Tensile and superelastic fatigue characterization of NiTi shape memory cables

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Abstract
This paper discusses the tensile response and functional fatigue characteristics of a NiTi shape memory alloy (SMA) cable with an outer diameter of 5.5 mm. The cable composed of multiple strands arranged as one inner core and two outer layers. The results of the tensile tests revealed that the SMA cable exhibits good superelastic behavior up to 10% strain. Fatigue characteristics were investigated under strain amplitudes ranging from 3% to 7% and a minimum of 2500 loading cycles. The evolutions of maximum tensile stress, residual strains, energy dissipation, and equivalent viscous damping under a number of loading cycles were analyzed. The fracture surface of a specimen subjected to 5000 loading cycles and 7% strain was discussed. Functional fatigue test results indicated a very high superelastic fatigue life cycle for the tested NiTi SMA cable.

Keywords: shape memory alloys, superelastic, functional fatigue, residual strain, tensile

(Some figures may appear in colour only in the online journal)

1. Introduction
Shape memory alloys (SMAs) are a class of smart materials that have received increasing interest in engineering applications over the last few decades [1]. Due to their reversible phase transformations between two solid phases, SMAs can return to their original shape after undergoing large deformations. This shape recovery can be either stress-induced (superelastic effect) or heat-induced (shape memory effect) [1].

Superelastic SMAs offer various advantageous properties such as excellent self-centering ability, energy dissipation capacity, and high corrosion resistance, which can be exploited in structural engineering applications. There have been a large number of studies where SMAs were explored for vibration control of civil structures. For example, several researchers developed SMA-based damping devices in order to mitigate the seismic response of buildings [2–6]. SMAs have also been used as beam-column connectors [7, 8], bridge deck restrainers [9–11], and reinforcing elements to provide seismic resiliency [12–15]. Some other researchers have investigated the use of SMAs in reducing the vibrations in structural cables subjected to wind loading [16–20]. A detailed review on the use of SMAs in structural applications is presented in [21].

Since in these damping applications SMAs will undergo cyclic loading, it is important to study fatigue characteristics of superelastic SMAs. For SMAs, fatigue is usually classified into two categories: structural fatigue and functional fatigue [22]. Structural fatigue refers to the fracture of the SMA material under high cyclic loads, while functional fatigue is the degradation of the functional properties such as shape recovery or dissipated energy due to cyclic loading. Superelastic fatigue is a type of functional fatigue where SMA material losses its superelastic characteristics gradually.

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Several researchers have investigated the superelastic fatigue of SMA materials. Maletta et al. [23, 24] conducted both structural and functional fatigue tests on flat dog-bone shaped specimens obtained from NiTi sheets. The tests were conducted at different strain amplitudes ranging from 0.7% and 4.5%. They observed that degradation in superelastic properties becomes more evident at larger strain amplitudes. Isalgué et al. [25] conducted tensile testing on 2.46 mm diameter NiTi superelastic wires subjected to a loading strain of 8% for 100 loading cycles to assess the variation in hysteresis response. Soul et al. [26] investigated the effect of loading frequency on the superelastic fatigue of 0.50 mm and 2.46 mm diameter NiTi wires. Morin et al. [27] tested NiTi wires with a diameter of 2 mm for 50 cycles at different strain rates.

A few studies have been conducted to explore functional fatigue behavior of SMA bars. Treadway et al. [28] tested 6 mm diameter NiTi superelastic bars heat-treated at different temperatures up to 100 tensile loading cycles. Shrestha et al. [29] analyzed the functional fatigue of polycrystalline and single-crystal CuAlMn superelastic SMAs with a diameter of 5 mm. The Cu-based SMA bars were subjected to 1000 loading cycles under 6% and 7% strains. Liu et al. [30] characterized the superelastic fatigue of columnar-grained 5 mm diameter CuAlMn bars at tensile strains of 4% to 10%.

When SMA elements are used to control vibrations in civil structures, large diameter structural elements are usually needed. Due to relatively higher costs associated with manufacturing of large diameter SMA bars, a number of researchers have investigated the performance of superelastic SMA cables composed of multiple small diameter wires. Reedlun et al. [31] studied the tensile response of SMA cables with 7×7 and 1×27 configurations and outer diameters of 2.48 mm and 1.58 mm, respectively. Carboni et al. [32] conducted tensile testing on 1×7 SMA strands with an outer diameter of 1.8 mm. Ozbulut et al. [33] characterized the tensile behavior of a large size superelastic SMA cable. The cable consisted of 0.885 mm diameter individual wires laid in 7×7 configuration to have an outer diameter of 8 mm. Although these studies highlighted the advantageous characteristics of SMA cables such as good superelastic response and low cost, functional fatigue of SMA cables has yet to be investigated.

In this paper, the evolution of the functional properties of a NiTi SMA cable in terms of superelastic response was investigated. The SMA cable composed of seven 1×7 strands and six 1×19 strands arranged in a multi-layer configuration. Initially, the tensile response of the cable at different strain amplitudes was characterized. The cable was then subjected to a minimum of 2500 loading cycles at strain loadings ranging from 3% to 7%. The evolution of several parameters such as the maximum tensile stress, residual strains and energy dissipation was systematically studied. In addition, the fracture surface of a specimen cycled at 7% strain was analyzed through Scanning Electron Microscopy (SEM) images.

2. Experimental tests

2.1. Material and specimen
NiTi superelastic cable with chemical composition shown in table 1 was obtained from Fort Wayne Metals Research Products Corp. The SMA cable consisted of 163 individual wires with an overall outer diameter of 5.5 mm. The cable had a non-conventional multi-layered construction with an inner core and two outer layers. The inner core strand consisted of a central straight wire with six outer wires wrapped in a right-handed layout (i.e., 1×7 configuration). The first outer layer consisted of six strands each having a 1×7 configuration and wrapped in a right-handed layout around the core strand. The second outer layer composed of six strands with a 1×19 configuration wrapped in a left-handed layout. The core and first outer layer strands were made out of NiTi wires with a diameter of 0.279 mm, while the second outer layer strands were made out of wires with a diameter 0.300 mm. Figure 1 shows an image of cable cross-section obtained from SEM. Eight specimens were prepared for tensile and superelastic fatigue characterization of the cable. Each specimen had a total length of 127 mm with a gauge length of 76.2 mm. To alleviate the stresses in gripping regions, the outside of the cable was coated with epoxy at the ends of the specimens.

2.2. Testing procedure and setup
An MTS servo-hydraulic fatigue load frame with a capacity of 100 kN was used to carry out the experimental tests.
Strains were monitored using an MTS LX1500 laser extensometer. Figure 2 illustrates the test setup. The data sampling rate for the MTS data acquisition as well as laser extensometer was set to 50 Hz during the testing. Prior to tensile testing of the cable, a training test procedure including 20 loading cycles at 4% strain with a strain rate of \(5 \times 10^{-3} \text{s}^{-1}\) was conducted. To investigate the tensile response of the SMA cable, the specimen was subjected to target strain amplitudes of 3% to 10% for three cycles. Then, the superelastic fatigue tests were conducted at target strain amplitudes of 3%, 4%, 5%, 6%, and 7%. During fatigue tests, the number of loading and unloading cycles was at least 2500. All tests were conducted in displacement control. Note that the measured strain amplitudes are somewhat different but close to these target strain amplitudes. The tests were conducted at room temperature of \(27 \pm 1^\circ\text{C}\) and at a strain rate of \(5 \times 10^{-3} \text{s}^{-1}\), which corresponds to loading frequencies ranging from 0.036 Hz for 3% strain amplitude and 0.025 Hz for 10% strain amplitudes.

3. Experimental results

3.1. Tensile response

Results from the tensile testing of the NiTi SMA cable are shown in Figure 3. Figure 3(a) shows the stress-strain curves for three cycles for a specimen subjected to 5% strain. Since the cycles were stable, only the second cycle of the loading cycles is presented. Figure 3(b) illustrates the tensile response at different strain amplitudes. It can be observed that the stress-strain curve of the cable exhibits a high positive stress-strain slope.
over the transformation range. This indicates a non-uniform transformation initiation in the individual wires of the cable. Nominal permanent deformations for cycles at loading strains of 3% to 7% were observed. The residual strains for cycles at loading strains of 8%, 9%, and 10% were 0.20%, 0.52%, and 0.76%, respectively. A decrease at forward transformation stress level and transformation plateau was observed at 7% strain. A similar decrease in the stress levels was visible for cycles with 10% strain.

3.2. Cyclic response

3.2.1. Stress-strain curves. In this section, the hysteretic response of NiTi SMA cable subjected to cyclic loading at different strain amplitudes is presented. For fatigue testing at each strain amplitude, stress-strain curves were plotted at the 1st, 5th, 10th, 50th, and 100th cycles for the first 100 cycles. For the following cycles, the stress-strain curves of every 250th cycle were presented. Figure 4 illustrates the cyclic response of the NiTi superelastic cable subjected to 3% strain. It can be seen that both the forward and reverse transformation stress levels decreased with increasing the number of loading cycles. However, the rate of decrease in reverse transformation stresses was smaller than that of forward transformation. Therefore, the area of hysteresis loop decreased. The response was stable at higher loading cycles, especially after the first 500th cycles.

The stress-strain curves for the SMA cable subjected to 4% strain are shown in figure 5. The decrease in the transformation stresses was more pronounced in the first 50 cycles. Between the 100th cycle and 2250th cycle, there was no significant change in the hysteretic response. After the 2500th cycle, the transformation stresses were not visible and the flag-shaped response vanished. The decrease in stress levels was obvious until the 3500th cycle; after which the stress-strain curves were stable up to the 5000th cycle.

Figure 6 illustrates the hysteresis loops of NiTi superelastic cable with a strain of 5%. The results for the first 100 cycles were similar to those observed for the specimen tested at 4%. After the 100th cycle, a relatively stable behavior was observed up to the 1750th cycle as opposed to the stable behavior observed until 2250th cycle for the tests at 4% strain. After the 1750th cycle, the degradation in the hysteresis continued and the stress levels decreased until the 5000th cycle.

The stress-strain curves of superelastic NiTi cable subjected to a strain of 6% for 2500 loading cycles are presented in figure 7. It is deduced that the decrease in the forward transformation stresses was more rapid as compared to the response at lower strain amplitudes. Hysteresis loops considerably narrowed in the first 100 cycles. The stress-strain curves were stable after 250th cycle, with an almost complete stable response between the 1000th cycle and 2000th cycle. The forward transformation stress level decreased again at loading cycles of 2250 and especially at the 2500th cycle.

The evolution of the stress-strain response of the SMA cable subjected to a 7% strain is shown in figure 8 for 5000 loading-unloading cycles. For this strain amplitude, the
degradation in hysteretic response continued with the increase of the number of loading cycle without any stable response range. The flag-shaped hysteresis can be observed only up to the 1250th cycle. After the 3500th cycle, a rapid decrease in the tensile stress was observed with almost a complete loss of load carrying capacity after 4000th cycles.

3.2.2. Maximum tensile stress. The variation in maximum tensile stress of SMA cables during fatigue testing at different strain amplitudes is presented in figure 9(a) for 2500 loading cycles. As expected, the SMA cable reached higher tensile strengths with the increased strain amplitude in the initial cycles. For all strain amplitudes, the maximum tensile stress experienced a relatively high drop in the first 100 cycles. The variation in the maximum stress after the initial 100 cycles exhibited different characteristics depending on the strain amplitude. At loading strains of 3% and 4%, there was a very slow degradation in the tensile stress and almost a stable maximum tensile stress was observed up to 2500 cycles. Cycles with 5% strain also exhibited a stable tensile stress, but only up to the 1500 cycles; after which a continuous degradation in the maximum tensile stress was noted. At a loading strain of 6%, the decrease in the maximum tensile stress continued until about the first 1000 cycles and then a stable tensile stress was observed. The maximum tensile stress, observed at loading strain of 6%, dropped below the one observed at a loading strain of 5% at about cycle 300; indicating a higher degradation rate in tensile stress for 6% loading strain. When the SMA cable was cycled at 7% strain, an approximately linear degradation in tensile stress was observed after the first 100 cycles. However, at around the 1300th cycle, a small drop in tensile stress was noted, which

Figure 5. SMA cable stress-strain curves at 4% strain for 5000 loading cycles.
might be due to a rupture of a single wire. In addition, around the same loading cycle, the maximum stress became lower than that of the 5% strain loading cycles. A fitted model in the form of the following equation is developed to describe the variation in the maximum tensile stress with the number of loading cycles at each strain amplitude:

$$\sigma_{\text{Max}} = a \times N_{\text{Cycles}}^b$$  \hspace{1cm} (1)

The coefficients a and b of equation (1) are given in table 2 together with the R-square ($R^2$) and root mean squared errors (RMSE) of the models. As can be seen from figure 9(a), the fitted models can adequately predict the actual data except 5% and 7% loading amplitude, where the models exhibit an RMSE of 12.42 and 27.50 MPa, respectively.

Figure 9(b) illustrates the evolution curves of the maximum tensile stress for loading cycles between 2500 and 5000 for SMA cables cycled at loading strains of 4%, 5%, and 7%. It can be seen that all specimens experienced a continued degradation in the maximum tensile stress after the 2500th cycle. The reduction rate of tensile stress was the smallest at 4% loading strain. At the end of the 5000th cycle, the specimen tested at 4% strain reached a maximum of 125 MPa tensile stress, which is about 52% of the maximum stress observed on the first cycle. At loading strain of 5%, almost a linear decrease in the tensile strength was observed for all cycles between 2500 and 5000. The maximum tensile stress at the end of the 5000th loading cycle was 110 MPa, indicating a 69% reduction when compared to the initial tensile stress of 350 MPa. For the specimen tested at 7% strain, the rate of decrease in the tensile stress was similar to that of the specimen cycled at 6% strain for cycles between
2500 and 3650. Afterwards, a sudden and significant drop in the maximum tensile stress was detected up to 4200th cycle. This was due to the occurrence of fracture of the wires in the inner core and the first outer layer of the cable. At the end of the 4200th cycle, the wires of the outer layer of the cable were the only component that did not fracture.

### 3.2.3. Residual strain

Figure 10(a) illustrates the evolution of the residual strain for the 2500 loading and unloading cycles under loading strains of 3% to 7%. During the first 100 cycles of cyclic tension at different strain amplitudes, the maximum residual strain was in the range of 0.2% to 0.4%. At 3% loading strain, the rate of the residual strain accumulation was very slow, and the peak residual strain at cycle 2500 was 0.89%. The stable values of residual strains were also observed for cyclic tension under 4% and 5% strain amplitudes. The accumulation of residual strain started at cycle 2000 for loading strain of 4% and at cycle 1674 for loading strain of 4%. The peak residual strains were 1.16% and 1.43% for loading strains of 4% and 5%, respectively, at the end of 2500th cycle. In addition, it was observed that the residual strains for 5% strain loading was slightly lower than that of 4% strain loading during the first 1750 cycles. A gradual increase in the residual strain was observed for the specimens cycled under 6% and 7% strain amplitudes up to 2500th cycle. However, at strain loading of 7%, an abrupt increase in residual strains was observed at around 1300th cycle. This might be attributed to failure of some wires within the cable since there was also a decrease in the maximum tensile strain as shown in figure 9(a) at around these cycles. During the first 1350 cycles, a lower residual strain was present in the specimen tested at 7% strain compared to that cycled at 6%. The residual strains reached 2.63% and 3.01% at the 2500th cycle for the specimens tested at 6% and 7% strain amplitudes, respectively.

The variations in residual strains between cycles 2500 and 5000 for the specimens with loading strains of 4%, 5% and 7% are illustrated in figure 10(b). The specimens cycled under 4% and 5% strains possessed almost stable residual strains until the end of 5000th cycle with peak residual strains of 1.90% and 2.20%, respectively. The specimen subjected to cyclic loads under 7% strain showed a slow rate of increase in residual strain from 3.00% at cycle 2500 to 3.30% at cycle 3650. After cycle 3650, there was a rapid increase in the residual strain due to the failure of the inner core as well as the first outer layer. The residual strains reached 5.70% at cycle 4700 and 6.2% by the end of the 5000th cycle.

### 3.2.4. Energy dissipation

Figure 11 shows the evolution of the dissipated energy (ΔE) and the equivalent viscous damping ratio (ζ_eq) as a function of loading cycle up to 2500 cycles for different values of maximum strain. The dissipated energy is determined by computing the area between the loading and unloading paths of force-displacement curves. The equivalent
viscous damping ratio is calculated as [34]:

$$\zeta_{eq} = \frac{\Delta E_i}{4\pi E_{eq(i)}}$$  \hspace{1cm} (2)

where $\Delta E_i$ and $E_{eq(i)}$ are the dissipated energy and the maximum strain energy for the cycle $i$.

A rapid decrease in both the dissipated energy and $\zeta_{eq}$ occurred during the first 50 cycles for all loading strain amplitudes. This decrease continued after cycle 50, especially for cases with higher strain amplitudes, however, the dissipated energy and $\zeta_{eq}$ reached stable values with increasing loading cycles. At loading strains of 3%, 4%, and 5%, the stabilized values were around 42%, 48% and, 30% of the values of the first cycle for the dissipated energy and around 54%, 59%, and 51% of the values of the first cycle for the $\zeta_{eq}$. The dissipated energy reached an almost stable value between cycles 1300 and 2500 for loading strain of 6% and between cycles 600 and 1300 for loading strain of 7%, but then slightly decreased until cycle 2500. To relate the variation in the dissipated energy and equivalent viscous damping to the number of loading cycle, non-linear regression models based on the following equation:

$$y = a \times x^b + c$$  \hspace{1cm} (3)

are developed. The coefficients of the models for each loading amplitude are given in table 3. To assess the goodness-of-fit of each model, the R-square for each model is also given in the table. The fitted models for the dissipated energy and equivalent viscous damping are illustrated in figures 11(a) and (b), respectively. The largest model error is observed at 5% loading amplitude for the dissipated energy and at 7% loading amplitude for the equivalent viscous damping. However, the...
developed models follow the data almost exactly at other strain amplitudes.

To better visualize the effect of cyclic loading at various strain amplitudes on energy parameters, surface plots are illustrated in figure 12. It can be seen that for earlier stage of the loading cycles, the dissipated energy rapidly increased with the increased strain amplitude, while the $\epsilon_{eq}$ exhibited an initial increase and then approached a constant value. However, at the later stage of the loading cycles, both the dissipated energy and $\epsilon_{eq}$ attained their peak value at about 5% loading strain.

The variations in energy parameters with number of loading cycles for specimens tested under 4%, 5%, and 7% strain amplitudes for cycles between 2500 and 5000 are shown in figure 13. All specimens displayed a continuous reduction in the dissipated energy after the 2500th cycle. The rate of the reduction was the least for the loading strain of 4% and was almost the same for loading strains of 5% and 7%. A sudden decrease at around the 3650th cycle for 7% loading strain was noted due to the failure of most of the individual wires of the cable as discussed earlier. On the other hand, the $\epsilon_{eq}$ showed only a slight decrease between cycles 2500 and 3650 for 7% loading strain. This is due to a higher decrease observed in the maximum tensile stress, i.e. in the maximum elastic energy, at that loading strain amplitude. For 4% loading strain, the $\epsilon_{eq}$ gradually decreased and reached 1.4% at cycle 5000. The $\epsilon_{eq}$ initially decreased for 5% loading strain and remained stable at a value of about 1.5% between cycles 3200 and 4100, and then increased up to 2% by the end of the 5000th cycle.

3.3. SEM analysis of the fracture surfaces

The fracture surfaces of the SMA cable tested under 7% strain were characterized through SEM imaging. Figure 14(a) illustrates an SEM micrograph of the inner core and first outer layer zoomed at 30X. Figures 14(b) and (c) show the topographic and secondary images for a single wire zoomed at 255X. In figure 14(c), an indentation at the longitudinal surface, which is marked in the image as local surface stress, was observed. The main reason for this type of surface indentations is the twisting effect since each wire rubs the surfaces as the cable elongates. The images also clearly distinguish the fatigue and fracture surfaces that are characterized with different morphologies. It is noted that the fatigue region with striations of shear lines is small as compared to the fracture region characterized with a dimpled morphology as shown in figure 14(d).

Figure 14(e) illustrates a topographic imaging of another single wire zoomed at 300X. Similar to the previous images, the three regions, fatigue, ductile fracture, and local surface stress are visible. However, the fatigue region has an inclined surface; indicating that the material had a crack growth at an angled position. Moreover, the fracture region possesses a relatively flat surface. This indicates that a change in the angle of crack growth occurred at the same time as the fracture occurrence. Figures 14(f) and (g) display a secondary imaging of the wire zoomed at 700X and 5000X. The fatigue bands,
which are of an average width of 0.30 μm, are clearly identified in figure 14\textsuperscript{(g)}. Figure 14\textsuperscript{(h)} illustrates a secondary imaging of a third wire zoomed at 30X, with a size indicator for the fatigue region. Figure 14\textsuperscript{(i)} represents a zoomed image of the crack initiation region for this wire. It is noticeable that the fatigue region initiated from an inclusion.

4. Conclusion

In this paper, tensile response and functional fatigue characteristics of a superelastic NiTi cable within the stress-induced transformation region were investigated. The cable specimens were subjected to cyclic tensile loads for a
minimum of 2500 loading and unloading cycles under various loading strain amplitudes. The stress-strain curves were plotted and the evolutions of different parameters such as maximum tensile stress, residual strain, and dissipated energy with the number of loading cycle were analyzed. The findings of this study are summarized hereafter.

- The results of the tensile tests confirmed that the SMA cables exhibit superelastic behavior with no or minimal residual deformations up to 6% strain and a maximum of a 0.76% residual strain for a strain of 10%.
- A high positive stress-strain slope over forward transformation range was observed, which might be due to a non-uniform transformation initiation in the individual wires of the cable.

- Cyclic loading tests under different strain amplitudes revealed a very high functional fatigue life for the NiTi cable. The influence of the number of loading cycles on the superelastic properties of the SMA cable was more apparent for the first 100 cycles.
- The peak residual strain was only 0.8% by the end of the 2500th cycle for a loading strain of 3%, while the specimens tested under loading strain of 4% and 5% exhibited residual strains of 2% and 2.18%, respectively, by the end of the 5000th cycle.
- Under a loading strain of 6%, the stress-induced martensite transformations were still apparent by the end of the 2500th cycle, while there was about 2.6% residual strain.
- The specimen subjected to 7% strain had a complete fracture of the inner core as well as the first outer layer
above cycle 3650, but showed a flag-shaped hysteresis until loading cycle number 1250.

- In terms of energy dissipation, the cable exhibited the highest dissipated energy and equivalent viscous damping ratio under 5% loading strain when a high number of loading cycles was applied.

- SEM images taken from the cross-section of the cable failed under 7% strain fatigue loading illustrated minor local stresses due to the configuration of the cables and re-orientation of wires.

Overall, the results indicate that SMA cables possess a high superelastic fatigue capacity and can endure hundreds of cycles without significant degradation in their superelastic properties. Note that considerably lower superelastic fatigue properties were reported for similar diameter monolithic SMA bars in the literature [28–30]. Therefore, SMA cables might serve better than monolithic SMA bars in structural applications where SMAs are used as large-diameter tensile elements and subjected to cyclic loading. However, as indicated by Zhang et al [35], the fatigue life of SMAs are highly dependent to loading rate. Therefore, further research is needed to evaluate superelastic fatigue properties of SMA cables at different strain rates.

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