CHARACTERIZATION AND OPTIMIZATION OF SHAPE MEMORY ALLOY BEHAVIOR FOR SEISMIC VIRBATION CONTROL APPLICATIONS IN BUILDINGS

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ABSTRACT :

One means of developing self-centering structural systems for seismic applications is through the use of materials with inherent recentering capability. Superelastic NiTi shape memory alloys are one such metallic alloy which can undergo large deformations while returning to its original shape upon unloading. To explore their feasibility for structural applications, tension-only, quasi-static cyclic tests to a constant strain level and dynamic cyclic tests with non-uniform strain cycles were preformed on large diameter NiTi bars. Unlike past studies, hot-rolled, rather than cold formed, large diameter bars were considered as a more cost effective alternative. The results showed that residual strain levels remained below 1% even after 20 cycles at 6% strain. However, equivalent viscous damping values also remained below 4%. Dynamic loading rates caused an approximate 5°C increase in the surface temperature of the bars resulting in a further decrease in the damping capacity, but no significant effect on the residual deformation values were observed. To further optimize the cyclic properties of NiTi shape memory alloys, a mechanical training study of NiTi wire specimens was also undertaken. Mechanically training the wire specimens for 40 cycles to 6-7% strain stabilized the properties in terms of the forward transformation stress, residual strain, and equivalent viscous damping. In general, the results of this study suggest that large diameter NiTi superelastic shape memory alloys are a viable material for the development of self-centering structural systems for earthquake mitigation applications.

KEYWORDS: shape memory alloys, self-centering, residual strain, mechanical training, damping

1. INTRODUCTION

Over the last two decades, seismic events in urban area, such as the 1994 Northridge earthquake in the United States and 1995 Hyogoken-Nanbu (Kobe) earthquake in Japan, caused significant economic losses. These events helped to propel the structural and earthquake engineering community into the development of a performance-based framework for seismic design in order to ensure a more predictable and reliable response of structures under design level earthquakes (Hamburger et al. 2003). Within this framework, inter-story drift is often used as the limit state criteria to evaluate the performance of a structure. This has led to the successful emergence of new technologies to limit inter-story drift levels in building structures and an increased interest in developing systems that can further control the behavior of structures during an earthquake. One type of system that has recently received consideration is the self-centering structural system which focuses on also limiting residual deformation in structures after an earthquake. One means of providing self-centering capability to a structure is through control of both the form and location of the inelastic behavior through the implementation of materials which inherently provide recentering capability, such as superelastic shape memory alloys.

Shape memory alloys are unique metallic alloys which have the ability to undergo large deformation while returning to their original undeformed. This shape recovery capability is related to the reversible martensitic phase transformation which the material undergoes during the deformation process, rather than the formation of permanent dislocations along the slip plane typically associated with yielding of metals (Duerig et al. 1990). When the shape memory alloy is in its austenitic phase at room temperature, it is considered superelastic and requires only the removal of the load for shape recovery (superelastic effect) as opposed to when it is in its martensitic phase where heat is required to recover the shape (shape memory effect). The superelastic behavior has shown particular promise in engineering applications because shape recovery does not require heating. A typical stress-strain curve associated with the superelastic effect is shown in Figure 1 with the phase transformations labeled. The repeatable recentering capability, loading plateaus which limit the amount of force transferred to other members at intermediate strain levels, supplemental damping associated with the flag-shape hysteresis, stiffening at large strain levels, and excellent low- and high-cycle fatigue properties make superelastic shape memory alloys ideal candidates for seismic vibration control applications.

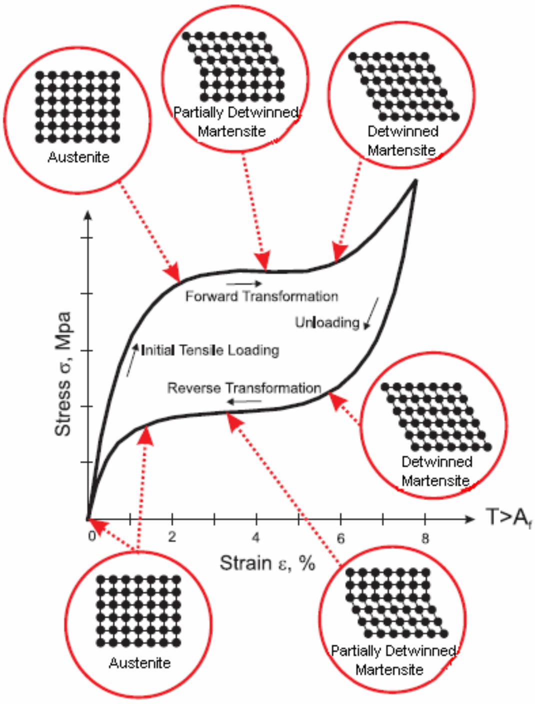

Figure 1 Typical stress-strain curve for a superelastic shape memory alloy cycled in tension.

Initial research into the use of shape memory alloys for structural and seismic applications was first conducted in 1991 by Grasser and Cozzarelli (1991) who studied the use of NiTi for seismic isolation. However, the most significant early studies of shape memory alloys for applications in structural systems was the Memory Alloys for New Seismic Isolation and Energy Dissipation Devices (MANSIDE) conducted by the European Union which looked at the behavior of bars and wires, developed and tested a shape memory alloy based bracing system, and conducted shake table studies on a reinforced concrete shape memory alloy braced structure (Dolce et al, 2000; Dolce and Cardone, 2001; Dolce et al. 2005). Recently, several other applications of shape memory alloys have been considered for steel structures (McCormick et al 2007), reinforced concrete structures (Saiidi et al 2007), wood frame structures (van de Lindt et al 2008), and bridges (Andrawes and DesRoches 2007). However, applications of large diameter shape memory alloys are still limited due to cost and a lack of knowledge in regards to the behavior of large diameter specimens. This is of particular importance given the fact that large diameter shape memory alloys may be more suitable for seismic applications because of their larger capacity and buckling resistance.

In order to address these limitations in implementing large diameter superelastic shape memory alloys in structural systems for seismic vibration control and self-centering capabilities, an experimental study to characterize and optimize the behavior of large diameter NiTi shape memory alloys was conducted. The experimental study consisted of three phases. The first two phases focused on the behavior of large diameter NiTi bars under quasi-static, constant strain level cycling and dynamic tensile cycling at non-uniform strain levels in order to simulate a typical seismic excitation. The third phase looked to optimize the cyclic properties of NiTi through mechanical training.

2. MATERIALS AND TEST SETUP

A set of 12.7 mm and 19.1 mm diameter NiTi shape memory alloy bars were obtained from a commercial supplier. All of the bars were processed from the same stock of material to prevent biasing from composition difference. The bars had a Ni-rich composition of Ti-50.9 at %Ni (Ti-55.95wt %Ni) where at %Ni refers to the atom percentage of Nickel and wt %Ni refers to the weight percentage of Nickel. Processing of the bars was completed through hot rolling reducing the cost compared to typical cold drawn specimens. Until recently, it was thought that cold drawing was necessary to provide good shape recovery properties in large diameter specimens, but work by Frick et al. (2005) showed good shape recovery in hot rolled NiTi with proper precipitation hardening. However, the macroscopic cyclic behavior of hot rolled NiTi large diameter bars remained unknown. The 12.7 mm and 19.1 mm diameter bars were tapered down to diameters of 12.7 mm and 6.35 mm along the gage length and their dimensions can be seen in Figure 2. A two-stage annealing process was used in order to ensure good superelastic behavior. The initial heat treatment was performed at 350°C for 0.5 hours followed by air cooling. The second heat treatment of 300°C for 1.5 hours and immediate water quenching was performed after machining the bars to their final dimensions. All of the large diameter cyclic tests were conducted on previously uncycled bars.

Due to the large number of specimens required for the mechanical training study, 2.16 mm diameter NiTi wire was used in order to investigate the optimal training protocol. The results can be extrapolated to large diameter specimens based on the results of the previous two phases. The wires were as cold drawn, 40% cold worked and had an oxide free pickled surface. The austenite start temperature provided by the manufacturer was -19°C/ -18°C ensuring superelastic behavior at room temperature. All of the wire specimens were cut from a 15.24 m length of NiTi wire with the dimensions shown in Figure 2. All of the wires were annealed together at 350°C for 30 minutes and immediately water quenched before testing to ensure their behavior.

The tests all were performed using a 250 kN hydraulic uniaxial testing apparatus fitted with hydraulic wedge grips and were run under strain control using a digital controller with feedback from a 25.4 mm gage length extensometer attached to the specimen. The internal 254 kN load cell provided force measurements while the extensometer provided the corresponding strain values. Photographs of the test setup for both the bar and wire specimens are shown in Figure 3.

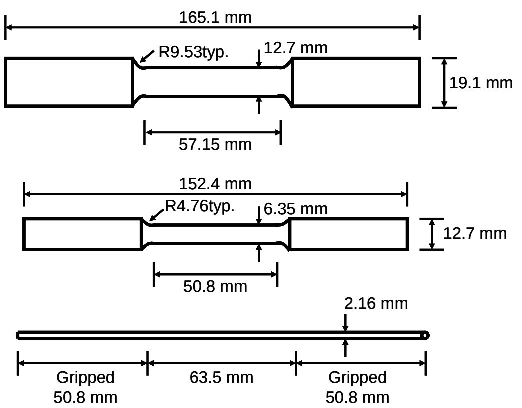

Figure 2 Drawings of the bar and wire specimens.

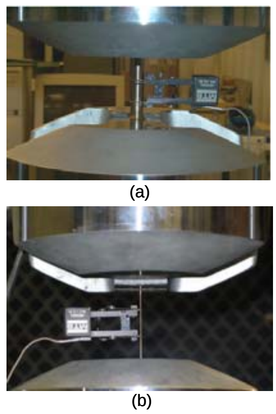

Figure 3 Test setup for the (a) bars and (b) wires.

3. BEHAVIOR OF LARGE DIAMETER NiTi SHAPE MEMORY ALLOY BARS

Initial studies into the behavior of large diameter NiTi shape memory alloys showed good superelastic properties suggesting the possibility for using them in structural control applications (DesRoches et al. 2004). However, size effects associated with the behavior of large diameter bars need to be verified under conditions where small composition differences will not influence the results. Likewise, characterization of the macroscopic behavior of hot rolled Ni-rich NiTi bars is important because of their reduced manufacturing cost making them a more viable candidate for structural applications. The large diameter bars were studied in two phases. The first phase used a quasi-static, constant strain cycle cyclic loading to ensure superelastic behavior could be obtained from the large diameter specimens and to determine any bar size effects that may be present. The second phase looked at loadings similar to those expected during a far-field type earthquake to determine the effects of non-uniform tensile cycles and increased loading rates.

The initial elastic modulus, forward transformation stress, residual strain, and equivalent viscous damping were monitored since they are important properties for utilizing NiTi elements in structural systems. The forward transformation stress refers to the stress at which the martensitic phase transformation initiates resulting in a significant stiffness change. This value is equivalent to the yield stress in typical structural materials, but it should be noted that the phase transformation does not imply yielding. The residual strain is a measure of the recentering capability of the NiTi and refers to the amount of plastic deformation accumulated during cycling. Finally, the equivalent viscous damping measures the hysteretic energy dissipation associated with the tension cycles. Table 1 provides a summary of the properties of the NiTi bars based on monotonic tests along with the corresponding properties of structural steel.

Table 1 Properties of the 12.7 mm and 19.1 mm diameter NiTi bars

	Bar Size		Structural
	12.7 mm	19.1 mm	Steel
Initial (Austenite) Modulus	29.1 GPa	25.5 GPa	200 GPa
Forward Trans. Stress	401 MPa	405 MPa	248-517 MPa
Failure Strain	18.5%	12.1%	~20%

3.1. Constant Strain Cycle Tests

In order to study the mechanical behavior and bar size effects due to cycling, previously untested 12.7 mm and 19.1 mm diameter NiTi bars were cycled through twenty 6% strain tension cycles. Hysteresis curves for a representative 12.7 mm and 19.1 mm diameter bar are shown in Figure 4 with dashed lines labeling the 1st, 5th, 10th, and 20th cycles. Both size specimens show typical superelastic shape memory alloy behavior with a clear flag-shape hysteresis and good shape recovery confirming the possibility of using less expensive hot rolled specimens for structural applications. Although each plot only represents one bar, the properties were found to be repeatable across the replicate tests.

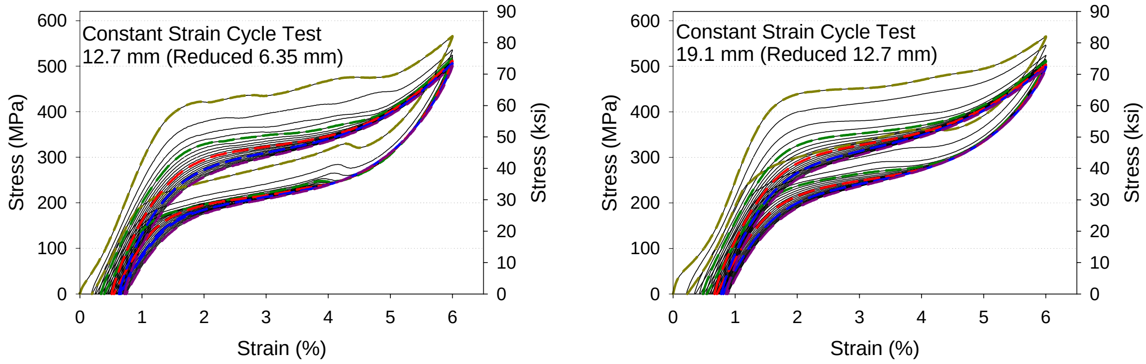

Figure 4 Constant strain cycle test stress-strain plots for a representative 12.7 mm and 19.1 mm diameter bar (dashed lines represent label the 1st, 5th, 10th, 15th, and 20th cycles).

The stress-strain curves in Figure 4 each showed some degradation or change in the hysteretic properties during cycling. For both size bars, the initial elastic modulus was similar and increased slightly during cycling, but not to an extent where it would significantly affect the overall behavior of a structure. The average initial elastic modulus at the 20th cycle was 37.2 GPa and 42.4 GPa for the 12.7 mm and 19.1 mm diameter bars. A clear decrease of the forward transformation stress with continued cycling was observed. This decrease was particularly evident over the first five cycles where the forward transformation stress decreased from 421 MPa to 329 MPa for the 12.7 mm diameter bar and from 439 MPa to 326 MPa for the 19.1 mm diameter bar. This decrease in the forward transformation stress could be attributed to the formation of permanent slip which assists the phase transformation process. (Miyazaki et al. 1986). However, the forward transformation stress did appear to stabilize with continued cycling suggesting that prior mechanical training may provide a means of obtaining consistent cyclic properties. In general, there was no discernable bar size effects associated with the initial elastic modulus and forward transformation stress.

The residual strain and equivalent viscous damping values are of particular importance for self-centering and supplemental damping within structural systems. Figure 5 provides the residual strain and equivalent viscous damping values for the two bars with respect to cycle number. The results suggest a minor bar size effect. The residual strains were larger for the 19.1 mm diameter specimen, but the equivalent viscous damping values were smaller. The difference remained consistent during cycling. The final residual strain measurements remained below 1.0% with average values of 0.75% and 0.88% for 12.7 mm and 19.7 mm diameter bar sets, respectively. Alternatively, equivalent viscous damping values only reached maximum values of 3.6% and 2.8% for the smaller and larger bars. The pinching of the hysteresis loop due to the decrease in the forward transformation stress and smaller increase in the reverse transformation stress led to an overall decrease in the hysteretic area. The average equivalent viscous damping values during the last cycle were 2.43% and 1.93%. As with the forward transformation stress, the accumulation of residual strain and equivalent viscous damping values stabilized with continued cycling.

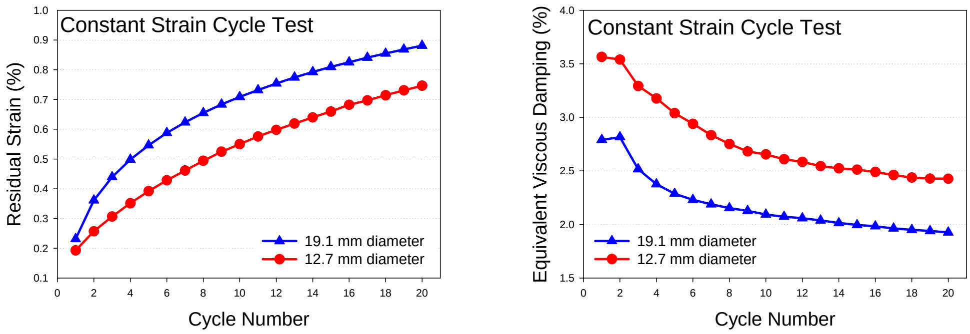

Figure 5 Residual strain and equivalent viscous damping properties with respect to cycle number.

3.2. Earthquake-Type Loading Tests

To utilize NiTi shape memory alloys for seismic applications, it is important to consider the behavior of large diameter NiTi bars under non-uniform loading cycles and dynamic loading rates. The loading protocol for this phase of the study consisted of increasing tensile strain cycles of 0.5%, 1.0%, 2.0%, 3.0%, 4.0%, and 5.0%, followed by six cycles to 6% strain. For both sizes of bars, tests were run on previously uncycled specimens at loading rates of 0.025 Hz (quasi-static), 0.5 Hz (dynamic), and 1.0 Hz (dynamic). A replicate of each test was conducted in order to ensure the consistency of the results.

Figure 6 shows representative stress-strain curves for the 0.025 Hz and 1.0 Hz tests conducted on 19.1 mm diameter bars. Even during non-uniform cycling at dynamic loading rates, the hot-rolled NiTi bars showed good superelastic behavior with shape recovery and a flag-shape hysteresis. Similar bar size effects as with the constant strain cycle tests were observed. Also, there was only a minor difference between the properties of the 19.1 mm diameter bars run at 0.5 Hz and 1.0 Hz. The largest observed differences were between the specimens which were loaded quasi-statically (0.025 Hz) and those that were loaded dynamically (0.5 Hz and 1.0 Hz).

The initial elastic modulus increased from 29.7 GPa for the quasi-static loading to 32.8 GPa for the 1.0 Hz loading at the 2% strain level. An even larger increase was observed during the last 6% strain cycles where the elastic modulus for the 1.0 Hz loading was 42% larger than that measured for the quasi-static loading. A similar trend was found for the forward transformation stress. Although, the forward transformation stress did decrease with increased cycling as was observed in the constant strain cycle tests. Considering the last 6% strain cycle, the forward transformation stresses for the 0.025 Hz and 1.0 Hz tests were 307 MPa and 372 MPa, respectively. The residual strain also increased from 0.64% to 0.88% for the 0.025 Hz and 1.0 Hz strain rates. However, these values still remain low and suggest the possibility of using large diameter bar specimen for self-centering structural systems. The equivalent viscous damping of the 19.1 mm diameter bar decreased from an average maximum value of 2.83% for the quasi-static tests to 1.94% for the dynamic tests at the first 6% strain cycle. This can be attributed to the significant increase in the reverse transformation plateau as seen in Figure 6.

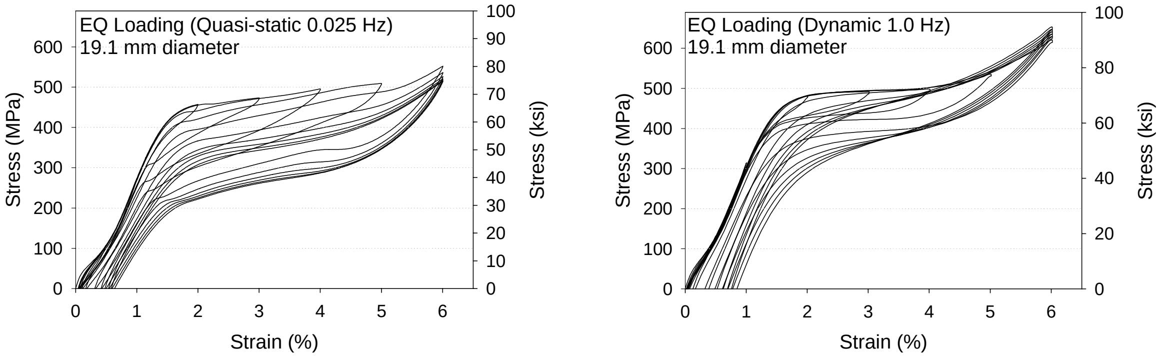

Figure 6 Earthquake-type loading test stress-strain plots for representative 19.1 mm diameter bars tested at 0.025 Hz (quasi-static) and 1.0Hz (dynamic).

The strain rate effects resulting in the limited increase in the forward transformation stress and more significant increase in the reverse transformation stress can be attributed to self heating of the specimen. At higher loading rates, the heat generated by the endothermic/exothermic martensitic phase transformation is not allowed to dissipate resulting in an overall rise in the temperature of the specimen. Figure 7 shows this phenomenon with the surface temperature plots of the 19.1 mm diameter bar tests conducted at 0.025 Hz and 1.0 Hz. For the dynamic tests, there is not only a fluctuation in temperature due to the phase transformation, but also an overall increase of 5°C from the initial ambient temperature.

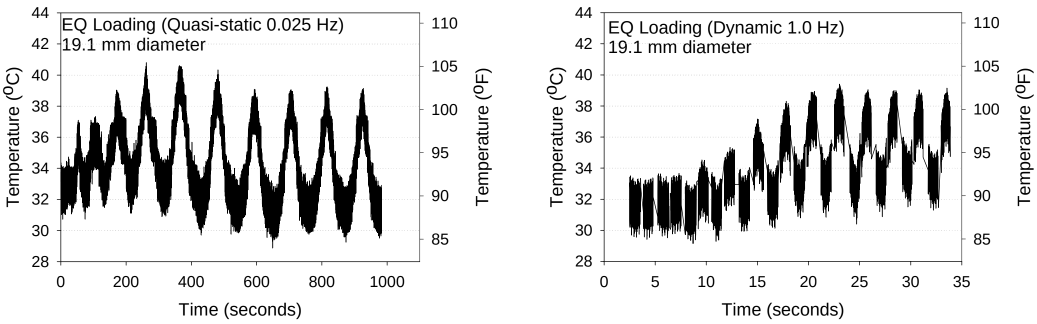

Figure 7 Surface temperature fluctuation during cycling of representative 19.1 mm diameter bars.

4. OPTIMIZING NiTi PROPERTIES THROUGH MECHANICAL TRAINING

Stable materials properties are required for a structure to fit within the performance-based design framework. However, the large diameter bar tests clearly show that the transformation stresses, residual strain, and equivalent viscous damping degrade during cycling until they stabilize. Miyazaki et al. (1986) recommended "training" superelastic shape memory alloys in order to limit fatigue effects, which was shown to be effective in a previous study (McCormick et al. 2005). To further this previous work, the optimal strain level and number of mechanical training cycles is explored through a response surface experimental study.

The response surface study was chosen to allow for the estimation of second order effects with respect to the two factors being considered, number of training cycles and strain level of the training cycles. A central composite face centered cube design was utilized. The low and high levels selected for the factors based on the previous study were 40 and 80 for the number of training cycles and 3% and 7% for the strain level, respectively. A total of 20 wires were tested as a result of replicating the experiment once and adding four center point runs. The testing procedure first consisted of training each of the wires for the specified number of cycles and at the specified strain level based on the layout of the response surface design. All of the training cycles were performed at a rate of 1.5% strain per second. After the mechanical training was completed, the 20 wire specimens were then retested using the previously introduced earthquake-type loading at a strain rate of 0.5 Hz. The percent change in the cyclic properties between the first and last 6% strain cycle was then used to determine the level of stabilization for each mechanical training protocol provide.

Figure 8 provides the contour plots showing the results from the response surface study. The number of training cycles was only significant in stabilizing the residual deformation, while the strain level of the training was important in the stabilization of the residual strain, equivalent viscous damping, and forward transformation stress. From the contour plot for the residual strain, it is clear that mechanical training above 6% strain for at least 40 cycles tends to reduce the accumulation of residual strain with continued cycling to almost nothing. Similar results are found for the forward transformation stress and equivalent viscous damping. However, the damping capacity still decreased by at least 15% during the six 6% strain cycles. The results suggest that mechanical training of superelastic NiTi for 40 cycles to strain levels of 6-7% can drastically reduce the fatigue and degradation effects seen during the large bar testing.

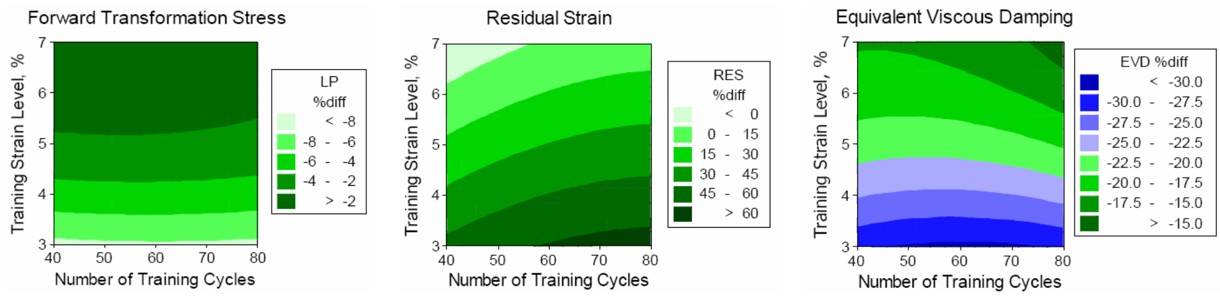

Figure 8 Response surface study results with respect to mechanical training factors.

5. CONCLUSIONS

This study explored the feasibility of using large diameter NiTi shape memory alloys for seismic vibration control of buildings. The recentering capability and flag shape hysteresis make NiTi a unique candidate for use in self-centering structural systems. The behavior of the large diameter specimens was considered under both a constant strain cycle loading and an earthquake-type loading to look at bar size, strain rate, and non-uniform loading cycle effects. A further study was conducted to optimize the properties by reducing fatigue and degradation effects through mechanical training. The major findings are summarized below:

1) Full-scale large diameter hot rolled NiTi specimens showed good superelastic properties, particularly those required for structural and earthquake engineering applications.
2) Bar size only significantly impacted the residual strain and equivalent viscous damping where the larger specimen showed increased residual strain levels and smaller equivalent viscous damping.
3) All properties showed significant degradation or fatigue effects due to cycling. However, the properties tended to stabilize with continued cycling.
4) Non-uniform strain cycles did not have any detrimental effects on the behavior of the NiTi bars, but

dynamic loading rates tended to cause self-heating of the specimen. This self-heating resulted in an increase in the transformation stresses and a subsequent drop in the equivalent viscous damping values.

5) An optimal mechanical training protocol of 40 cycles to 6-7% strain minimizes cyclic fatigue effects associated with the transformation stress, residual strain, and equivalent viscous damping properties.

REFERENCES

Andrawes, B. and DesRoches, R. (2007). Comparison between shape memory alloy seismic restrainers and other bridge retrofit devices. *Journal of Bridge Engineering (ASCE)* **12:6**, 700-709.

DesRoches, R., McCormick, J., Delemont, M. (2004). Cyclic properties of superelastic shape memory alloy wires and bars. *Journal of Structural Engineering (ASCE)* **130:1**, 38-46.

Dolce, M., Cardone, D., Marnetto, R. (2000). Implementation and testing of passive control devices based on shape memory alloys. *Earthquake Engineering and Structural Dynamics* **29**, 945-968.

Dolce, M., Cardone, (2001). Mechanical behaviour of shape memory alloys for seismic applications 2. Austenite NiTi wires subjected to tension. *International Journal of Mechanical Sciences* **43**, 2657-2677.

Dolce, M., Cardone, D., Ponzo, F.C., and Valente, C. (2005). Shaking table tests on reinforced concrete frames without and with passive control systems. *Earthquake Engineering and Structural Dynamics* **34**, 1687-1717.

Duerig, T.W., Melton, K.N., Stöckel, D., Wayman, C.M. (1990). Engineering Aspects of Shape Memory Alloys, Butterworth-Heinemann, Boston, MA, USA.

Frick, C.P., et al. (2005). Thermal processin of polycrystalline NiTi shape memory alloys. *Materials Science and Engineering A* **405**, 34-4

Graesser, E.J. and Cozzarelli, F.A. (1991). Shape-memory alloys as new materials for aseismic isolation. *Journal of Engineering Mechanics (ASCE)* **117:11**, 2590-2608.

Hamburger, R.O., Foutch, D.A., Cornell, C.A. (2003). Translating research practice: FEMA/SAC performance-based design procedures. *Earthquake Spectra* **19:2**, 255-267.

McCormick, J., Barbero, L., and DesRoches, R. (2005). Effect of mechanical training on the properties of superelastic shape memory alloys for seismic applications. *Proc. of SPIE: Smart Structures and Materials – Smart Structures and Integrated Systems* **5746**, 430-439.

McCormick, J., DesRoches, R., Fugazza, D., Auricchio, F. (2007). Seismic assessment of concentrically braced steel frames with shape memory alloy braces. *Journal of Structural Engineering (ASCE)* **133:6**, 862-870.

Miyazaki, S., et al. (1986). Effect of cyclic deformation on the pseudoelasticity characteristics of Ti-Ni alloys. *Metall. Trans. A.* **17A**, 115-120.

Saiidi, M.S., Sadrossadat-Zadeh, M., Ayoub, C., Itani, A. (2007). Pilot study of behavior of concrete beams reinforced with shape memory alloys. *Journal of Materials in Civil Engineering (ASCE)* **19:6**, 454-461.

van de Lindt, J.W. and Potts, A. (2008). Shake table testing of a superelastic shape memory alloy response modification device in a wood shearwall. *Journal of Structural Engineering (ASCE)* **134:8**, 1343-1352.