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Recent Progress in Materials

Original Research

The behaviour of Nitinol Wire Bundles for Structural Applications

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Academic Editor: Hossein Hosseinkhani

Recent Progress in Materials
2021, volume 3, issue 1
doi:10.21926/rpm.2101009

Received: August 19, 2019
Accepted: March 11, 2021
Published: March 30, 2021

Abstract

Shape memory alloys (SMA) belong to a family of smart materials, which undergo diffusionless phase transformations when subjected to thermo-mechanical changes making them ideally suitable for utilization in several structural engineering applications. Within this class of materials, Ni-Ti (Nickel-Titanium) alloys are predominantly used due to their non-linear behaviour. Nitinol, one of the Ni-Ti alloys, possesses unique properties such as super-elasticity and shape- memory effect, which makes it suitable for damping vibrations transmitted to structures like buildings and bridges during high wind and seismic events. This paper presents selected results obtained from a series of tests conducted on Nitinol 55 wires and bundles made from wires having diameters of 0.25, 0.5, 0.55, and 1 mm. The tests conducted include microstructure analyses, static tensile tests, hysteresis tests, and cyclic dynamic tests performed on wire bundles of various diameters. It is demonstrated that wires having small diameters (0.25 and 0.5 mm) exhibit greater ultimate strength compared with the ones having a larger diameter (1 mm). The bundles produced from these wires displayed hysteretic behaviour under cyclic-dynamic testing conditions confirming their suitability in structural engineering applications.

Keywords

Shape memory alloy; Ni-Ti alloy; mechanical testing

1. Introduction

Shape memory alloys (SMA) has increasingly been used in seismic-resistant designs of building and bridge structures as they can undergo apparent and permanent deformations, which can be fully recovered through thermo-mechanical changes [1-3]. SMA demonstrates two unique properties: the shape memory effect (SME) and super-elasticity (SE), which has particular relevance in achieving increased ductility of building and bridge structures built in areas prone to seismic activities. Nitinol, one of the key compositions in SMA that are commonly used in engineering applications, exists in two distinct phases: austenite and martensite. The austenitic phase is characterized by *B2 or CsCl* ordered structure and is stable at high temperatures, while the martensitic phase demonstrates a complex monoclinic structure (B19), which is stable at low temperatures [4, 5]. Other forms of the SMA have austenite - martensite crystal structure arrangements, which are different from Nitinol; however, high symmetry during the austenite phase and low symmetry during martensite is commonly observed in the crystal structures of most SMA.

The SE displayed by the SMA occurs under isothermal conditions. Under this property, an SMA specimen stretched under mechanical stress recovers back to its original shape upon unloading. The SME, on the other hand, is the recovery of the strain and the original shape that is achieved by changing the temperature experienced by an SMA. The SMA, which consisted of an austenitic microstructure in their parent phase, undergoes a diffusionless transformation during deformation. The deformed SMA is characterized by the martensitic microstructure. When heated, the deformed SMA transforms from the martensite phase to the austenite phase and regains its original shape.

The possibilities of these alloys in structural engineering applications are interesting, where the SMA absorbs energy as they undergo deformation due to large external forces. The absorbed energy is gradually released when the alloy recovers to its original form due to either an increase in temperature or stress reduction.

Potential applications of these alloys in earthquake engineering are significant [6]. The SMA has been tested positive to be effective materials for the preservation of structures during seismic events. The SMA reduces or eliminates the structural damage incurred on built infrastructure by absorbing the seismic energy and facilitating the re-centering of these structures (Energy Dissipation Methods) [7, 8]. The large recoverable strain and the hysteresis characteristics are the main properties of the SMAs, which may possess practical applications for the protection of civil structures during earthquakes. This study contributes to the body of knowledge related to the implementation of SMA in the design of damper elements and for limiting the displacements transmitted between the structural components.

Alloys made of Nickel and Titanium have gained considerable attention from engineering researchers as they present SE and fully recover strains of up to 8% [9-13]. The SE property of these materials facilitates the strain recovery through the removal of mechanical stress, and no heating is necessary to recover the original shape [14-16]. Nitinol alloys were developed at the beginning of the 1960s, but there is scope for continued research regarding the behaviour of small diameter wires made from these alloys before the applicability in civil engineering could be effectively exploited [17, 18]. Nitinol was initially used in a variety of biomedical applications; recently, however, structural applications have been proposed by engineers [19-23]. This material presents interesting characteristics in terms of shape-memory and superelastic capabilities, but its utilization requires precise control of its mechanical properties, especially before and after phase transformation. These characteristics allow Nitinol to provide functionality that is not easily possible with more traditional alloys [24-26]. Typical mechanical properties of Nitinol are reported in Table 1.

Table 1 Typical mechanical characteristics of Nitinol [27, 28].

Density (g/cm^3)	6.45
Poisson's Ratio	0.33
Young's modulus (austenite) (GPa)	75-83
Young's modulus (martensite) (GPa)	28-40
Yield (Transformation) strength (austenite) (MPa)	195-690
Yield (Transformation) strength (martensite) (MPa)	70-140
Coefficient of thermal expansion (austenite) (1/°C)	11×10^{-6}
Coefficient of thermal expansion (martensite) (1/°C)	6.6×10^{-6}

The super-elasticity of SMA has been exploited in numerous forms [29]: Sohn et al. used SMA pseudo-rubber metals, which were utilized as damping materials for vibration control [30]. The crystalline structures of Nitinol during phase transformations are shown in Figure 1. This alloy is stable within a range of temperature conditions, known as the Temperature Transformation Range (TTR); however, it undergoes permanent damage when subjected to temperatures apart from the TTR [31, 32]. When this material is subjected to loading, it deforms during the martensite phase, and this does not cause any damage or modification to the crystalline structure. The removal of mechanical stress or an increase in the temperature leads to the transformation of the crystalline structure (Austenite phase).

The typical mechanical behaviour as a function of the axial strain, σ_A and the normal stress, σ_B is summarized in Figure 2. Below the martensite temperature, the SMA (including Nitinol) exhibit the shape memory effect. The strain caused due to an applied load or stress is recovered by heating SMA at a temperature above the austenite temperature. Above this temperature, the SMA is in its parent phase, austenite. Upon loading, the stress-induced martensite is formed, but upon unloading, the SMA reverts to austenite at lower stress. In metals, deformation causes the translocation of the atoms into new crystal positions, but there is no "memory" of where the atoms were before the deformation.

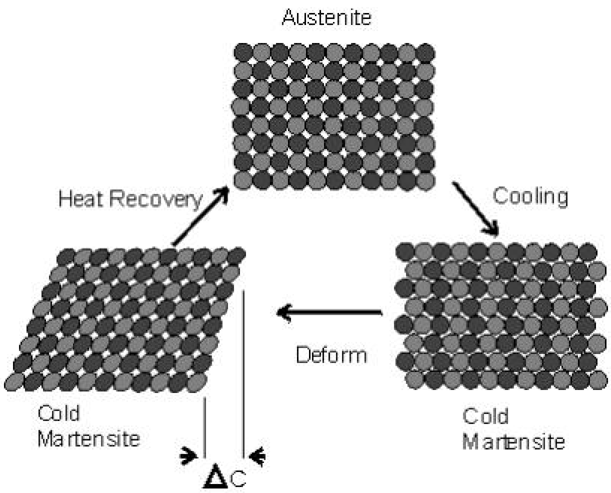

Figure 1 Phase transformations of Nitinol [33].

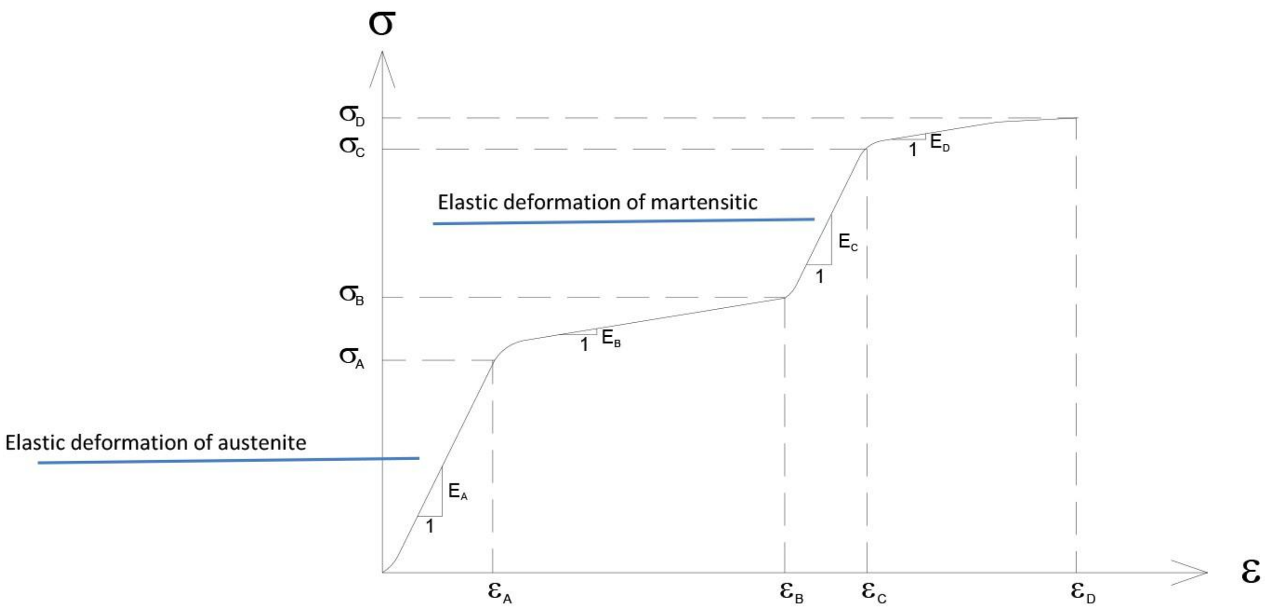

Figure 2 Stress-strain diagram of Nitinol. σ_A and σ_B are the critical stresses at which martensitic transformation starts and finishes [34].

Recently, several applications have been proposed in civil and earthquake engineering [35]: Dolce and Cardone [36] studied the cyclic tensile behaviour of the superelastic NiTi shaped memory alloy wires. The research was carried out within a large experimental test program made for the MANSIDE project (Memory Alloys for New Seismic Isolation and Energy Dissipation Devices) to verify the suitability of SMA super-elastic wires as kernel components for seismic protection devices. Vemury and Renfrey [18] noted that along with the composition of the alloy, the geometry of Nitinol wires has a significant effect on the energy dissipation of these SMA. This research involves an experimental study of the damping or energy dissipation characteristics of the Nitinol wire-bundles. Table 2 shows several requisites for possible applications of Nitinol in passively controlled devices.

Table 2 Requisites for applications of Nitinol in passive control devices [37, 38].

High fatigue resistance	Yes
Low sensitivity to temperature in the range 5-35◦C	Yes
Low sensitivity to strain rate (frequency in sinusoidal vibrations) 1-10 Hz, for energy dissipation techniques	Yes
Limited degradation for environmental actions	Yes
Modulus E_1	as high as possible
Modulus E_2	as low as possible

2. Materials and Methods

The Nitinol 55 wires used were sourced from a commercial supplier called Memry Corporation (Bethel, Connecticut, USA). The Nitinol 55 wires used in this study consists of 55.8% Nickel by weight and the rest with Titanium. Nitinol 55, also referred to as 55 Nitinol, comprises about 53 - 57% of Nickel by weight. The name given to this alloy represents its chemical composition [11]. The product description made available by the manufacturer/supplier states that the Nitinol wires were straight and annealed so that they are slightly surface oxidized. Nickel-Titanium alloys, such as Nitinol shows complete super-elasticity, and hence high levels of energy dissipation during the loading and unloading, provided these cold-drawn wires are annealed at the complete annealing temperature. The super-elastic wires supplied were not subjected to any further heat treatment and were prepared for testing in as-received condition. The wires studied went through the same elemental analysis (confirmed in a scanning electron microscope with EDX attachment) and were found to be 50.6% Ni and 49.4% Ti in terms of atomic percent and on the surface, oxygen was detected, confirming the oxidation caused by heat-treatment from the manufacturer. Examination of the wire surfaces suggested that the finer wires showed more surface damage (longitudinal grooves) and that it might be related to the increased drawing of the wire needed to obtain such fine wires. It is worth mentioning that the Nitinol 55 wires showcased super-elasticity under ambient temperature conditions. As the oxide surface made it a challenge for gripping the wires while conducting static and dynamic testing, considerate attention was paid toward developing a gripping methodology that ensured efficient load application and the prevention of shear failure of the wires close to the grip.

Three stages of testing were performed: the bundling of wires, static uniaxial tensile testing, and cyclic dynamic testing. The properties of these SMA of interest in structural engineering applications are transformation stresses ($\boldsymbol{\sigma_f}, \boldsymbol{\sigma_r}$) and transformation strain ($\boldsymbol{\varepsilon_t}$). Bundles of Nitinol wires having different diameters were prepared, with each bundle comprising of 5 wires each. The wire diameters used were 0.25, 0.5, 0.55, and 1.0 mm. The set of wires in each of the bundles was twisted and secured at the ends using electrical terminal blocks.

2.1 Construction of the Wire Bundles

Nitinol wire bundles made from 5 single wires of small diameters were prepared. The aim was to investigate the structural response of the bundles by comparing them to the individual Nitinol wires. Bundles of wires were created by twisting the wires into a helical formation. The twisting arrangement used in this study was inspired by the methodology used for preparing cable bundles used in bridge structures. A hand drill was used to twist the wires to form a helical arrangement of the bundles. Figure 3 demonstrates a typical wire bundle arrangement. Due care was taken to ensure that the bundles had a uniform helical structure along the full length of the sample. The geometrical properties of the wire bundles are as shown in Table 3.

Figure 3 Typical bundled wire arrangement.

Table 3 Wire bundle dimensions.

Wire Diameter (mm)	**Final Bundle Diameter** (mm)	**Total Length of the Bundle** (mm)	**Number of Drill Turns**
1.00	3.50	320	10
0.55	1.665	320	16
0.50	1.05	320	15
0.25	0.60	700	7

2.2 Laboratory Testing

2.2.1 Instrumentation for Microscope Analysis

Energy-Dispersive X-ray (EDX) Spectroscopy of the Nitinol wires was performed using a Jeol 5600LV scanning electron microscope along with an Oxford Instruments X-act thin-window detector system. These studies were performed at the Electron Microscopy and Analysis Unit, Newcastle University. Optical microscopy images were also captured using a Zeiss Axiovert 100A microscope with a Leica DC295 camera.

2.2.2 Static Tensile Testing

The Nitinol wire bundles were individually subjected to a single static loading-unloading cycle to establish the salient points in their forward and reverse transformations. The stress-strain behaviour of the wire bundles was recorded. A series of static-cyclic tests were conducted on the second set of wire bundles to assess their hysteresis characteristics. The final set of bundles was tested under cyclic-dynamic testing conditions. These tests were carried out using a uniaxial Instron 8801 Servo Hydraulic Fatigue Testing System available at Teesside University, UK. The cyclic-dynamic tests involved 100 cycles per bundle at varying rates of extension, covering the elastic through plastic deformation. The deformation rates implemented in this testing fell within the range of 5 to 20 mm per minute.

3. Results

The Nitinol samples were all prepared and tested at a room temperature of 20-21 °C.

3.1 Microstructure Analysis

Microstructural analysis was conducted on wires having diameters of 0.25 mm, 0.5 mm, and 1.0 mm and some of those results are presented here. The images in Figure 4 and Figure 5 are from the microstructure analysis of Nitinol wires having diameters of 1.0 mm and 0.5 mm. The EDX Spectroscopy of Nitinol wires of 0.25 mm, 0.5 mm and 1.0 mm diameter confirmed that these are Nickel-Titanium binary alloy wires with near 50:50 compositions. As shown in Figure 4 (a) and Figure 4 (b), the Nitinol wires of 1 mm diameter are 50.6% Nickel and 49.4% Titanium in terms of atomic composition. Figure 5 (a) shows the presence of a significant number of inclusions found within 1 mm of the wire. These inclusions appear to have been elongated to stringers during the wire- - drawing process. Figure 5 (b) is indicative of the stringers found in the wires considered in this study. The etchant that was used to reveal the microstructure of the wire was a mixture of 3% HF, 15% HNO_3 and distilled water for around 5 min. Based on the EDX Analysis, it is evident that the Nitinol wires would be strain- hardened by the wire-drawing process before the microstructure analysis and would contain inclusion stringers that are largely oxygen-rich affecting the mechanical properties of these wires. The Nitinol wires having a diameter of 0.25 mm, 0.5 mm, and 1.0 mm, in their as-received condition, have a thin layer of oxide on the surface. This finding is consistent with the information supplied by the manufacturer.

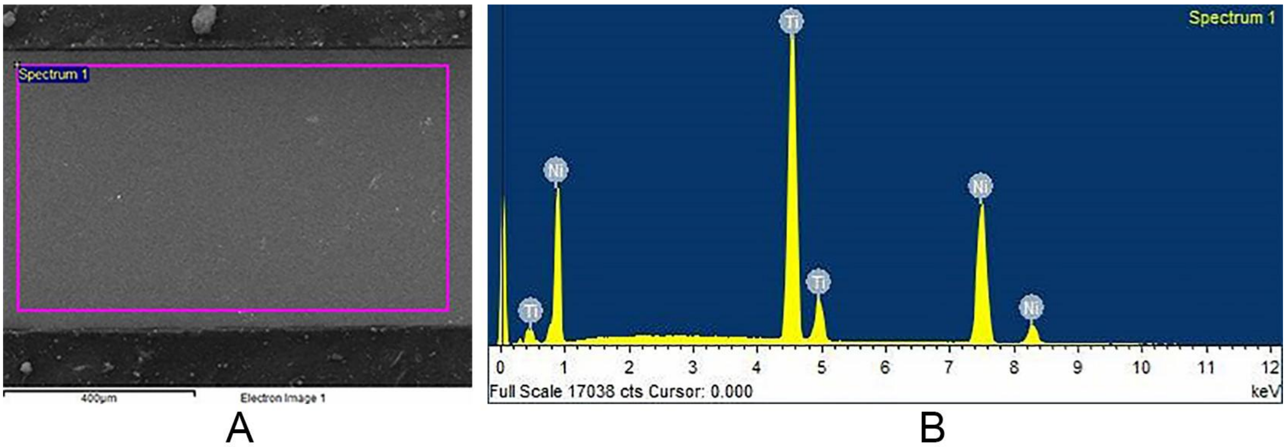

Figure 4 (a) EM Image of the bulk area of 1 mm diameter Nitinol wire section; (b) DX elemental analysis of 1 mm diameter Nitinol wire.

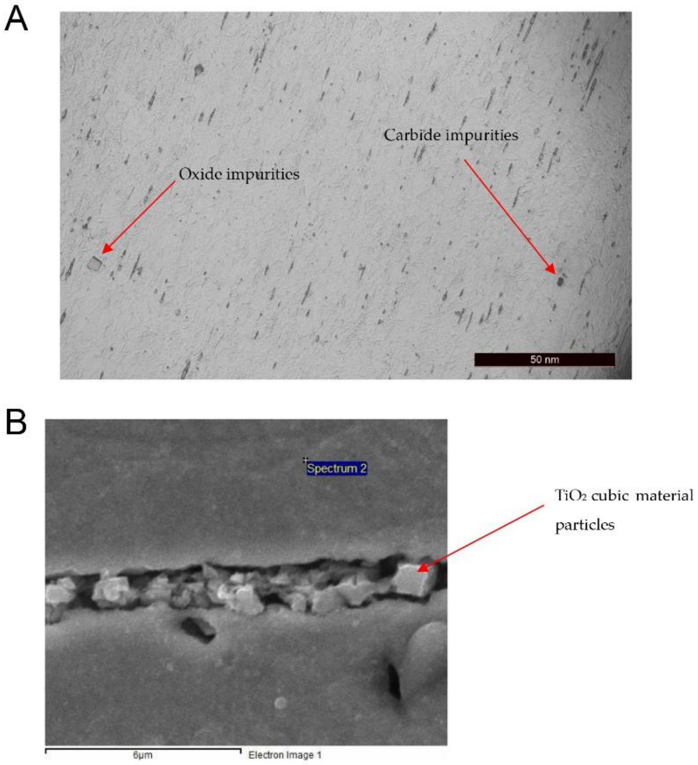

Figure 5 (a) The optical microscope image of the etched 1.0 mm diameter Nitinol wire; (b) electron Microscope Image of particles in the stringer of 0.5 mm diameter Nitinol wire.

As shown in Figure 5 (b), EDX indicated the presence of cubic titanium dioxide (LHS) and titanium nickel oxide, Ti_2NiO (middle region).

3.2 Tensile Tests on Nitinol Single Wires

Initial mechanical characterization of the properties of the unbundled wires was conducted at the Structures Laboratory of Newcastle University, UK [18]. Key phase-transition points, elastic and plastic behaviours and tensile strength were measured and studied by developing a static test procedure. Wires having diameters of 0.25, 0.5 and, 1 mm were chosen for the mechanical characterization. Nitinol wires were subjected to incremental tensile loading using an Instron 100-kN dynamometer. Three specimens were tested for each of the wire diameters.

Table 4 and Figure 6 report the results of the stiffness properties (Young's moduli). Four different stiffness values were found. The first elastic behaviour showed a stiffness that varied between 39.3 and 52 GPa. A subsequent plastic plateau with an equivalent stiffness of 0.5-1.6 GPa was measured. Finally, stiffness increased to approximately 25 GPa in the following phase.

Table 5 reports the results in terms of limit stresses and tensile strengths. The maximum stress incurred was within the range of 1000-1500 MPa. It can be noted that specimens with a smaller diameter typically exhibited a higher tensile strength. The 0.25 mm diameter specimens had an average tensile strength of 1556.4 MPa. This trend was supported by the literature on thin wires [39, 40]. It was proposed that the effect may be due to one, or both of the following reasons:

a) that the oxide layer on the wires as received had a greater contribution to the strength of the smaller wires because of the surface area to bulk ratio effect.

b) that smaller wires contain a smaller number of defects or insignificant defects and hence appear to have a higher tensile strength.

Table 4 Mechanical characterization of Nitinol wires (stiffness characteristics).

Wire Diameter (mm)	E_A (GPa)	E_B (GPa)	E_C (GPa)	E_D (GPa)
0.25	47.6	1.6	27.3	10.9
0.50	52.0	0.5	25.6	7.7
1.00	39.3	1.1	21.7	-

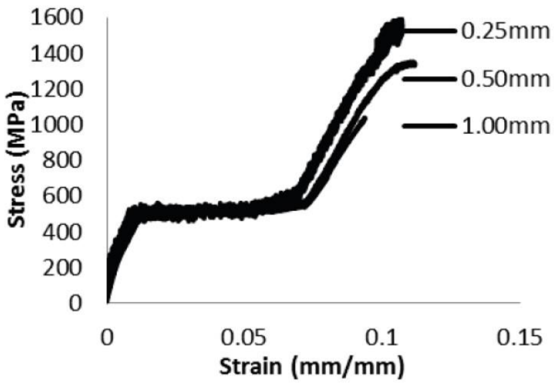

Figure 6 Stress vs. strain (tensile testing of single wires).

Table 5 Results of the mechanical characterization of Nitinol wires (stress limits).

Wire Diameter (mm)	σ_A (MPa)	σ_B (MPa)	σ_C (MPa)	**Tensile Strength** σ_D (MPa)
0.25	492.3	590.1	1491.2	1556.4
0.50	520.3	550.3	1242.2	1342.7
1.00	489.1	556.2	1012.8	1012.8

3.3 Tensile Tests on Nitinol Wire Bundles

The variability in the effectiveness of the bundling action could adversely collectively affect the ultimate tensile strength of the wires in individual bundles. The wire bundles having a smaller diameter were much easier to grip and demonstrated optimal behaviour under static test conditions.

Three-wire bundles were tested under tension, using the same method as the one used to test single wires. A total of 12 bundles were tested. Table 6 shows the mean strength results of static tensile tests on the wire bundles. It can be noted that wire bundles exhibited a tensile strength that is smaller compared with the tensile strength of the corresponding single wire. For bundles having a diameter of 3.5 mm (made of 1 mm diameter wires), the reduction was large: from 1102 MPa to 212 MPa. For bundles having smaller diameters and wires, the ratio between the tensile strength of the bundle and the wires was closer to 1, demonstrating a smaller reduction of strength due to the arrangement in the bundles. For 0.6 mm bundles, the tensile strength (1501 MPa) was similar to the one measured on the corresponding single wires (0.25 mm in diameter) (1556.4 MPa).

Table 6 Wire bundle: Static.

Wire Bundle Diameter (mm)	**Number of wires**	**Single Wire Diameter** (mm)	**Single Wire Cross Sectional Area** (mm^2)	**Bundle Ultimate Stress** (MPa)
3.50	5	1.00	0.785	212
1.665	5	0.55	0.237	438
1.05	5	0.50	0.196	1167
0.60	5	0.25	0.049	1501

The ability of a material to dissipate energy transmitted toward it during a dynamic action such as a seismic event is characterized by its hysteresis curve. Tests were conducted on the wire bundles under static-cyclic testing conditions, and the results for a 0.25 mm wire bundle are shown in Figure 7 and Figure 8. The samples were subjected to cyclic tests, each at different amounts of maximum strain, to ensure that the martensitic transformation led to the strain recovery and that the material was prevented from undergoing permanent deformation.

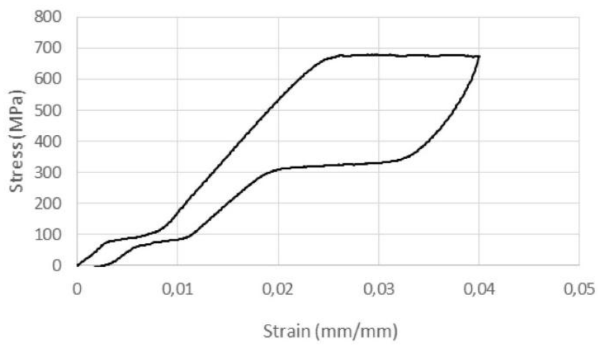

Figure 7 Typical hysteresis behaviour of 0.25 mm Nitinol wire bundles.

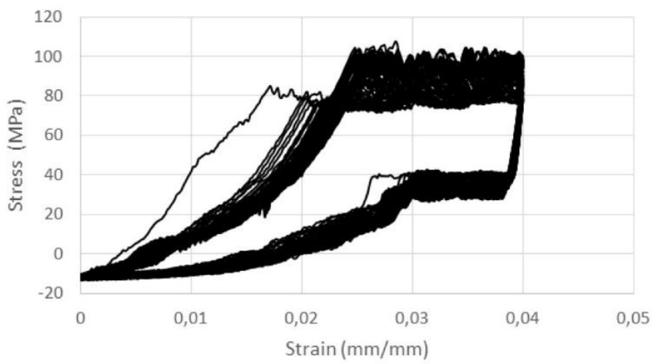

Figure 8 Typical cyclic-dynamic testing of 0.25 mm Nitinol wire Bundles (4% strain).

The wire bundles were also subjected to cyclic-dynamic tensile tests at varying levels of maximum strain with each bundle receiving 100 cycles of loading and unloading. It should be noted that the wire bundles demonstrated non-linear, hysteretic behaviour even under the action of dynamic loads. The test results of 0.25 mm wire bundles are as shown in Figure 8 and Figure 9 for a maximum strain of 4% and 6%, respectively.

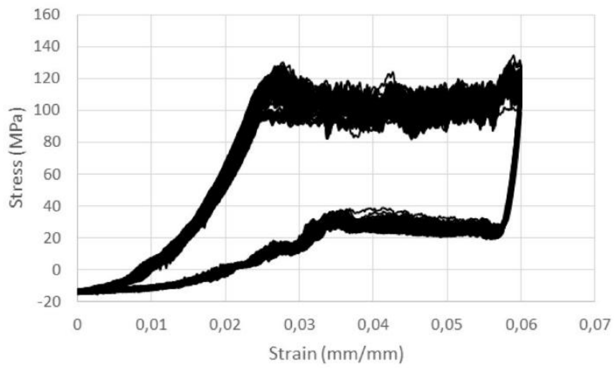

Figure 9 Typical cyclic-dynamic testing of 0.25 mm Nitinol wire bundles (6% strain).

4. Conclusions

Nitinol is one of the most commonly used SMA with a wide range of applications in several engineering disciplines. Particular interest is taken by authors regarding the applications of Nitinol in earthquake engineering. It is possible to recommend dampers that can be designed using Nitinol wires due to their recoverable deformation and hysteresis properties.

The tested Nitinol wires exhibited high tensile strength (up to 1550 MPa) and hysteretic behaviour under dynamic loading. A basic methodology for assembling and bundling the Nitinol wires was developed as a part of this study. The wire bundles showed a significant reduction in strength compared with the strength of the single wires used for the assemblage. This reduction varied between 3.5% (for 0.25 mm diameter wires) and 79% (for 1 mm diameter wires), respectively. The EDX analysis revealed that the wires considered in this study were Nickel-Titanium binary alloy wires, which were composed of 50.6% Ni and 49.4% Ti. The wires in their as-received condition had a thin layer of oxide on the surface. It is worth noting that when used in devices such as dampers, the wear of the oxide surface layer on individual Nitinol wires within wire-bundles induces fretting corrosion and hence, incurs a loss of stiffness and deterioration of the damping device. Appropriate precautions may be taken to address this potential for induced corrosion. The presence of oxygen-rich inclusion stringers suggests that the data presented is not of a bulk alloy sample; instead, they represent the wires, which gained inclusions during the drawing process. Upon completion of the cyclic-dynamic tests, the elemental composition and surface deterioration of wires were studied using a scanning electron microscope along with an EDX attachment. Finer wires (of 0.25 mm diameter) displayed more surface damage compared with wires having a diameter of 1 mm. Despite the reduction in strength compared with the single wires and the apparent surface damage incurred after cyclic-dynamic loading, all wire bundles demonstrated non-linear, hysteretic behaviour under the dynamic loading. This confirms that Nitinol wires would be suited for seismic applications, although further controlled testing and modeling should be carried out to better explain the reasons behind the reduction in strength and optimize the wire-bundle layout and the energy dissipation behaviour. The authors recognize the significance of having a consistent approach during the formation of wire bundles, and hence, further tests are recommended to understand better the effect of the geometry of wire bundles on the mechanical properties of Nitinol wire bundles.

The super-elastic and re-centering capabilities of the SMA make them particularly suitable for those applications where the energy is to be absorbed from civil engineering structures. The previous work of Vemury and Renfrey [18] established the energy dissipating capabilities of the individual, Nitinol wires of small diameter. In this case, bundled wires have been subjected to static tensile and cyclic-dynamic tensile tests to confirm their super-elastic behaviour and their response toward dynamic loading conditions.

Acknowledgments

The authors would like to thank Professor Luigi Torre, director of the Materials Science and Technology laboratory of the University of Perugia, Italy for his help with this project. They also thank Teesside University, Newcastle University and the Institution of Structural Engineers (IStructE, London, UK) for their research support.

Author Contributions

C.M.V.: Conceptualization, methodology, writing—original draft preparation, writing—review and editing, supervision. M.C.: Methodology, investigation, data curation, writing—review and editing, visualization. F.A.: Methodology, formal analysis, investigation, data curation, writing—review and editing. A.C.: Electron Microscopy, EDX, metallography, document review. D.H.: Methodology, investigation, visualization, data curation, writing—review and editing.

Funding

This research was supported with internal research funding allocated to University of Perugia and Newcastle University researchers.

Competing Interests

The authors have declared that no competing interests exist.

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