ROSE School
EUROPEAN SCHOOL FOR ADVANCED STUDIES IN
REDUCTION OF SEISMIC RISK

EXPERIMENTAL INVESTIGATION
ON THE CYCLIC PROPERTIES OF
SUPERELASTIC NiTi
SHAPE-MEMORY ALLOY WIRES AND BARS

Individual Study Submitted in Partial
Fulfilment of the Requirements for the Doctor of Philosophy Degree in
EARTHQUAKE ENGINEERING

By
DAVIDE FUGAZZA

Supervisors: Prof. FERDINANDO AURICCHIO
Prof. REGINALD DESROCHES

Pavia, August 2005
The individual study entitled “Experimental Investigation on the Cyclic Properties of Superelastic NiTi Shape-Memory Alloy Wires and Bars”, by Davide Fugazza, has been approved in partial fulfilment of the requirements for the Doctor of Philosophy Degree in Earthquake Engineering.

Ferdinando Auricchio

Reginald DesRoches
The presented study investigates the cyclic properties of superelastic NiTi shape-memory alloy (SMA) elements to assess their potential for seismic applications.

Superelastic SMA wires and bars of different size and chemical composition are subjected to both static and dynamic cyclic loadings, in order to evaluate their dependence on the frequency of excitation.

Attention is devoted to the quantities that are of interest in earthquake engineering, in particular damping properties, material strength and recentering capabilities.

**Keywords:** shape-memory alloys, cyclic loadings, damping, strain rate
I would like to express my gratitude to my advisors, Professor Ferdinando Auricchio and Professor Reginald DesRoches, for their comments and suggestions.

I am indebted with Dr. Lorenza Petrini of the European Centre for Training and Research in Earthquake Engineering (Pavia, Italy) as well as Mrs. Federica Onano of the Parco Scientifico Tecnologico e delle Telecomunicazioni in Valle Scrivia (Tortona, Italy) for their help during the experimental tests.

I also thank Dr. Elena Villa of CNR-IENI (Lecco, Italy) for the useful information on the material as well as Mr. Tim Wilson of Memry Corp. (Menlo Park, USA) for providing the wires.

Finally, the financial support of the Progetto Giovani Ricercatori - Bando 2002 of the University of Pavia (Pavia, Italy) is kindly acknowledged.

_Pavia, August 2005_
EXPERIMENTAL INVESTIGATION ON THE CYCLIC PROPERTIES OF SUPERELASTIC NITI SHAPE-MEMORY ALLOY WIRES AND BARS

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Chapter 1. General Features of Shape-Memory Alloys

1. GENERAL FEATURES OF SHAPE-MEMORY ALLOYS

1.1 INTRODUCTION

Shape-memory alloys (SMAs) are materials with an intrinsic ability to remember an original shape. If subjected to imposed deformations, they have the capacity to regain their undeformed configuration either by removal of the external load (known as the superelastic effect) or by means of thermal cycles (known as the shape-memory effect). Due to these unique characteristics, not possessed by traditional materials used in engineering, SMAs lend themselves to innovative applications in many scientific fields, especially in the biomedical and aerospace area (Auricchio 1995; Humbeeck 1999b).

1.2 SUPERELASTIC EFFECT AND SHAPE-MEMORY EFFECT

The unique properties of SMAs are related to reversible martensitic phase transformations, that is, solid-to-solid diffusionless processes between a crystallographically more-ordered phase, the austenite, and a crystallographically less-ordered phase, the martensite.

Typically, the austenite is stable at low stresses and high temperatures, while the martensite is stable at high stresses and at low temperatures. These transformations can be either thermal-induced or stress-induced (Duerig, Melton, and Wayman 1990; Humbeeck 1999a).

In the stress-free state, a SMA is characterized by four transformation temperatures: $M_s$ and $M_f$ during cooling and $A_s$ and $A_f$ during heating. The former two (with $M_s > M_f$) indicate the temperatures at which the transformation from the austenite, also named as parent phase, into martensite respectively starts and finishes, while the latter two (with $A_s < A_f$) are the temperatures at which the inverse transformation, also named as reverse phase, starts and finishes.

The phase transformations between austenite and martensite are the key to explain the superelastic effect and the shape-memory effect. For the simple case of uniaxial tensile stress, a brief
Chapter 1. General Features of Shape-Memory Alloys

explanation follows.

- **Superelastic effect** (Figure 1). Consider a specimen in the austenitic state and at a temperature greater than $A_f$; accordingly, at zero stress only the austenite is stable. If the specimen is loaded, while keeping the temperature constant, the material presents a nonlinear behavior ($ABC$) due to a stress-induced conversion of austenite into single-variant martensite. During unloading, while again keeping the temperature constant, a reverse transformation from single-variant martensite to austenite occurs ($CDA$) as a result of the instability of the martensite at zero stress. At the end of the loading-unloading process no permanent strains are present and the stress-strain path is a closed hysteresis loop.

- **Shape-memory effect** (Figure 2). Consider a specimen in the multiple-variant martensitic state and at temperature lower than $M_s$; accordingly, at zero stress only the martensite is stable, either in a single-variant or in a multiple-variant composition. During loading, the material has a nonlinear response ($AB$) due to a stress-induced conversion of the multiple-variant martensite into a single-variant martensite. During unloading ($BC$), residual deformations show up ($AC$). However, the residual (apparently inelastic) strain may be recovered by heating the material to a temperature above $A_f$, thus inducing a temperature-driven conversion of martensite into austenite. Finally, upon cooling, the austenite is converted back into multiple-variant martensite.

1.3 AN EXAMPLE OF SHAPE-MEMORY ALLOY MATERIAL: NITINOL

The nickel-titanium$^1$ (NiTi) system is based on the equiatomic compound of nickel and titanium. Besides the ability of tolerating quite large amounts of shape-memory strain, NiTi alloys show high stability in cyclic applications, possess an elevate electrical resistivity and are corrosion resistant (Table 1.1).

For commercial exploitation, and in order to improve its properties, a third metal is usually added to the binary system. In particular, a nickel quantity up to an extra 1% is the most common modification. This increases the yield strength of the austenitic phase while, at the same, time depressing the transformation temperatures.

The manufacturing process of NiTi alloys is not an easy task and many machining techniques can only be used with difficulty. This explains the reason for the elevated cost of such a system. Anyway, despite this disatvantage, the excellent mechanical properties of NiTi alloys (Table 1.2) have made them the most frequently used SMA material in commercial applications.

---

$^1$Sometimes the nickel-titanium alloy is called Nitinol (pronounced night-in-all). The name represents its elemental components and place of origin. The “Ni” and “Ti” are the atomic symbols for nickel and titanium. The “NOL” stands for the Naval Ordinance Laboratory where it was discovered.
Chapter 1. General Features of Shape-Memory Alloys

<table>
<thead>
<tr>
<th>Property</th>
<th>NiTi SMA</th>
<th>Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting temperature</td>
<td>1300 °C</td>
<td></td>
</tr>
<tr>
<td>Density</td>
<td>6.45 g/cm³</td>
<td></td>
</tr>
<tr>
<td>Resistivity austenite</td>
<td>≈ 100 [μΩ cm]</td>
<td></td>
</tr>
<tr>
<td>Resistivity martensite</td>
<td>≈ 70 [μΩ cm]</td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity austenite</td>
<td>18 [W/(cm°C)]</td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity martensite</td>
<td>8.5 [W/(cm°C)]</td>
<td></td>
</tr>
<tr>
<td>Corrosion resistance</td>
<td>similar to Ti alloys</td>
<td></td>
</tr>
<tr>
<td>Elasticity Modulus austenite</td>
<td>≈ 80 [MPa]</td>
<td></td>
</tr>
<tr>
<td>Elasticity Modulus martensite</td>
<td>≈ 20 to 40 [MPa]</td>
<td></td>
</tr>
<tr>
<td>Yield strength austenite</td>
<td>190 to 700 [MPa]</td>
<td></td>
</tr>
<tr>
<td>Yield strength martensite</td>
<td>70 to 140 [MPa]</td>
<td></td>
</tr>
<tr>
<td>Ultimate tensile strength</td>
<td>≈ 900 [MPa]</td>
<td></td>
</tr>
<tr>
<td>Transformation temperature</td>
<td>-200 to 110 °C</td>
<td></td>
</tr>
<tr>
<td>Shape-memory strain</td>
<td>8.5 [%]</td>
<td></td>
</tr>
</tbody>
</table>

Table 1.1: Properties of binary NiTi SMAs.

<table>
<thead>
<tr>
<th>Property</th>
<th>NiTi SMA</th>
<th>Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recoverable elongation [%]</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>Modulus of elasticity [MPa]</td>
<td>8.7x10⁴ (A), 1.4x10⁴ (M)</td>
<td>2.07x10⁵</td>
</tr>
<tr>
<td>Yield strength [MPa]</td>
<td>200-700 (A), 70-140 (M)</td>
<td>248-517</td>
</tr>
<tr>
<td>Ultimate tensile strength [MPa]</td>
<td>900 (f.a.), 2000 (w.h.)</td>
<td>448-827</td>
</tr>
<tr>
<td>Elongation at failure [%]</td>
<td>25-50 (f.a.), 5-10 (w.h.)</td>
<td>20</td>
</tr>
<tr>
<td>Corrosion performance [-]</td>
<td>Excellent</td>
<td>Fair</td>
</tr>
</tbody>
</table>

Table 1.2: NiTi SMAs versus typical structural steel: comparison of the mechanical properties. Letters A and M stand for, respectively, austenite and martensite while abbreviations f.a. and w.h. respectively refer to the names “fully annealed” and “work hardened” which are two types of treatment.
Chapter 1. General Features of Shape-Memory Alloys

Figure 1.1: Superelastic effect. At a constant high temperature the material is able to undergo large deformations with zero final permanent strain. Note the closed hysteresis loop.

Figure 1.2: Shape-memory effect. At the end of a loading-unloading path (ABC) performed at a constant low temperature, the material presents residual deformations (AC) which can be recovered through a thermal cycle (CDA).
2. MECHANICAL BEHAVIOR OF SHAPE-MEMORY ALLOY ELEMENTS

2.1 INTRODUCTION

The mechanical behavior of SMA elements, such as wires, bars and plates, has been studied by many authors (Graesser and Cozzarelli 1991; Lim and McDowell 1995; Strnadel et al. 1995; Piedboeuf and Gauvin 1998; Tobushi et al. 1998; Wolons et al. 1998; Dolce and Cardone 2001a; Dolce and Cardone 2001b; Moroni et al. 2002; Tamai and Kitagawa 2002; DesRoches et al. 2004) in order to understand the response of such elements under various loading conditions. In the following, we present a state-of-the-art review of the most recent experimental investigations, focusing only on papers dealing with a material characterization.

2.2 MECHANICAL PROPERTIES OF SMA WIRES, BARS AND PLATES

Graesser and Cozzarelli (1991) focused on Nitinol samples machined from a raw stock of cylindrical bar having a 15.1 mm diameter. The tests were carried out at different strain rates (\(\dot{\varepsilon}\) equals to 1.0 \(\times\) 10\(^{-4}\) sec\(^{-1}\) and 3.0 \(\times\) 10\(^{-4}\) sec\(^{-1}\)) and up to a 3% strain in tension and compression. The researchers summarized different points of interest.

1. The stress levels at which both phase transformations take place do not show a pronounced sensitivity to the varying levels of strain rate applied.

2. The inelastic response of Nitinol is rate-dependent and affects the overall shape of the fully developed cyclic hysteresis.
Lim and McDowell (1995) analyzed the path dependence of SMAs by performing experimental tests on 2.54 mm diameter wires. In particular, they focused attention on both the cyclic uniaxial tension behavior and the cyclic uniaxial tension-compression behavior. The most significant results they found were the following.

1. Under condition of cycling loading with a maximum imposed strain, the critical stress to initiate stress-induced martensite transformation decreases, the residual strain accumulates and the hysteresis energy progressively decreases over many cycles of loading.

2. The stress at which either forward or reverse transformation occurs depends on the strain level prior to the last unloading event. This behavior is attributed to the distribution and configuration of austenite-martensite interfaces which evolve during transformation.

Strnad el et al. (1995) tested both NiTi and NiTiCu thin plates in their superelastic phase to evaluate the cyclic stress-strain characteristics of the selected alloys. They also devoted particular attention to the effect of the variation of the nickel content in the specimens’ mechanical response. Interesting were the aspects that the research group pointed out.

1. Ternary NiTiCu alloys display lower transformation deformations and transformation stresses than binary NiTi alloys.

2. In both NiTi and NiTiCu alloys, the higher the nickel content, the lower the residual deformation as the number of cycles increases.

Piedboeuf and Gauvin (1998) studied the damping behavior of SMA wires. They performed experiments on 100 μm diameter NiTi wires at three levels of amplitudes (2, 3 and 4% of strain), over four frequency values (0.01, 0.1, 1, 5 and 10 Hz) and at two different temperatures (25 and 35 °C). Different were the findings carried out by the researchers.

1. An increase in temperature causes a linear increase in transformation stresses and a shift of the stress-strain curves upward.

2. Up to a frequency of 0.1 Hz and for a fixed value of deformation of 4%, the stress difference between the two superelastic plateaus increases, producing an increase in the dissipated energy as well. For higher frequencies, instead, the lower plateau stress level rises, causing a pronounced reduction of the surface hysteresis.

3. Frequency interacts with the deformation amplitude. In particular, at 2% strain, there is only a slight variation in the dissipated energy by varying the frequency while, at 4%, the variation is more important and the maximum occurs at around 0.1 Hz. For higher values of frequency the dissipated energy decreases.
Tobushi et al. (1998) investigated the influence of the strain rate (i.e. $\dot{\varepsilon}$) in the superelastic properties of 0.75 mm diameter NiTi superelastic wires. The tensile tests were conducted at strain rates ranging from $1.67 \cdot 10^{-3}\% \cdot \text{sec}^{-1}$ to $1.67\% \cdot \text{sec}^{-1}$. They also took into account the effects of the temperature variation in the wires’ mechanical response. Their main considerations were the following.

1. When $\dot{\varepsilon} \geq 1.67 \cdot 10^{-1}\% \cdot \text{sec}^{-1}$, the larger $\dot{\varepsilon}$, the higher the stress at which the forward transformation starts and the lower is the stress at which the reverse transformation starts.

2. For each temperature level considered, the larger $\dot{\varepsilon}$, the larger is the residual strain after unloading. Also, the higher the temperature, the larger is the residual strain.

3. As the number of cyclic deformation increases, the stress at which forward and reverse transformation start decreases with a different amount of variation. Also, the irrecoverable strain which remains after unloading increases.

4. The strain energy increases with an increase in temperature, while the dissipated work slightly depends on the temperature variation. Also, at each temperature level, it is observed that both quantities do not depend on the strain rate for values of $\dot{\varepsilon} \leq 3.33 \cdot 10^{-2}\% \cdot \text{sec}^{-1}$. Instead, for values of $\dot{\varepsilon} \geq 1.67 \cdot 10^{-1}\% \cdot \text{sec}^{-1}$, the dissipated work increases and the strain energy decreases.

Wolons et al. (1998) tested 0.5 mm diameter superelastic NiTi wires in order to understand their damping characteristics. They studied in detail the effect of cycling, oscillation frequency (from 0 to 10 Hz), temperature level (from about 40 °C to about 90 °C) and static strain offset (i.e. strain level from which the cycling deformation starts). On the basis of the experimental data, they observed that:

1. A significant amount of mechanical cycling is required for an SMA wire to reach a stable hysteresis loop shape. The amount of residual strain is dependent on both temperature and strain amplitude, but it is not a function of the cycling frequency.

2. The shape of hysteresis loop changes significantly with frequency. The reverse transformation is affected more than the forward transformation.

3. Energy dissipation is a function of frequency, temperature, strain amplitude and static strain offset. The energy dissipated per unit volume initially decreases up to 1-2 Hz, then appears to approach a stable level by 10 Hz. Dissipation capacity at 6-10 Hz is about 50% lower than the corresponding value at very low frequencies. Moreover, it decreases as temperature increases above 50 °C.
4. By reducing the static strain offset, the energy dissipated per unit volume increases.

5. Energy dissipation, per unit volume, of SMA wires undergoing cyclic strains at moderate strain amplitudes (about 1.5 %) is about 20 times bigger than typical elastomers undergoing cyclic shear strain.

Dolce and Cardone (2001a) investigated the mechanical behavior of several NiTi SMA bars in both austenitic and martensitic phase subjected to torsion. The SMA elements were different in size (7-8 and 30 mm diameter), shape (round and hexagonal bars) and physical characteristics (alloy composition, thermomechanical treatment and material phase). The experimental results were carried out by applying repeated cyclic deformations. Strain rate, strain amplitude, temperature and number of cycles were considered as test parameters. The most important findings of the experimental investigation can be summarized as follows:

1. The mechanical behaviour of SMA bars subjected to torsion is independent from loading frequency in case of martensite, or slightly dependent on it in case of austenite.

2. The effectiveness in damping vibrations is good for martensite (up to 17% in terms of equivalent damping), but rather low for austenite (of the order of 5-6% in terms of equivalent damping).

3. Austenite bars present negligible residual deformations at the end of the action, being of the order of 10% of the maximum attained deformation.

4. The fatigue resistance under large strains is considerable for austenite bars (hundreds of cycles) and extraordinary for martensitic bars (thousands of cycles). In both cases, the cyclic behaviour is highly stable and repeatable.

Dolce and Cardone (2001b) concentrated on the mechanical behavior of superelastic NiTi wires subjected to tension. The experimental tests were carried out on austenite wire samples with 1-2 mm diameter and 200 mm length. Several kinds of wires were considered, differing in alloy composition and/or thermomechanical treatment. Firstly, cyclic tests on pre-tensioned wires at room temperature ($\approx 20 ^\circ C$), frequency of loading ranging from 0.01 to 4 Hz and strain amplitude up to 10% were performed. Secondly, loading-unloading tests under temperature control, between 40 $^\circ C$ and 10 $^\circ C$ (step 10 $^\circ C$), at about 7% strain amplitude and 0.02-0.2 Hz frequency of loading were conducted. The authors deeply investigated the superelastic behaviour, focusing on the dependence of the mechanical properties on temperature, loading frequency and number of cycles. In the following, their most important findings are listed:
Chapter 2. Mechanical Behavior of Shape-Memory Alloy Elements

1. The dependence on temperature of the tested materials appears compatible with the normal range of ambient temperature variations, if this is assumed to be of the order of 50 °C.

2. Loading frequency affects the behaviour of SMAs, especially when passing from very low frequencies (0.01 Hz or even less) to higher frequency levels (0.2-4 Hz). A considerable decrease of energy loss and equivalent damping occurs because of the increase of temperature, due to the latent heat of transformation, which cannot be dissipated in case of high strain rates.

3. The number of undergone cycles considerably affects the superelastic behaviour of austenitic SMAs, worsening the energy dissipating capability and increasing the cyclic strain hard-ending.

Moroni et al. (2002) tried to use copper-based SMA bars as energy dissipation devices for civil engineering structures. They performed cyclic tension-compression tests on martensitic bars, with a diameter of 5 and 7 mm, characterized by different processing histories (hot rolled or extrusion) and grain size composition. The experimental investigation was conducted both in strain and stress control at different frequencies of loading (from 0.1 to 2 Hz). On the basis of the results, the researchers drew the following major conclusions:

1. The martensitic CuZnAlNi alloy dissipates substantial energy through repeated cycling.

2. Damping is a function of strain amplitude and it tends to stabilize for large strains. Also, frequency (0.1-2 Hz) has a small influence on the damping values.

3. The considered mechanical treatments (rolling and extrusion) do not influence the bars’ mechanical behavior.

4. Observed fractures are due to tensile actions and present a brittle intergranular morphology.

Tamai and Kitagawa (2002) observed the behavior of 1.7 mm diameter superelastic NiTi wires for a possible use of SMAs in innovative bracing systems as well as exposed-type column base for buildings. Monotonic and pulsating tension loading tests were performed with constant, increasing and decreasing strain amplitudes. Also, the effects of the ambient temperature was taken into consideration. As a result of the experimental observations, they provided the following conclusions.
1. A spindle shaped hysteresis loop without residual deformation is observed

2. The stress which starts the phase transformation is very sensitive to ambient temperature. Furthermore, wire temperature varies during cyclic loading due its latent heat.

3. The residual deformation increment and dissipated energy decrement per cycle decreases with the number of loading cycles.

4. The rise and fall of the wire temperature during forward and reverse transformation have almost the same intensity. In particular, forward transformation is exothermal while reverse transformation is endothermal.

DesRoches et al. (2002) performed several experimental tests on superelastic NiTi wires and bars to assess their potential for applications in seismic resistant design and retrofit. In particular, they studied the effects of the cycling loading on residual strain, forward and reverse transformation stress levels and energy dissipation capability. Specimens were different in diameters (1.8, 7.1, 12.7 and 25.4 mm respectively) with nearly identical composition. The loading protocol used consisted of increasing strain cycles of 0.5%, 1% to 5% by increments of 1%, followed by four cycles at 6%. The research group considered two series of tests. The first one, in quasi-static conditions, was performed at a frequency of 0.025 Hz while the second one was conducted at frequencies of 0.5 and 1 Hz in order to simulate dynamic loads. After carrying out the experiments, they proposed the following observations:

1. Nearly ideal superelastic properties are obtained in both wires and bars. The residual strain generally increases from an average of 0.15% following 3% strain to an average of 0.65% strain following 4 cycles at 6% strain. It seems to be independent on both section size and loading rate.

2. Values of equivalent damping range from 2% for the 12.7 mm bars to a maximum of 7.6% for the 1.8 mm wires and are in agreement with the values found by other authors (Dolce and Cardone 2001a). Bars show a lower dissipation capability than wires.

3. The initial modulus of elasticity and the stress level at which the forward transformation starts in the 25.4 mm diameter bars are lower by about 30% than the corresponding values in the wires.

4. Increase of the loading rates leads to lower values of the equivalent damping but has negligible influence on the superelastic effect.
3. EXPERIMENTAL INVESTIGATION

3.1 INTRODUCTION

In this chapter, we focus attention on the experimental investigation, which is aimed at studying the cyclic properties of superelastic NiTi SMA wires and bars. Firstly, we describe the available SMA materials as well as the selected loading protocol. Subsequently, we provide the main characteristics of the material testing system used to carry out the tests and we introduce the mechanical properties that we want to evaluate for each SMA. Finally, we list and discuss the most important outcomes coming from the analysis of the results.

3.2 SHAPE-MEMORY ALLOY MATERIALS

This section is dedicated to the description of the available SMA materials. All tests were carried out at the Parco Scientifico Tecnologico e delle Telecomunicazioni in Valle Scrivia\(^1\) (Tortona, Italy).

- **Set 1**: The material consists of a commercial superelastic NiTi straight wire with circular cross section of diameter 1.00 mm provided by CNR-IENI (Lecco, Italy). The testing frequencies were 0.001 Hz (static) and 1 Hz (dynamic).

- **Set 2**: The material consists of a commercial superelastic NiTi straight wire with circular cross section of diameter 0.76 mm provided by Memry Corp. (Menlo Park, USA). The testing frequencies were 0.001 Hz (static) and 0.1 Hz (dynamic).

\(^1\)Information on the Center and on its facilities can be found at http://www.pst.it
• **Set 3**: The material consists of commercial superelastic NiTi bars (Figure 3.2) with circular cross section of diameter 8.00 mm provided by CNR-IENI (Lecco, Italy). The testing frequencies were 0.001 Hz (static) and 1 Hz (dynamic).

As far as the material from CNR-IENI is concerned, the wire specimens were heat treated at 400 °C for 30 minutes and then water quenched in order to obtain the desirable superelastic properties. No specific information, instead, is available for the CNR-IENI bars and for the Memry wires.

### 3.3 LOADING PROTOCOL

The loading protocol consists of cycles of increasing strain amplitude of 1% to 6% by increments of 1%. The tests were performed at frequencies of 0.001 Hz, 0.1 Hz and 1 Hz in order to simulate both static and dynamic loading conditions.

### 3.4 EXPERIMENTAL SETUP

Experimental tests were performed using a 100 kN MTS 810 multipurpose servohydraulic testing apparatus\(^2\). The above mentioned loading protocol was input by using an MTS TestStar II control System running MultiPurpose TestWare software which used strain output from the extensometer to control the movement of the actuator. Strains were determined with a 5 mm gage length extensometer when testing wires and with a 25 mm gage length extensometer when testing bars with the load being measured by the internal cell of the actuator. To avoid sliding or breaking between wires and grips, an *ad hoc* device was realized at the Department of Structural Mechanics of the University of Pavia (Figure 1).

### 3.5 MONITORED OUTPUT QUANTITIES

In order to evaluate the cyclic performance of superelastic SMAs, a number of output quantities are considered. They are the equivalent viscous damping, the effective stiffness, the recentering capability and the transformation stresses.

\(^2\)Information on the mechanical characteristics can be found at http://www.mts.com.
The equivalent viscous damping expresses the effectiveness of the material in vibration damping. It is expressed through the following formula:

\[ \xi_{eq} = \frac{1}{4\pi} \frac{A_{hysteresis}}{A_{elastic}} \]

where \(A_{hysteresis}\) represents the area under the stress-strain curve and \(A_{elastic}\) is the elastic strain energy for a complete cycle.

The effective stiffness is computed through the expression:

\[ E = \frac{(\sigma_{max} - \sigma_{min})}{(\epsilon_{max} - \epsilon_{min})} \]

where \(\sigma_{max}\) and \(\sigma_{min}\) are, respectively, the maximum and minimum stress and \(\epsilon_{max}\) and \(\epsilon_{min}\) are, respectively, the maximum and minimum deformation.

The recentering capability refers to the capacity of the material to return to its original undeformed shape upon unloading. Its measure is the maximum recoverable strain obtained after the imposed deformation.

The transformation stresses are the stress levels at which both the forward (i.e. from austenite to martensite) and reverse (i.e. from martensite to austenite) phase transformation starts and finishes. They are denoted as \(\sigma_{ASs}\), \(\sigma_{ASf}\), \(\sigma_{SAs}\) and \(\sigma_{ASf}\) respectively and, as an example, they are represented in Figures 3.15, 3.16 and 3.17 for the 6% deformation cycle.

For the sake of completeness, on Figure 3.18 we review the terminology that will be used in the forthcoming discussion.

### 3.6 CYCLIC PROPERTIES OF WIRES AND BARS UNDER STATIC LOADING CONDITIONS

This section is dedicated to the discussion of the most important results from the experimental tests undertaken under static loading conditions.

- Both wires and bars show a very good superelastic behavior. The value of residual strain after each cycle is much lower than the corresponding maximum deformation attained (Figure 3.3, 3.5 and 3.7). Wires and bars seem to have the same performance. At 9% CNR-IENI wires display plastic behavior since they are not able to recover the imposed deformation. The other available SMA material has not been tested up to that strain level.

- The cyclical properties of the two types of wires are different. In particular, Memry wires display a higher reduction of the stress \(\sigma_{ASs}\) than CNR-IENI wires as the number...
of cycles increase (Figure 3.3, 3.5 and 3.7). This is most likely due to both the different chemical composition and the thermo-mechanical treatments of the two alloys. The effect of degradation, commonly referred to as fatigue, is considered to be associated with the introduction of small levels of localized slip that assist the forward transformation, which results in lower values of the stress level at which it takes place.

- CNR-IENI and Memry wires have similar values of equivalent viscous damping while bars have a worse capacity to dissipate energy (Figures 3.9, 3.11 and 3.13).

### 3.7 CYCLIC PROPERTIES OF WIRES AND BARS UNDER DYNAMIC LOADING CONDITIONS

In the following, we summarize the most important outcomes from the experimental tests undertaken under dynamic loading conditions.

- The recentering capability, measured from the residual strain, seems to be insensitive to the strain rate. More precisely, it is observed that the residual strain after the 6% cycle is approximately the same as the one obtained under static loadings (Figure 3.4, 3.6 and 3.8).

- The increase of the strain rate leads to an increase of the stress levels at which both phase transformations (i.e. forward and reverse) take place (i.e. \(\sigma_{AS}^s\) and \(\sigma_{SA}^s\)) with larger increase observed for the unloading stress \(\sigma_{SA}^s\). Such a variation is probably due to the increase of temperature in the specimen during the transformation that requires larger stresses to induce martensite. This results in a reduction of the hysteresis size with a consequent decrease of the equivalent viscous damping (Figures 3.9, 3.10 and 3.11).

- The values of the equivalent stiffness are higher than those coming from the test performed under static loading conditions. This change is due to the slope increase of both plateaus, in particular in the upper one (Figure 3.10, 3.12 and 3.14).

### 3.8 EFFECT OF CYCLIC TRAINING

In view of a possible use of SMA materials in earthquake engineering, we investigate the effect of the cyclic training. In particular, we focus on the response of a CNR-IENI wire undergoing 10 loading-unloading cycles up to 4% strain performed at a frequency of 0.1 Hz. Figure 3.19 reports the experimental results and in the following we provide a list of comments.
• The cyclic training does affect the response of a superelastic SMA. The upper plateau stress level needed to initiate the forward phase transformation decreases with a consequent decrease of the hysteresis size which is the quantity that defines the energy dissipation capability of the material.

• The material behavior becomes quite insensitive to cyclic loading after a certain number of cycles which is of the same order as that experienced during a seismic event. In order to get a stable behavior, a SMA should then be subjected to a pre-established initial training.

3.9 EFFECT OF THERMAL TREATMENTS

The influence of the temperature plays an important role in the behavior of SMAs. As an example, in Figure 3.20 we show the cyclic behavior of the material, at a frequency of 0.1%, before being thermally treated. Different are the considerations that can be drawn.

• The material does not exhibit the superelastic effect displaying, instead, an increasing plastic deformation that leads to failure of the specimen.

• The stress level at which the forward phase transformation starts is higher than that experienced by the SMA after thermal treatments.

• Breaking of the specimen has been observed at about 8% strain.
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Figure 3.1: Gripping system of the MTS apparatus (left) and close-up view of the device used when testing wires (right).

Figure 3.2: CNR-IENI bar.
Figure 3.3: CNR-IENI wires: static tests.

Figure 3.4: CNR-IENI wires: dynamic tests.
Figure 3.5: Memory wires: static tests.

Figure 3.6: Memory wires: dynamic tests.
Figure 3.7: CNR-IENI bars: static tests.

Figure 3.8: CNR-IENI bars: dynamic tests.
Figure 3.9: CNR-IENI wires: equivalent viscous damping versus deformation level.

Figure 3.10: CNR-IENI wires: equivalent stiffness versus deformation level.
Figure 3.11: Memry wires: equivalent viscous damping versus deformation level.

Figure 3.12: Memry wires: equivalent stiffness versus deformation level.
Figure 3.13: CNR-IENI bars: equivalent viscous damping versus deformation level.

Figure 3.14: CNR-IENI bars: equivalent stiffness versus deformation level.
Figure 3.15: CNR-IENI wires: elastic properties and transformation stress levels.

Figure 3.16: Memry wires: elastic properties and transformation stress levels.
Figure 3.17: CNR-IENI bars: elastic properties and transformation stress levels.

Figure 3.18: CNR-IENI wires: loading-unloading cycle up to 9% strain.
Figure 3.19: CNR-IENI wires: effect of cyclic training.

Figure 3.20: CNR-IENI bars: effect of thermal treatments in the cyclic behavior.
4. CONCLUSIONS

This study involved the testing of superelastic SMA wires and bars, with different size and chemical composition, to determine their potential in view of applications in earthquake engineering. The effects of the loading frequency in the mechanical properties such as recentering ability, material strength, and damping capacity, are evaluated to judge the cyclic properties of the available SMA materials.

Both wires and bars show a very good superelastic behavior. During the deformation process the residual strain gradually increases, however, its value turns out to be very low if compared to the maximum strain attained in each cycle. This feature highlights then the possibility of using SMAs as recentering devices, able to bring the structure back to its undeformed configuration after that the external solicitation is over.

Due to fatigue effects, the stress level at which the forward transformation starts decreases as the number of cycles increases but it stabilizes to an almost constant level after a few of them.

Rate effects do influence the mechanical response of SMAs. In particular, the higher the frequency of excitation, the bigger the hysteresis size reduction. As a consequence, the corresponding values of equivalent viscous damping are then too low for considering superelastic SMAs as energy dissipation devices. Anyway, for purely damping applications, SMAs in their martensitic form could be successfully added because of their wider hysteresis loops.

Finally, careful attention should be taken into account when considering the possibility of using either wires or bars in SMA-based seismic devices. Bars are usually more expensive than wires and more difficult to manufacture but can be designed in such a way to withstand both tension and compression forces.
Bibliography


