Damping Properties of Shape Memory Alloys for Seismic Applications

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Abstract

Shape memory alloys (SMAs) in martensitic form and austenitic form are studied to evaluate their damping potential for applications in earthquake engineering. Shape memory alloy wires and bars are subjected to cyclical loadings similar to that expected during a seismic event. The damping properties of the shape memory alloys in both the martensitic form and austenitic form are compared with respect to bar size, loading rate, and maximum strain cycle. The results show that in the superelastic form, the damping properties of shape memory alloys are generally low, ranging from 2%-7% equivalent viscous damping. The damping properties generally peak at 4%-5% strain and begin to degrade at larger strains. In the martensitic form, shape memory alloys have significant energy dissipation with equivalent viscous damping ratios ranging from 15%-25%. Strain rate effects are evaluated by loading the bars at rates up to 2Hz (maximum strain rate of 7.90% per second). The results show that increased strain rates lead to a reduction in the energy dissipation capabilities of shape memory alloys in both forms. The effectiveness of using shape memory alloys for damping applications is evaluated through a comparison with current passive energy dissipation technology in the field of earthquake engineering showing the viability of using shape memory alloys for passive damping applications.

Introduction

Shape memory alloys are a unique class of alloy which can undergo large deformations while reverting back to their original undeformed shape through the applications of heat (shape memory effect) or removal of stress (superelastic effect). Although the unique properties of SMAs were first discovered in the 1930's, it was not until 1960's that Buehler and Wiley found that NiTi (also known as Nitinol) possessed shape memory properties. Due to a lack of clear understanding of the behavior, inconsistency in the properties, and high cost upon initial discovery, it was not until the past decade that SMAs have been implemented in the medical, commercial, and aerospace industries as these deficiencies have been resolved and manufacturing cost has decreased.

Over the past decade, the focus in seismic design and retrofit has become more performance based. This has led to the use of passive energy dissipation devices in structures in order to reduce interstory drifts and structural response, while also controlling the location of inelastic behavior and protecting the load-bearing members of the structure. A total of 103 building structures in North America have implemented passive energy dissipation devices as of the year 2000 with many occurring in the last five years due to increased research focusing on metallic yield dampers, friction dampers, viscoelastic dampers, viscous fluid dampers, and tuned mass dampers (Soong and Spencer, 2002). Many applications of these devices are discussed in detail in works by Constantinou et al. (1998) and Hanson and Soong (2001).

The unique properties of martensitic and superelastic (austenitic) SMAs have led to interest in using them as dampers for applications in seismic resistant design and retrofit of structures. Graesser and Cozzarelli (1991) first suggested the use of NiTi SMAs as seismic dampers after studying the effect of loading history and loading frequency on the energy dissipation capacity of Nitinol wires. Since then, several other studies have been conducted to determine the effect of strain amplitude, loading frequency, cycling, and temperature effect on the damping properties of NiTi superelastic wires and martensitic bars (Piedboeuf et al., 1998; Wolons et al., 1998; Hodgson, 2002). Inaudi and Kelly (1994) investigated the effectiveness of a tuned mass damper with SMA wires in a four-story steel-frame model using a unidirectional shake table. The study found a significant improvement in the dynamic response of the structure, particularly when the SMA wire prestress tension was tuned to the first natural frequency of the structure. An analytic study by Sweeney and Hayes (1995) showed the effectiveness of SMA devices in reducing interstory displacements during a seismic event. The most substantial effort in the use of SMAs for seismic applications is the Memory Alloys for New Structural Vibrations Isolating Devices (MANSIDE) Project conducted by the European Union (MANSIDE, 1998). As a result of this project, Dolce et al. (2000) developed and tested a conceptual device using both martensitic and superelastic SMA wires. The results of these projects show promise for the use of SMAs in seismic applications. However, significant research still needs to be done particularly in characterizing the damping properties of large diameter specimens which would typically be necessary in earthquake engineering applications.

Shape Memory Alloys

Shape memory alloys are a unique metallic alloy which can undergo large deformations with little residual strain through either the shape memory effect or the superelastic effect. The phase transformation and formation of detwinned martensite upon deformation rather than the occurrence of permanent slip due to the formation of intergranular dislocations results in this ability to recover the deformation. Two stable phases are associated with SMAs: the low temperature, less symmetric crystalline martensitic phase and the high temperature, symmetric crystalline austenitic (parent) phase. The martensitic phase is stable at low temperatures and high stress, while the austenitic phase is stable at high temperatures and low stresses. A dependence of the mechanical behavior on stress, strain, and temperature is due to the thermoelastic nature of SMAs. The thermo-elastic nature of SMAs causes an increase in temperature to act as a decrease in stress on the material. At temperatures below the martensitic finish temperature, M_f, the material exhibits the shape memory effect resulting in residual strain upon unloading which can be recovered by heating the material above its austenite finish temperature, A_f. At temperatures above A_f, but below a given temperature M_d, the SMA exhibits the superelastic effect where residual strain is recovered immediately upon unloading. SMAs undergo typical plastic deformation in their pure austenitic form with a much higher strength at temperatures above M_d.

The excellent low- and high-cycle fatigue, strain hardening at large strains, stress-plateaus to limit force transfer, and hysteretic damping properties make SMAs desirable for applications in seismic design and retrofit.

Experimental Testing

The martensitic and superelastic properties of shape memory alloys makes them ideally suited for use as passive energy dissipation devices in seismic resistant design and retrofit. Several studies have been conducted to characterize the cyclic properties with respect to damping capacity of NiTi SMAs, but very few of these studies have focused on loading rates and strain levels that would typically be experienced by structural members during an earthquake. Even fewer studies have focused on the damping performance of larger diameter SMA specimens that would be necessary for civil engineering applications.

In this study, both mid-size and large diameter martensitic and superelastic bars are tested to determine their damping properties with respect to bar size, strain rate, and maximum cyclical strain. Superelastic wire specimens are also tested to provide a comparison to smaller specimen sizes. Cyclic tension and compression loadings are applied to the martensitic specimens and cyclic tension loadings are applied to the superelastic specimens. The specimens are subjected to a maximum of 6% strain under both quasi-static and dynamic rates. The results from this study are intended to provide insight on how SMAs can function as passive energy dissipation devices. The energy dissipation is measured as equivalent viscous damping, ξ_{eq}, and energy dissipated per unit volume, U_o. The equivalent viscous damping is a measure of the energy dissipated during a single cycle divided by the product of 4π and the strain energy associated with the complete cycle. The energy dissipated is specified as the area enclosed in one-cycle of the force displacement plot and the maximum strain energy is calculated as one-half of the maximum strain of a cycle. The energy dissipated per a unit volume is determined by calculating the area inside the hysteresis of the stress-strain curve for a single cycle.

Test Specimen and Loading Protocol

Two sets of near-equiatomic NiTi martensitic SMA specimens and three sets of near-equiatomic NiTi superelastic SMAs specimens are tested to determine their damping characteristics. The 6.5 mm (0.26 in.) and 36.5 mm (1.44 in.) diameter specimens have transformation temperatures above room temperature causing them to be martensitic during testing. The gauge length of the 6.5 mm (0.26 in.) and 36.5 mm (1.44 in.) diameter specimens are 57 mm (2.25 in.) and 279 mm (10.75 in.), respectively. All of the martensitic specimens are annealed for 60 minutes at 350^{o}C (662^{o}F) and immediately water quenched as recommended by the manufacturer.

A number of 1.8 mm (0.07 in.), 7.1 mm (0.28 in.), and 25.4 mm (1.0 in.) specimens are also tested. These specimens had low austenite start temperatures resulting in the wires and bars being superelastic at room temperature. Details of the gauge length, A_s, composition, processing, and cold working can be found in Table 1. The 7.1 mm (0.28 in.) diameter specimens are hot rolled (processed to final shape at a high temperature) where the 1.8 mm (0.07 in.) and 25.4 mm (1.0 in.) diameter specimens are both cold drawn to 30% and 25%, respectively, with the percentage of cold working referring to the reduction in the cross-sectional area during drawing. Both the wire specimens and the mid-size bars are annealed at 350^{o}C (662^{o}C) for 30 minutes. Due to the larger cross-section, the 25.4 mm (1.0 in.) specimens were annealed at 450^{o}C (842^{o}F) for 60 minutes per the manufactures recommendations to ensure optimal superelastic properties.

Table 1. Properties of Superelastic SMAs

Diameter (mm)	Length (mm)	Gauge Length (mm)	A_s (^{o}C)	Weight % Ni	Weight % Ti	Processing	Cold Work
1.8	152	63.5	-26	56.05	43.95	Cold Drawn	30%
7.1	152	57	-10	56.00	44.00	Hot Rolled	None
25.4	279.4	152	-11	56.00	44.00	Cold Drawn	25%

Loading protocols of ramp functions are used for both the martensitic and superelastic tests. The loading protocols are chosen so as to represent typical loadings of far-field earthquakes in order to ensure proper evaluation of the damping properties at strain levels typical of an earthquake (4%-8%). The first sets of tests are run quasi-statically at a loading rate of 0.025 Hz. Dynamic tests are also conducted with loading rates ranging from 0.25 Hz to 2.0 Hz. The loading protocols cycled the martensitic specimens in both tension and compression and cycled superelastic specimens in only tension as is typical of past use of the material.

Experimental Test Setup

The wire specimens (1.8 mm (0.07 in.)) and mid-size bar specimens (6.5 mm (0.26 in.) and 7.1 mm (0.28 in.)) are tested using a 250 kN (55 kip) MTS hydraulic testing frame fitted with MTS 647 hydraulic wedge grips. Round specimen wedges are used to grip the bar specimens with flat specimen wedges being used for the wire specimens because of their small diameter. The desired loading protocol is input using an MTS Testar controller which allowed for different loading rates to be achieved for dynamic testing. Due to the high strength and size of the 25.4 mm (1.0 in.) diameter bars and 36.5 mm (1.44 in.) diameter bars, a 2.7 MN (600 kip) MTS uniaxial servo controlled hydraulic load frame is used to perform the cyclic tests. The large diameter bars are threaded in order to facilitate gripping of the specimens and reduce the occurrence of slip during the cyclic tests. An INSTRON 8500 Plus controller is used to input the desired loading protocol for the larger bar specimens.

Quasi-Static Test Results

To date, the majority of studies and applications focusing on the damping properties of SMAs have focused on wire and thin bar specimens. For this reason, little information exists about the damping properties of larger diameter sections that are typically needed for structural engineering applications. Further, SMA specimens have not been tested under conditions that are typical of an earthquake resulting in a lack of knowledge of the damping properties of SMAs at high strain levels. This lack of knowledge has inhibited the implementation of NiTi SMAs in seismic applications.

Comparison of the Damping Properties of Martensitic and Superelastic SMAs

Figure 1 shows the stress-strain curves for both a 36.5 mm (1.44 in.) martensitic NiTi SMA bar and a 25.4 mm (1.00 in.) superelastic NiTi SMA bar subjected to cyclic tension-compression loading up to 5% strain and cyclic tension loading up to 6% strain, respectively. Although the superelastic specimen reaches higher stress values for a given strain level (480 MPa (70 ksi) at 5% strain) as compared to the martensitic specimen (370 MPa (50 ksi) at 5% strain), the hysteresis for the martensitic bar is much larger than that of the superelastic bar. This occurrence can be attributed to the formation of the unloading plateau associated with the superelastic effect, which leads to a decrease in the area of the hysteresis.

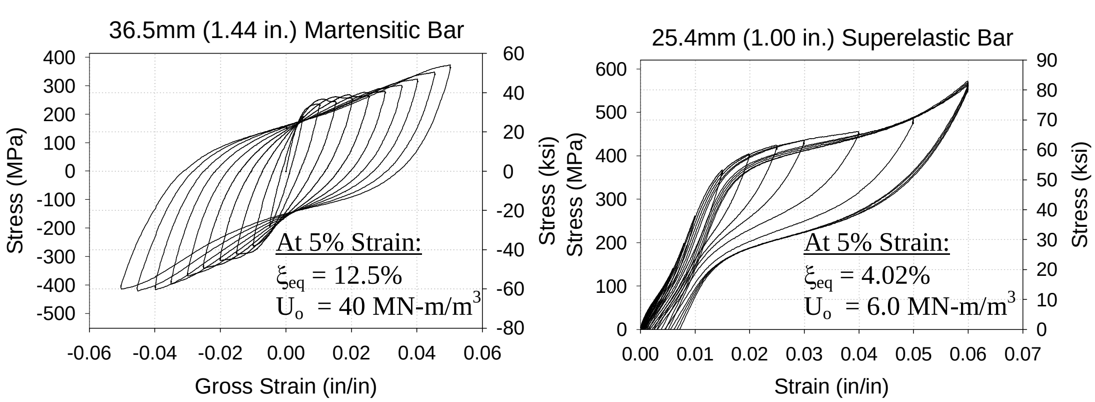


Figure 1. Quasi-static cyclic stress-strain curves for martensitic and superelastic specimen.

Comparing the damping properties at the 5% strain cycle, the equivalent viscous damping ratio, ξ_{eq}, for the martensitic and superelastic bar are 12.5% and 4.02%, respectively. The martensitic SMA provides more damping even if only half of the ξ_{eq} is accounted for since the martensitic specimen is cycled in both tension and compression. Previous studies have shown ξ_{eq} for martensitic specimens can reach as high as 20-25% providing significantly more damping than superelastic specimens (MANSIDE, 1998; Delemont, 2001). Similar results are found when looking at the energy dissipated per unit volume, U_o. U_o for the martensitic bar is approximately 40.0 MN-m/m^3 (5.8 k-in/in^3) and 6.0 MN-m/m^3 (0.9 kip-in/in^3) for the superelastic bar. These results show martensitic NiTi SMAs to be more viable for damping applications than superelastic NiTi SMAs.

Effect of Bar Size on Damping Properties

The ξ_{eq} and U_o for the 6.5 mm (0.26 in.) and 36.5 mm (1.44 in.) diameter martensitic bars are shown with respect to maximum strain per a cycle in Figure 2. The ξ_{eq} increases with increased cycling for both the mid-size and large diameter bars at small strains, but the maximum equivalent viscous damping value occurs at smaller strains levels, ε=2.5%, for the larger diameter specimens as compared to the mid-size specimens, ε=4.0%. Figure 2 shows a reduction of approximately 25% in the maximum ξ_{eq} with and increase in bar size. The equivalent viscous damping decreases from ξ_{eq}=20% for the 6.5 mm (0.26 in.) bars to approximately ξ_{eq}=14.5% for the 36.5 mm (1.44 in.) bars. This phenomenon can be attributed to the disappearance of the loading plateau as strain levels increased resulting in a decrease in the slope of the loading curve (Liu et al., 1999). U_o increased with increased strain levels providing a maximum value of approximately 40.0 MN-m/m^3 (5.8 kip-in/in^3) for the large diameter bars and 44.6 MN-m/m^3 (6.5 kip-in/in^3) for the mid-size diameter bars. This resulted in similar energy dissipation per unit volume for all bar sizes.

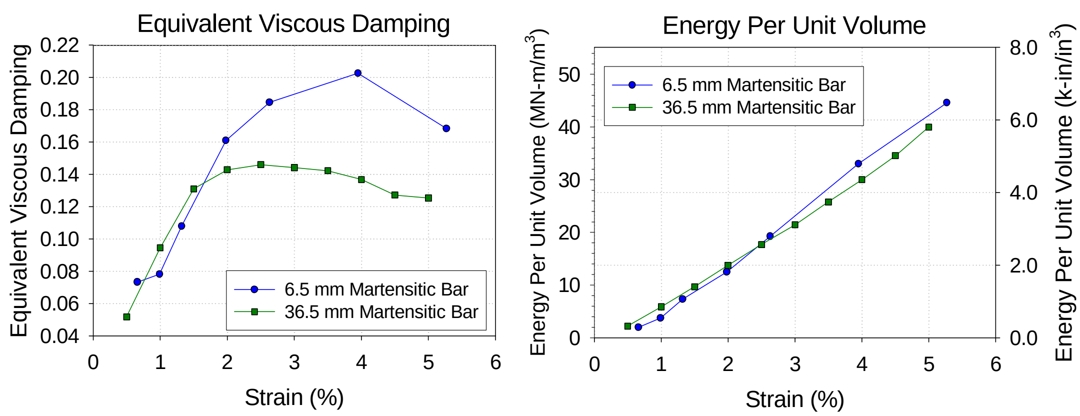


Figure 2. Comparison of martensitic damping properties with respect to bar size.

Figure 3 provides a comparison of ξ_{eq} and U_o for the 1.8 mm (0.07 in.) diameter superelastic wires, 7.1 mm (0.28 in.) diameter superelastic bars, and 25.4 mm (1.00 in.) diameter superelastic bars with respect to maximum strain per a cycle. The ξ_{eq} for the superelastic specimens are considerably less than those of the martensitic specimens ranging from maximum values of approximately ξ_{eq}=7.6% for the wire specimens to a maximum of approximately ξ_{eq}=4% for the large diameter specimens. These values are generally too low for superelastic SMAs to be used in a purely damping application. The maximum ξ_{eq} occurred during the 4% to 5% strain cycles. The decrease at larger strain levels can be attributed to strain hardening at larger strains and a narrowing of the hysteresis (Dolce and Cardone, 2001; DesRoches et al., 2004). The wire specimens clearly provide more energy dissipation than the bar specimens due to a larger hysteresis, but both the mid-size and large diameter bars show similar ξ_{eq} values. Similar results were found for the U_o with respect to bar size. The wire specimen provided a slightly higher maximum U_o of approximately 16 MN-m/m^3 (2.3 kip-in/in^3) while the bar specimens had maximum U_o of approximately 7.0 MN-m/m^3 (1.0 kip-in/in^3). As with the martensitic specimens, the energy dissipated per unit volume increased with increased strain level.

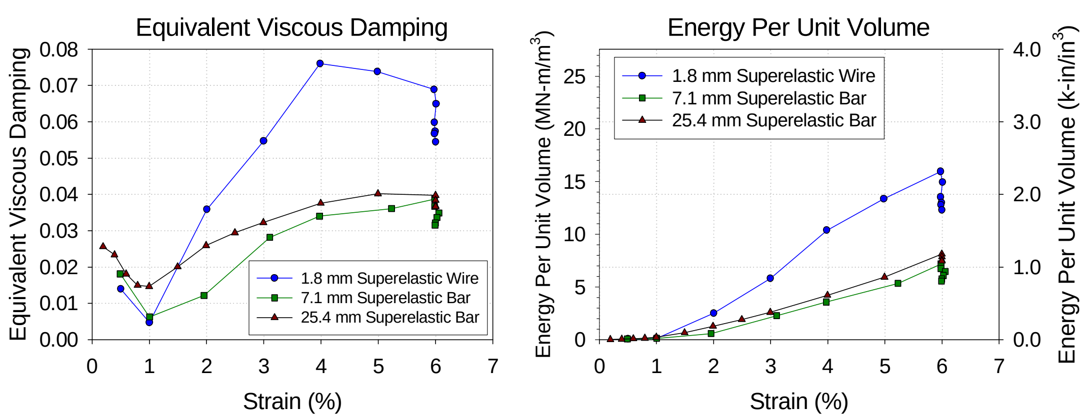
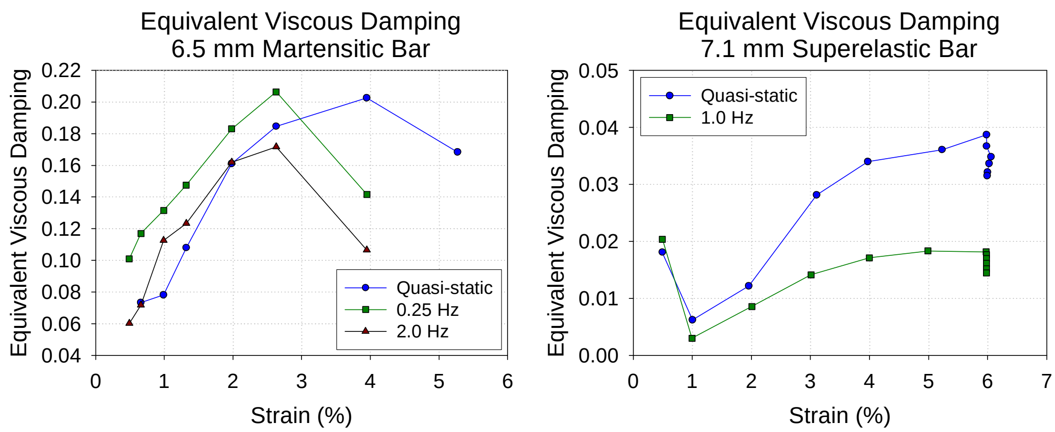


Figure 3. Comparison of superelastic damping properties with respect to bar size.

Dynamic Loading Effects on Damping Properties

During an earthquake, structures typically vibrate at a wide range of frequencies reaching as high as 5 Hz depending on the structure and characteristics of the earthquake. This results in structural components undergoing dynamic loadings at various strain rates. Since this study focuses on the evaluation of the damping properties of SMAs for seismic applications, it is important to examine the effect that dynamic loading has on the equivalent viscous damping properties of both martensitic and superelastic SMAs. Very few studies have focused on the effect that dynamic loading has on NiTi SMA properties. Wu et al. (1996) found that little change occurred in the stress-strain curve of martensitic SMAs with increased cycling rate. Studies on superelastic bars have shown conflicting results. Tobushi et al. (1998) and Leo et al. (1993) reported an increase in hysteresis with increased loading rate while

Dolce and Cardone (2001) and DesRoches et al. (2004) found a decrease in hysteresis with increased loading rate.



(a) **(b)**

Figure 4. Comparison of equivalent viscous damping with respect to loading rate for (a) martensitic bars and (b) superelastic bars

Figure 4 compares the equivalent viscous damping results for the 6.5 mm (0.26 in.) diameter martensitic bars and 7.1 mm (0.28 in.) diameter superelastic bars with respect to maximum strain level per cycle and loading rate. Figure 4a shows the maximum ξ_{eq} for the martensitic bars cycled quasi-statically and at 0.25 Hz are approximately 20.2% and 20.6%, respectively. Increasing the loading rate to 2 Hz resulted in a decrease in the maximum ξ_{eq} by 20% to approximately ξ_{eq}=16%. Although the energy dissipation decreases with an increase in loading rate, it still remains large enough for earthquake engineering application. Increasing the loading rate also shifted the strain level at which the maximum ξ_{eq} occurred from 4% strain for the quasi-statically tested bars to approximately 2.6% strain for the dynamically tested bars. Figure 4b shows a reduction in the ξ_{eq} of the superelastic bars for the first 6% strain cycle when cycled dynamically from ξ_{eq}=3.87% during quasi-static loading to ξ_{eq}=1.82% during dynamic loading at 1 Hz. This decrease is explained by the large increase in the unloading plateau with the increased loading rate resulting in a narrowing of the hysteresis. This increase in the unloading plateau can be attributed to a self-heating of the specimen as a result of the increased loading rate and the thermo-elastic nature of SMAs. As mentioned previously, the small ξ_{eq} associated with superelastic SMAs will prevent their use in purely damping seismic applications.

SMA Damping Capacity versus Current Passive Energy Dissipation Devices

Several types of passive energy dissipation systems including metallic yielding hysteretic devices, frictional hysteretic devices, viscoelastic solid devices, and viscous fluid devices have been implemented in the United States and other high seismic areas (Hanson and Soong, 2001). The effectiveness of these devices in reducing drift and preventing damage has been proven both analytically and experimentally. This has led to the search for more efficient and reliable passive energy dissipation devices, such as SMAs, in order to address the shortcomings of current devices which has hindered more widespread use of such technology. Viscoelastic dampers have been shown to provide upwards of 15% to 25% equivalent viscous damping of critical, but their performance is highly dependent on vibration frequency, strain amplitude, ambient temperature, and aging (Constantinou et al., 1998). Martensitic SMAs provide similar energy dissipation capacity to viscoelastic dampers and can be designed for the particular working temperature that is needed. Even at high strain levels and loading frequencies, martensitic SMAs provide good energy dissipation capacity. Viscous fluid devices can provide up to approximately 60% equivalent viscous damping (Constantinou et al., 1998) but tend to be complex in nature and require regular maintenance which can increase cost. Although SMAs provide only about half of this energy dissipation capacity, the fact that SMA devices would require minimal maintenance (even after an earthquake if superelastic SMAs are used) and are much smaller makes them a viable option rather than using viscous fluid devices. Yielding devices also provide energy dissipation in the same form as SMAs, but due to the accumulation of large permanent deformation they must be replaced after an earthquake. Chen et al. (2001) found that metallic yield dampers provide between 10%-30% equivalent viscous damping with cycling. The unique recentering capability of SMAs and ability to undergo large strains removes the need to replace superelastic SMAs after an earthquake and martensitic SMAs can be heated to recover there shape while also providing added energy. Many of the shortcomings associated with current passive energy dissipation devices can be overcome by implementing both martensitic and superelastic SMAs.

Conclusion

Damping is an important part of reducing the response of structures during seismic events. Both martensitic and superelastic SMAs demonstrate a hysteresis upon loading, but little investigation has been done into the damping properties of large diameter specimens to determine the feasibility of implementing them into seismic design and retrofit strategies. This study looked at the damping properties of large diameter specimens with respect to equivalent viscous damping and energy dissipated per unit volume. The dissipated energy as a function of cyclic strain levels is normalized with respect to the stiffness and peak strain in order to determine the equivalent viscous damping while the energy dissipated per unit volume is determined by calculating the area under the stress-strain curve for each strain cycle.

Equivalent viscous damping increased until a maximum value between the 4% and 5% strain cycles and then decreased slightly for larger strain levels for both the martensitic and superelastic specimens. The energy dissipated per unit volume continuously increased with increasing strain level. The martensitic specimens provided much more energy dissipation as compared to the superelastic specimens with the 36.5 mm (1.44 in.) diameter martensitic bars providing 12.5% equivalent viscous damping as compared to the 25.4 mm (1.00 in.) superelastic bar which provided only 4.02% equivalent viscous damping at the 5% strain level. Increased bar size led to a decrease in the equivalent viscous damping for both specimen types of NiTi SMAs. Dynamic loading resulted in the equivalent viscous damping decreasing by approximately 20% for the martensitic specimens and decreasing by approximately 50% for the superelastic specimens. The damping capacity of superelastic SMAs is considered too low to use superelastic SMAs in purely damping applications. However, superelastic SMAs do have recentering capabilities which makes them still viable for seismic applications. Based on this study, the possibility of using a combination of martensitic (large energy dissipation) and superelastic (recentering capabilities) SMAs shows promise in seismic design and retrofit leading to such devices replacing current passive energy dissipation technology.

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