SHAPE MEMORY ALLOYS IN SEISMIC RESISTANT DESIGN AND RETROFIT: A CRITICAL REVIEW OF THEIR POTENTIAL AND LIMITATIONS

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Shape memory alloys (SMAs) are a class of materials that have unique properties, including Young's modulus-temperature relations, shape memory effects, superelastic effects, and high damping characteristics. These unique properties, which have led to numerous applications in the biomedical and aerospace industries, are currently being evaluated for applications in the area of seismic resistant design and retrofit. This paper provides a critical review of the state-of-the-art in the use of shape memory alloys for applications in seismic resistant design. The paper reviews the general characteristics of shape memory alloys and highlights the factors affecting their properties. A review of current studies show that the superelastic and high-damping characteristics of SMAs result in applications in bridges and buildings that show significant promise. The barriers to the expanded use of SMAs include the high cost, lack of clear understanding of thermo-mechanical processing, dependency of properties on temperature, and difficulty in machining.

Keywords:

1. Introduction

Shape memory alloys are a class of materials that can recover from large strains through the application of heat (known as the shape memory effect) or removal of stress (known as the superelastic effect). This results in several unique characteristics, including Young's modulus-temperature relations, shape memory effects, superelastic effects, high damping characteristics, and re-centering capabilities.

The first observation of the shape memory effect was recorded in 1932 [Chang and Read, 1932]. Chang and Read noted the reversibility of the transformation in AuCd through metallographic observations and resistivity changes. The shape memory effect was seen in CuZn and AuCd in 1938 and 1951, respectively. In 1961, Buehler and Wiley developed a series of alloys exhibiting the shape memory effect while working for the US Naval Ordinance Laboratory [Buehler and Wiley, 1961]. These alloys consisted of an equi-atomic composition of Nickel and Titanium (NiTi). This alloy is commonly referred to as Nitinol, an acronym for Nickel Titanium Naval Ordnance Laboratory [Jackson et al., 1972].
These discoveries sparked research investigating both the characteristics of the material as well as their potential use in practical applications. Previously, the use of SMAs had been limited for several reasons. In addition to the high cost for raw materials, the required processing, machining, and heat treatment further increased the cost. Another drawback was the lack of information about the thermomechanical properties of shape memory alloys. Over the past 10 to 15 years, several studies have provided a better understanding of the behaviour of shape memory alloys, and illustrated their potential use in practical applications. Additionally, the cost has decreased significantly, and is no longer considered prohibitively expensive. This has led to the use of SMAs in a number of medical and commercial products.

The biomedical field was the first to fully exploit the unique characteristics of SMAs. Since SMAs have excellent biocompatibility, their unique characteristics could be utilised for the development of numerous medical tools and devices. The need to find less invasive medical procedures resulted in several medical applications of SMAs [O’Leary et al., 1990]. Included among these are medical stents [Duerig et al., 1997], filters [Duerig et al., 1999] and dental archwires [Sachdeva and Miyazaki, 1990]. Other fields have also found uses for SMAs. The aerospace industry has adopted SMAs as a means to control the vibration of helicopter blades [Schetky, 1999] and airplane wings during flight [eSMART, 2002]. Several commercial products, such as eyeglass frames [Chute and Hodgson, 1990], golf clubs [Pixl, 2002] and cellular phone antennas [NDC, 2001], are made using SMAs. Advances in research have led to the continuing increase in the number of applications using SMAs.

SMAs are beginning to emerge as a potential material for various applications within the field of civil engineering. The unique properties that make SMAs useful for commercial and biomedical applications can also be utilised in seismic resistant design and retrofit applications. SMAs have demonstrated energy dissipation capabilities, large elastic strain capacity, hysteretic damping, excellent high/low-cycle fatigue resistance, re-centering capabilities and excellent corrosion resistance. All of these characteristics give SMAs great potential for use within seismic resistant design and retrofit applications.

While shape memory alloys have demonstrated excellent potential for use in seismic resistant applications, there is a limited understanding about the potential and limitations of the material. There have been conflicting experimental results among the various studies of SMAs. Much debate has occurred over the energy dissipation and re-centering capabilities of the material. Analytical and experimental studies in which SMAs have been used within a structure have reported varying degrees of success. Many of the discrepancies are due to the differences in the material characteristics, which may be a result of different manufacturers, sizes and compositions. Nevertheless, it can be stated that the unique properties make shape memory alloys extremely attractive as a tool for future use within seismic protection systems. This paper summarises the basic characteristics of shape memory alloys, highlights the factors affecting their response,
SUMMARISES THE CURRENT STATE-OF-THE-ART IN RESEARCH ON SHAPE MEMORY ALLOYS AS IT RELATES TO SEISMIC APPLICATIONS, AND ILLUMINATES THE POTENTIAL, AS WELL AS THE LIMITATIONS OF THE MATERIAL FOR SEISMIC APPLICATIONS.

2. SHAPE MEMORY ALLOYS: THE SHAPE MEMORY AND SUPERELASTIC EFFECTS

Shape memory alloys (SMAs) are a class of alloys that display several unique properties, including shape memory and superelastic effects. In its low temperature phase, SMAs exhibit the shape memory effect (SME). Originally in its martensitic form, the SMAs are easily deformed to several percent strain. Unloading results in a residual strain, as shown in Fig. 1. Heating the resulting specimen above a pre-determined temperature results in phase transformation, and a recovering of the original shape (i.e. removal of the residual strain).

In its high temperature form, SMAs exhibit a superelastic effect. Originally in austenitic phase, martensite is formed upon loading beyond a certain stress level, resulting in the stress plateau shown in Fig. 1. However, upon unloading, the martensite becomes unstable, resulting in a transformation back to austenite, and the recovery of the original, undeformed shape.

While Nitinol has become the most commonly used types of SMA, due to its relatively low cost when compared to other types of shape memory alloys as well as its superior mechanical behaviour, several other compositions of SMAs have been developed. Several studies have investigated the different types of SMAs, partially to define the characteristics of the different alloy, but also to find the optimal alloy for seismic applications [Koval and Monastyrsky, 1995; Serneels, 1999; Zhao, 2001]. The MANSIDE project, a multiple-year effort funded by the European Union, studied the effect of various compositions for SMAs, including NiTi, CuZnAl, CuAlNi, FeMn, MnCu and NiTiNb [MANSIDE, 1998]. From their study, it was found that NiTi is the most appropriate shape memory alloy due to its excellent superelasticity, large recoverable strains and excellent corrosion resistance. CuZnAl

Fig. 1. (left) Idealised stress-strain curve for shape memory, and (right) superelastic effect.
and CuAlNi exhibit superior damping within a very limited range of temperature, while FeMn and MnCu exhibit no superelasticity. NiTiNb exhibits better superelastic behaviour and is less dependent on temperature variations than other alloys. However, it is approximately 50% more expensive than NiTi and had only demonstrated superelastic properties when it is in wire form.

3. Mechanical Properties of Shape Memory Alloys

The mechanical properties of SMAs, as well as how they vary under different conditions, need to be understood before the potential and effectiveness of SMAs within seismic retrofit applications can be evaluated. Previous studies, focusing on the cyclical properties, strain rate effects, and temperature effects are discussed below.

3.1. Cyclical properties

The cyclical behaviour of SMAs are critical if they are to be used in seismic applications. Figure 2 shows a stress-strain diagram of a Nitinol SMA wire (Austenitic) subjected to cyclical loads. Several observations could be made from the figure. First, repeated cyclical loading leads to gradual increases in the residual strains. This results from the occurrence of microstructural slips during the stress-induced martensitic transformation, which causes residual strains and internal stresses. [Xie et al., 1998; Liu et al., 1999; Sehitoglu et al., 2001]. The other observation is that the forward transformation stress decreases for increasing cyclical loading. This also occurs because of the microstructural slips, which inhibits the formation of stress-induced martensite upon additional cycling. As a result, the martensitic forward transformation stress is reduced. Following the same logic, the stress required to induce the reverse transformations is also reduced by repeated cycling. However, the reduction in the reverse transformation is less than that in

![Stress-strain hysteresis of superelastic NiTi bars](Kaounides, 1995).
the forward phase transformation. This results in a decrease in the hysteresis and energy dissipation of the specimen [Miyazaki et al., 1990; Tobushi et al., 1992; Picornell et al., 1994; Kaounides, 1995; Tobushi et al., 1996; Van Humbeeck, 1999]. For earthquake applications, the number of cycles, $N$, that would be considered is in the range of $5 - 10$. According to Fig. 2, this would result in an approximately 40% decrease in the stress plateau in later cycles, as compared with the first cycle.

The degradation of the cyclical properties of the SMAs, known as fatigue, could be improved with larger amounts of cold-working, annealing at lower temperatures, cycling under lower stresses and cycling at faster rates [Friend and Morgan, 1999]. Training, which consists of pre-cycling of the specimen, has been shown to decrease the fatigue effect [Scherngell and Kneissl, 1999].

A few studies have investigated the effects of prestressing SMA wires before cycling. Several studies have shown that that for efficient energy dissipation, SMA wires must be pretensioned to half of the maximum strain and cycled around the pretrained value [Wolons et al., 1998; Kolomytsev et al., 1998; Inaudi and Kelly, 1994; Whittaker et al., 1995]. Furthermore, increasing the pretensioning decreases the amount of energy dissipation obtained. Therefore, the pretension should be limited to less than half of the maximum strain, in order to maintain an optimal design.

### 3.2. Strain rate effects

Studies on strain rate effects have led to conflicting results. In these studies, loading rates were varied from essentially quasi-static (less than 0.01 Hz) to very high rates of loading (greater than 10 Hz). However, the rates which are most appropriate for seismic applications are those in which the loading rates are moderate (0.5–2 Hz). Liu and Van Humbeeck [1997] were able to demonstrate that the damping capacity of the superelastic NiTi increased as the strain rate increased. Studies by Lin et al. [1993], Wolons et al. [1998], and Peidboeuf et al. [1998] found similar results for a study of moderate strain rates. However, other researchers have found that increased loading rates have led to reductions in hysteresis and energy dissipation of the SMAs [DesRoches et al., 2002; Kolomytsev et al., 1998; Dolce and Cardone, 2001]. It is generally believed the rate effects during cycling are due to the heat generated while going through the transformation.

The results from strain rate studies have led to conflicting conclusions. Part of this can be explained by the wide range of strain rates tested. Generally, studies which did not vary the strain rates by a large amount showed little differences in the behaviour of the specimen as opposed to studies which varied strain rates greatly. However, differences were also due to the variations in material properties, testing conditions, and sample size. This clearly is an area where more research is required.

### 3.3. Temperature effects

Temperature is likely the single most important factor when predicting the behaviour of shape memory alloys. The shape memory process is a thermoelastic
process, meaning, a decrease in temperature is equivalent to an increase in stress. Therefore, as the temperature decreases, an increase in stress results, thereby a lower stress value is required to induce transformation, as shown in Fig. 3. A specimen tested at low temperature will exhibit the shape memory effect, while the same specimen tested at a high temperature may exhibit the superelastic effect. This can pose significant design issues if the operating temperature of SMAs is not known within a reasonable bound.

### 4. Wire-Based Seismic Devices Using Shape Memory Alloys

The unique properties of SMAs have led to the development of several devices which use SMA wire, as shown in Fig. 4. Krumme et al. [1995] investigated a “center-tapped” device. The device was constructed so that the SMA wire is always loaded in tension, whether the device is subjected to tensile or compressive loads. Advantages of this device includes large hysteretic damping, with the possibility of a variety of force-deflection hysteretic shapes, highly reliable and specific energy dissipation, negligible creep effects, temperature insensitivity, excellent low-cycle and high-cycle fatigue properties, as well as excellent corrosion resistance. Overall, center-tapped devices showed potential as part of a seismic resistant system, although full-scale devices have not been validated.

Dolce and Marnetto [1999] developed a similar, more complex device, based on the same concept as the center-tapped device. This hybrid device consisted of a bundle of NiTi wires that provided the re-centering capability, along with steel elements that provided the energy dissipation effect. By combining both types of elements, an optimal device could be achieved. Similar devices were created by Whitaker et al. [1995] and Clark et al. [1995].
5. Applications of SMA in Seismic Retrofit of Buildings

A study by Ohi [2001] investigated the use of SMA elements on steel frames. Superelastic bracing elements were developed using Ternary Ni-Ti-Co SMAs, and tested under cyclic loading to determine their characteristics. The braces were found
Ocel et al. [2002] investigated beam-column connections using martensitic NiTi SMA rods. The connection was designed such that the SMA rods (35 mm diameter, 381 mm in length) were the primary source of moment resistance in the connection. The SMA connection was tested quasi-statically and dynamically. The connection was found to exhibit a stable and repeatable hysteresis for cyclical loads up to 4% story drift (Figure 5), which corresponds to a strain of 5% in the SMA. After the initial test, the SMA rods were heated above the transformation temperature to evaluate the potential for recovering the residual deformation. After heating the rods for approximately 8 minutes at 300 degrees Celsius, the rods recovered approximately 76% of their undeformed shape. The connection was retested, and exhibited nearly identical behavior to the original connection. Comparisons of the envelop of the moment-rotation curve at 4% rotation shows that the difference between the moment for initial test, and the test following the shape recovering is less than 5 percent.

6. Existing Applications of Shape Memory Alloys in Seismic Rehabilitation

The first known example of SMAs being applied in a structure is a rehabilitation project undertaken by Indirli et al. [2001]. The S. Giorgio Church, located in Trignano, Italy, was struck by a 4.8 Richter magnitude earthquake on October 15, 1996, resulting in significant damage to the bell tower within the church. Following the earthquake, the tower was rehabilitated using SMAs. Four vertical prestressing steel tie bars with SMA devices were placed in the internal corners of the bell tower to increase the flexural resistance of the structure, as shown in Fig. 6. The SMA devices were made up of 60 wires, 1 mm in diameter and 300 mm in length. The bars were anchored at the top and bottom of the tower. The goal was to limit the
In a similar project, Croci [2001] and Castellano et al. [2001] studied the heavy damage in the Basilica of St. Francesco, in Assissi, Italy, caused by a September 1997 earthquake. The main challenge of the restoration was to obtain an adequate safety level, while maintaining the original concept of the structure. In order to reduce the seismic forces transferred to the tympanum, a connection between it and the roof was created using superelastic SMAs. The SMA device demonstrates different structural properties for different horizontal forces. Under low horizontal force applied to the masonry by post-tensioning the SMA devices, thus guaranteeing constant compression acting on the masonry walls and keeping the applied force below 20 kN. The retrofit was tested by a minor $m = 4.5$ Richter magnitude earthquake on June 18, 2000, with the same epicenter as the event in 1996. After the main shock, the tower was investigated and no evidence of damage was present. This Bell Tower retrofit is one of the first known applications of SMA technology for seismic resistant design and retrofit.

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forces, the SMA is stiff and allows for no significant displacements. Under high horizontal loads, such as an earthquake, the SMA stiffness reduces to allow for controlled displacements of the masonry walls. Under extremely intense horizontal loads, the SMA stiffness increases to prevent collapse. Figure 7 shows the SMAs used in the retrofit.

7. Applications to Bridges

There are several studies which have evaluated the potential of shape memory alloys in seismic response modification of bridges. Wilde et al. [2000] looked at a variable base isolation system for elevated highway bridges consisting of laminated rubber bearings and SMA bars. The system was mathematically modelled and analytically studied for earthquakes with accelerations of 0.2\(g\), 0.4\(g\) and 0.6\(g\). For the smallest earthquake (0.20\(g\)), the system provided a stiff connection between the pier and the deck. For the medium earthquake (0.40\(g\)), the SMA bars provided increased damping capabilities to the system due to the stress induced martensite transformation of the alloy. For the largest earthquake (0.60\(g\)), the SMA bars provided hysteretic damping and acted as a displacement control device, due to the hardening of the alloy after the phase transformation is completed.

In another study using SMAs devices in bridges, Adachi and Unjoh [1999] created an energy dissipation device out of a Nitinol SMA plate, designed to take the load only in bending. The proof-of-concept study is performed by fixing one end of the plate to the shake table and the other other to a large mass (representing the deck). Shake table tests and numerical models were used to confirm the feasibility of such a device. The SMA damper system reduced the seismic response of the bridge, and were found to be more effective in the martensite form than the austenite form. This is due to the improved damping properties when in the martensitic phase, as compared to the austenite phase.

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Figure 8: Application of Shape Memory Alloys to Bridge Retrofit. (Left) Shape Memory Alloy Restrainers Used at Intermediate Hinges in Bridge, and (right) Relative Hinge Displacement Comparison Using Conventional Restrainers and SMA Restrainers [DesRoches and Delemont, 2001].

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8. Conclusions: Advantages, Drawbacks and Potential

The unique properties of shape memory alloys makes them an ideal candidate for use as devices for seismic resistant design and retrofit. Experimental and analytical studies of shape memory alloys show that they are an effective means of improving the response of buildings and bridges subjected to seismic loading. The re-centering potential of superelastic shape memory alloys is perhaps the most important characteristic that can be exploited for applications in earthquake engineering. The ability to undergo cyclical strains greater than 6%, with minimal residual strain (typically less than 1%), has been shown to be useful as bracing elements in buildings, and as restraining elements in bridges. Furthermore, the recentering capabilities appear to be independent of the diameter of the specimen and insensitive to the strain rate of the loading.

In the martensitic form, NiTi SMA displays an equivalent viscous damping on the order of 15–20% [Dolce and Cardone, 2001; Ocel et al., 2002]. The material does not have nearly as high damping capacity in the austenitic form, which has typical equivalent viscous damping ratios of approximately 4–8% [Dolce and Cardone, 2001; DesRoches et al., 2002]. However, in this form the material demonstrates repeated hysteretic damping, allowing it to provide damping throughout the cyclic loading history. Researchers have shown that one can optimise the performance of SMAs by using a hybrid of both the martensitic form and the austenitic form, thereby obtaining both re-centering and high damping.

Studies have shown that properly trained SMAs can undergo many cycles of loading with little degradation of properties. This leads to the potential of SMAs to be used in other applications, including wind and vibration control.
In general, shape memory alloys can be formed as wires, rods, or plates. The ability for forming various shapes for SMAs provides them with the flexibility to be used in a variety of different types of application. Furthermore, superelastic and martensitic properties can be exploited in torsion and bending, as well as tension/compression.

While the aforementioned characteristics illustrate the significant potential for the development of a new class of seismic resistance devices based on SMAs, there are several potential barriers to their implementation. SMAs are extremely sensitive to compositional changes. Small changes to the components of an alloy can significantly change the mechanical properties of the material, potentially leading to undesirable characteristics. For SMAs to be widely used, quality control measures would be required to ensure the proper and consistent composition and the appropriate properties.

Additionally, SMAs can be expensive to use. The cost has decreased significantly, from approximately US$1100 per kilogram in 1996 to less than US$111 per kilogram today. The decrease in cost is due to increased demands and improvements in manufacturing techniques. It is expected that the price will continue to decrease as further applications using large quantities are sought. Also, due to the hardness of the material, machining large bars is extremely difficult, and requires special tools to be performed adequately. Welding of shape memory alloys is often difficult. In general, when Nitinol is welded to another material, it creates a brittle connection around the welding zone. Heat treatment is required to increase the ductility of the connection, however this generally eliminates the superelastic effect of the alloy.

One of the primary barriers of the use of Shape Memory Alloys is the dependency of the properties on the ambient temperature. Due to the thermo-mechanical nature of the material, an increase in temperature is equivalent to a decrease in stress, meaning larger stresses are now required for the forward transformation. For example, a 10°C change in ambient temperature can affect the transformation stress by as much as 140 MPa. Since the forward and reverse phase transformations are effected differently by changes to the temperature, the area of the hysteresis, and subsequently energy dissipation of the specimen are all a function of temperature. Furthermore, extreme temperature conditions can completely eliminate the shape memory or superelastic effects within a specimen.

Research in the use of SMAs for civil engineering applications is in its early stages and modest achievements have been seen in only the past five years. Many of the above-mentioned barriers can be overcome through research and close collaboration between the civil engineering community, material scientists, and manufacturers of shape memory alloys.

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