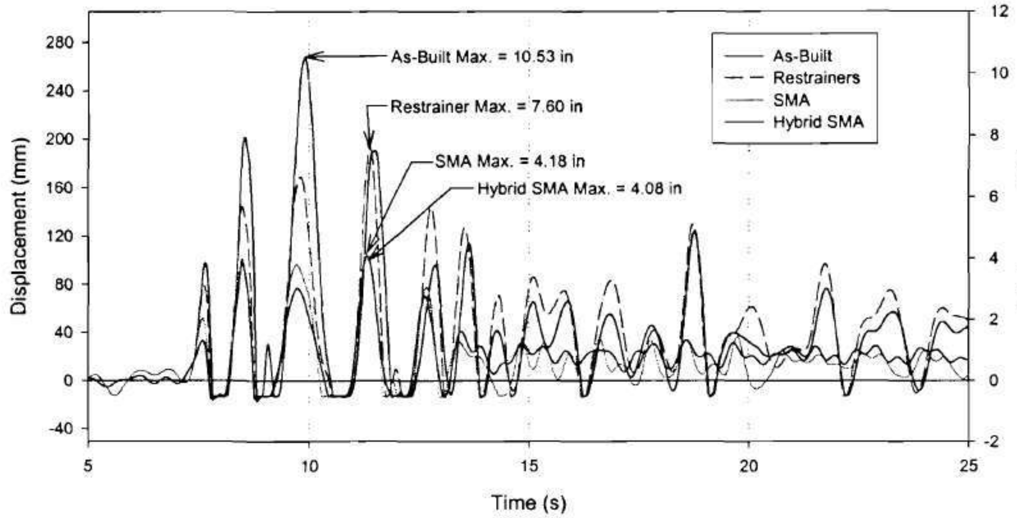


Figure 46 – Comparison of Joint 1 Displacement Response History for Hybrid SMA (Kobe City Record, 1995 Kobe Earthquake).

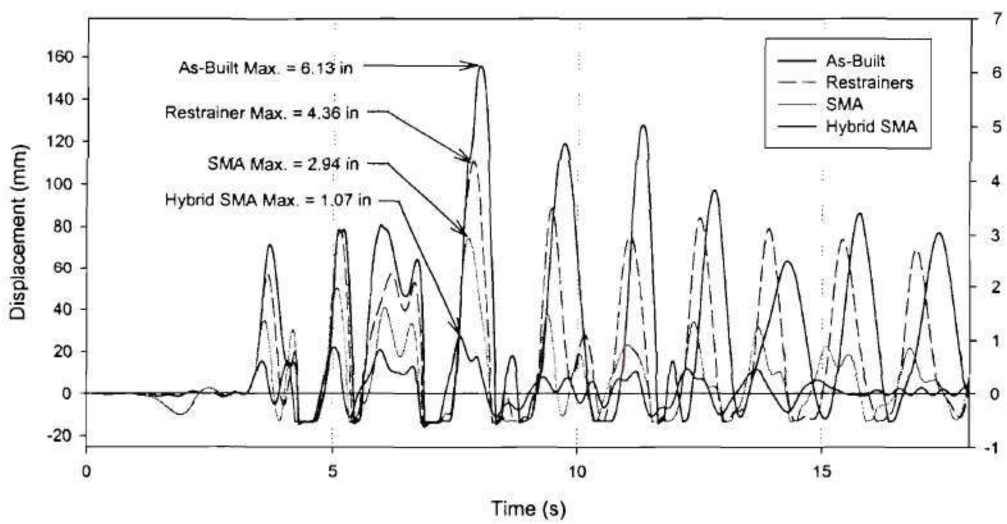


Figure 47 – Comparison of Joint 1 Displacement Response History for Hybrid SMA (Sylmar Earthquake).

Future Work

In order to further verify the efficacy of SMA restrainers it is necessary to perform several full-scale tests. In these tests, SMA restrainers will be loaded either cyclically or dynamically. These tests will show that larger bars are effective as restrainers on large structures. Currently, two series of tests are scheduled to be performed. The first will be performed at Georgia Institute of Technology and the second at University of Nevada, Reno.

The first series of tests will be a full-scale cyclic tests of SMA restrainers at Georgia Institute of Technology. This test will be performed on the full scale steel girder bridge model shown in Figure 48 which sits on concrete abutments. 6" long 1.375" diameter SMA bars will be connected to the bridge using stiffened angles similar to as shown in Figure 49. The bridge will then be loaded in cycles of varying frequencies and the response of the SMA bars will be measured.

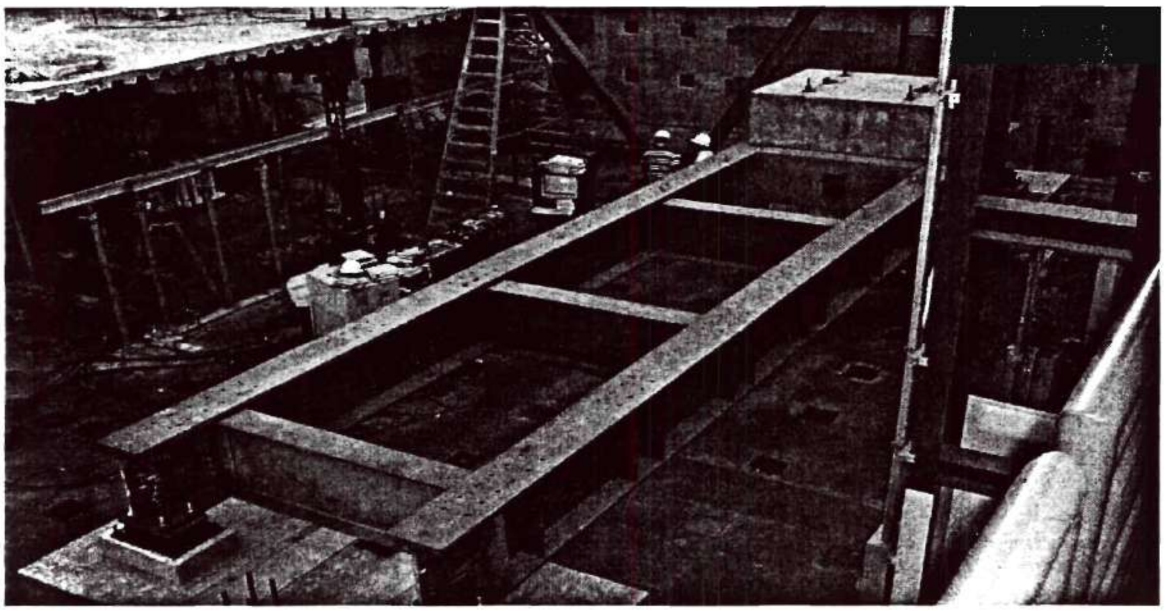


Figure 48 – Full-Scale Bridge

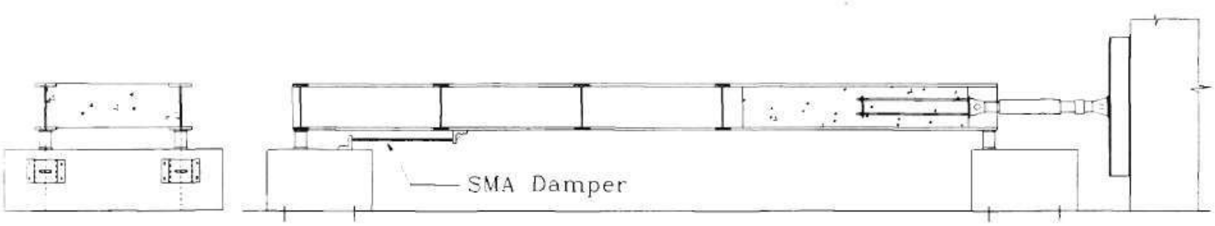


Figure 49 – Full-Scale Bridge Test Setup

The second series of tests will be quarter-scale tests of SMA restrainers on the shake table at University of Nevada, Reno shown in Figure 50. The two concrete blocks will model the ends of a multiple frame concrete box girder bridge. Each block sits on elastomeric bearing pads, which approximate the stiffness of a bridge frame. In order to achieve out of phase motion, both the mass of each block and the stiffness of the bearings will be different. 24" long 0.4" diameter SMA bars will connect the two concrete blocks as shown previously in Figure 16. The shake table will apply a dynamic load to the entire structure. The response of the structure will be monitored and compared to that of the structure without SMA bars.

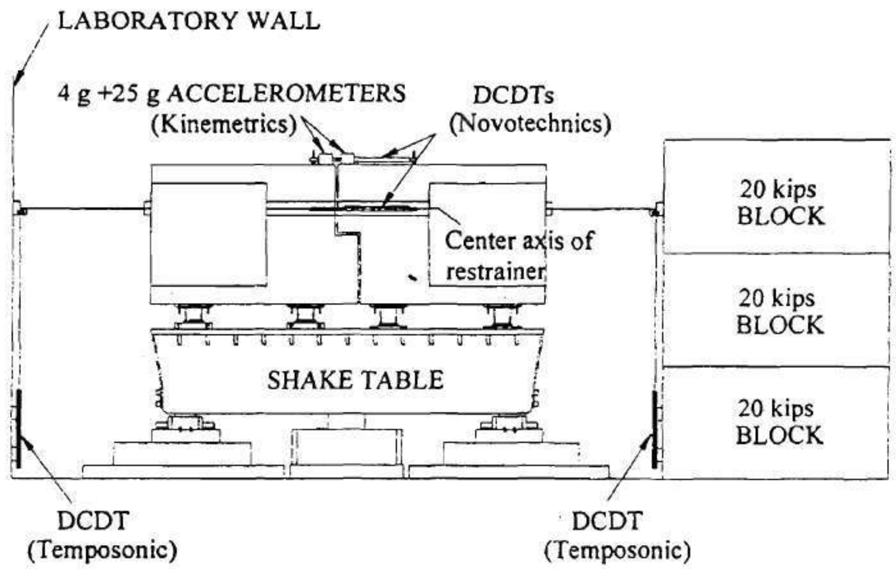


Figure 50 – Shake Table Test Setup

These tests will provide answers to many common questions regarding SMA restrainers. They will provide verification of the analytical models. They will demonstrate the efficacy of large bars under dynamic loading. They will provide tests of actual connections, which will give insight into what is the best method for connecting an SMA restrainer to an actual bridge. Most importantly, they will demonstrate the feasibility of using SMA restrainers to improve the response of a bridge structure in an earthquake.

Conclusions

This paper presents the results of a study evaluating the efficacy of using shape memory alloy 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.

Expert Panel Summary

The expert panel met on Friday, March 2nd, 2001 at the Georgia Institute of Technology to review the current status of the progress made in this research program. The panel consisted of the following end users;

FHWA
Dr. W. Philip Yen
Seismic Hazard Mitigation
Structures Division, HNR-10
6300 McLean, VA 22101
(ph) 703-285-2315 (fax) 703-285-2766
wen-huei.yen@fhwa.dot.gov

Illinois DOT
Dr. Manouchehr Karshenas (Karsh)
Bureau of Bridges and Structures
2300 South Dirksen Parkway
Springfield, IL 62764
(ph) 217-785-3054 (fax) 217-782-7960
karshenasmj@nt.dot.state.il.us

Missouri DOT
Dr. Jeffrey Ger
105 W. Capitol Avenue
P.O. Box 270
Jefferson City, MO 65102-0270
(ph) 573-751-3760 (fax) 573-526-5488
GERJ@mail.modot.state.mo.us

Caltrans Transportation Department
Mr. Ray Zelinski
Engineering Service Center - Office of Earthquake Engineering
1801 30th Street, Mail Stop 09
Sacramento, CA 95816
(ph) 916 227-8728 (fax) 916 227-8898
Ray_Zelinski@dot.ca.gov

Shape Memory Applications, Inc.
Darel Hodgson, President
1070 Commercial Street, Suite 110
San Jose, CA 95112
Tel: (408) 727-2221, Fax: (408) 727-2778
Darel.hodgson@sma-inc.com

The meeting lasted from 9:30 am until 4:00 pm. The morning was spend presenting the results of the research and the afternoon was primarily focused on a round table discussion and feed-back from the end users.

The feedback from the panel was extremely positive and they felt this technology had significant promise in seismic retrofit and new design of bridges in the United States. The panel expressed the following recommendations/comments:

1. More research is needed. Full-scale pseudo-dynamic and shake table testing should be completed.
2. Design procedures should be developed for using these materials in bridges.
3. While preliminary studies show that the restrainers are effective for near-field ground motion, this needs to be confirmed with a larger database of near field ground motion.
4. The use of restrainer cables (bundled SMA wire) would be very interesting.
5. While the cost is high compared to conventional materials, if it provides the enhanced performance that the initial studies indicate, it may be worth the cost.

The panel strongly encourages that this project seek funding from the FHWA through a pool-funds mechanism. The DOT's that were identified that would be interested include;

Caltrans, Washington DOT, Illinois DOT, Missouri DOT, South Carolina DOT, Tennessee DOT, Nevada DOT, and NY DOT. These are the states that currently have active seismic retrofit programs and that currently use restrainer cables.

Expert panel member Ray Zelinski from the California DOT stated that they would have strong interested in funded some of this research. He has recently notified me that he has requested additional funding from CALTRANS to included SMA restrainers in a shake table test currently being conducted at the University of Nevada, Reno.

Product Pay-Off Potential

There are thousands of bridges in the United States that are in need of seismic retrofit. The state of California alone has spent nearly $750 million in seismic retrofit since the 1989 Loma Prieta earthquake. Many other state DOT's are now beginning to initiate similar retrofit programs, including New York, Tennessee, Illinois, and South Carolina. Should this technology prove effective and cost efficient, it can become a widely-used seismic retrofit technology. Cost/benefit analyses will be performed to assess the cost and benefit of shape memory alloys compared with conventional restrainers.