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# Cyclic tensile of refurbish NiTi reinforcement bar for seismic mitigation

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**Abstract.** This research highlighting the novel properties of pseudo-elastic Ni-Ti bar owing to their ability to reverse macroscopically inelastic deformation during earthquake known as recentering capability and large elastic strain capacity which originated from the reversible austenite to martensite phase transformation. Hence, this paper presented and evaluates the cyclic properties of pseudo elastic Ni-Ti shape memory alloys to assess their prospective use for seismic applications to be exploited as seismic resistant design and retrofit. In addition, the correlation of hysteretic behavior of Ni-Ti alloy in terms of cyclic loading number and history, mechanical properties at ambient temperature, equivalent damping, energy dissipation and recovery stress were evaluate. The NiTi bar with weight percentage of Ti-43.98 at. % Ni 56.02 and diameter of 8 mm. The tensile cyclic test obtained demonstrated a rounded loading curve based on a 0.2% offset. The as received bar exhibited superior pseudo-elastic behaviour and recentering through repeated cycling without significant degradation or permanent deformation but low energy dissipation due to narrow hysteresis while the steel rebar shows vice versa. Experimental results show potential for the use of SMAs in seismic applications and provide areas for continued research. It was conclude that the as-received pseudo elastic Ni-Ti bar is suitable use for seismic mitigation despite of their ability to undergo cyclical strains is 6% which is greater than 5%, with minimal residual strain, 0.15% which is less than 1%.

## 1. Introduction

Shape memory alloys is one of the promising emerge as functional metallic materials due to its unique atomic bonding which causes significant changes in mechanical properties and crystallographic forms associated with the crystallographically reversible nature of the martensitic transformation or pseudoelastic property known as shape memory effect (SME) or pseudo-elasticity (PE) [1]. The superelasticity refers to the phenomenon that SMAs can undergo a large amount of inelastic deformations and recovers their shapes after unloading [1-2]. The discoveries of pseudo elastic alloy present new challenges and opportunities for structural engineers which is growing significantly, with wide range of applications, particularly in civil engineering application.

Pseudo-elastic SMA has exhibited energy dissipation capabilities, large elastic strain capacity, hysteretic damping, excellent high or low-cycle fatigue resistance, re-centering capabilities and excellent corrosion resistance [1] which promising a great impending for seismic resistant design and retrofit applications. For civil engineering applications, pseudo-elastic Ni-Ti alloy possess superior mechanical properties in term of Young's modulus, yield strength, ultimate tensile strength, elongation at failure, recovery strain and recovery stress at austenite and martensite phase [2] and the most suited



for use in the design of building, bridge structures and use as energy dissipating damper element subjected to earthquake loading conditions [3] and [4].

In order to evaluate the pseudo elastic SMA for structural application, many researchers tested mechanical behaviours of SMA wires in tension. The test results exhibit a promising of SMA for application in civil engineering due to their ability to spontaneously recover strain of up to 8%. It is found that temperature, strain amplitude, loading rate and cyclic loading had influence on the mechanical behaviours of SMA [5]. Mechanical behaviour of Shape Memory Alloys for seismic applications for Martensite and Austenite Ni-Ti bars subjected to torsion and Austenite Ni-Ti wires subjected to tension were experimentally evaluated by [2] and [6] respectively. Moro dolce (2001) demonstrate that superelastic wire is suitable for seismic application despite of their recentring and energy dissipation. The diameter is 1.84 mm of austenitic wire by taking into account their sensitivity to temperature and strain rate with alloy composition of (Ni-Ti-[Nb] about 50 at% Ni). Experimental work by [7] revealed that Ni-Ti wires have better energy dissipation characteristics than bars. Furthermore McCormick et al [8] discovered that the equivalent viscous and recentering capability decreases with increasing of bar size. [7], [9] and [10] distinguished the properties of pseudo elastic Ni-Ti bar and wire subjected to cyclic loading to assess their potential for applications in seismic resistant design and retrofit. It demonstrates that recentering properties can be negligible due to nearly ideal pseudo elastic obtained for bars and wire. However, the strength and damping properties of wire is higher than bar but equivalent damping decreases when loading rates increased. [11] describes experiments on the radial compression of super elastic wires and tubes between flat loading surfaces.

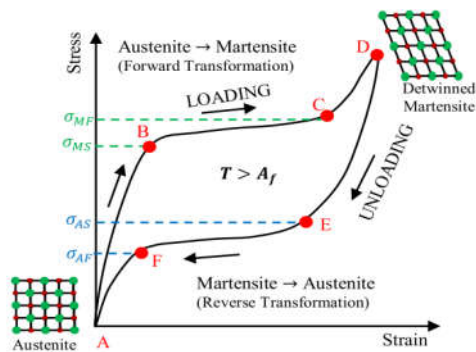
The shape memory effect and super-elasticity phenomena of the Ni-Ti alloy are influenced by the alloy's chemical composition, the annealing temperature and the history of its mechanical deformation [12]. Tyber et al [10] confirmed that heat treatment influence the transformation temperatures and hardness but not bar diameter. Futhermore, the pseudo-elastic alloy can be heat treated to produce super elastic response at room temperature [13] but, extreme temperature conditions can completely eliminate the shape memory or pseudo-elastic effects within a specimen [1]. Effect of annealing on the transformation behavior and superelasticity of Ni-Ti shape memory alloy were studied by [14] for 1mm superelastic wire. Nevertheless, little research has been conducted for heat treated of pseudo-elastic wire lesser than 1 mm.

Furthermore, no attention from the previous research is devoted to explicitly investigate of NiTi bar phase transformation changes on the number of cycles, recovery stress, residual strain, energy dissipation and energy viscous damping in comparison with mild steel rebar. Therefore, this study emphasized on the mechanical behavior of Ni-Ti alloy (Af -6.3) and steel with diameter of 12mm respectively in terms of fatigue resistant in cyclic loading, mechanical properties at ambient temperature, and the number of cycle, loading history, equivalent damping, energy dissipation and stress recovery were investigated experimentally. An attempt is made to correlate findings obtained from the NiTi and steel bar results from the tensile and tensile cyclic test at room temperature.

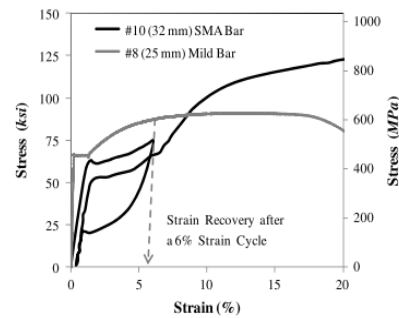
## 2. Stress-strain curve of pseudo elastic Shape Memory Alloy

The material behaviour of SMA effect can be characterised base on the stress strain temperature diagram [3]. The metallurgical basis of any of these effects is the reversible phase transformation from the high temperature phase, austenite into low temperature phase martensite. In the absence of heating or cooling, the SMA is at ambient temperature. Below  $M_f$ , the material is fully martensitic. The material is showing pseudoplastic deformation behaviour and is able to undergo large pseudoplastic deformation of up to 8% [4]. Between  $A_f$  and  $M_d$  the material is in the austenite phase where pseudoelastic (superelastic) occurs. The yield stress of the austenite state in SMA is higher than in martensite state [5]. Figure 1 shows the properties of stress-strain properties of austenitic and martensitic shape memory alloys. Both plots depict one cycle from zero load to a specific strain and back to zero load. These phase transformations refer to spontaneous shifts between martensitic and austenitic crystal forms. Conceptual pseudoelastic stress-strain curve depicting those properties important for structural applications.

Pseudo-elastic also called as super elasticity, which occurs when the load applied, is sufficient to change the austenite phase transformation into martensite phase whereby it happens when the alloy is above the martensite temperature.



**Figure 1.** Schematic stress–strain curve of superelastic Shape Memory Alloy showing the phenomena associated with the deformation process.



**Figure 2.** Schematic stress–strain curve the of Superelastic SMA and mild steel rebar.

Phenomena associated with the deformation process are shown Figure 1 and Figure 2. Figure 2 points out the key properties, which are important for the introduction of NiTi into structural applications: forward transformation stress,  $\sigma_{MF}$  reverse transformation stress,  $\sigma_{AF}$ ; initial elastic modulus,  $E_i$ ; residual strain,  $\epsilon_R$ ; and the equivalent viscous damping,  $\zeta_{eq}$ . The forward transformation stress refers to the stress at which the martensitic phase transformation initiates. The characteristics of a shape memory alloy can be denoted as  $A_s$  = austenite start,  $A_f$  = Austenite finish,  $M_s$  = Martensite start and  $M_f$  = Martensite finish. While Figure 2 shows the schematic stress-strain curve of the superelastic Shape Memory Alloy in comparison with mild steel rebar.

### 3. Experimental procedures

This study involved two set of austenitic NiTi bars of 12mm diameter provided by a commercial supplier with a Ni-rich composition of Ti-43.98 at. %Ni 56.02 as tabulated in the table 1 to prevent any influence from composition differences.

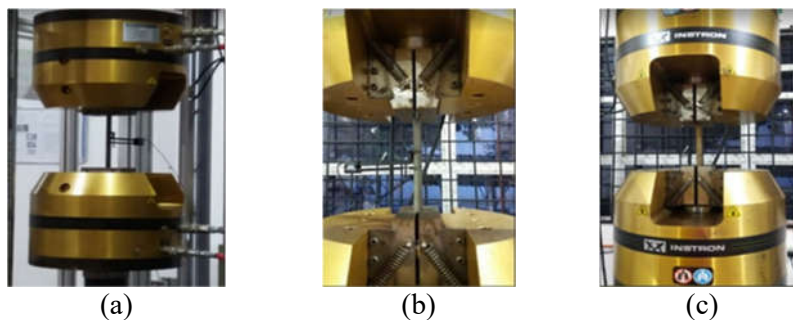
**Table 1.** Nominal composition ratio (wt%) for NiTi bar.

Element	Nickel	Titanium	Oxygen	Carbon
Nominal composition ratio (wt%)	56.02%	43.98%	0.045	0.041

The preparation of the specimens complies with the ASTM F2004-05 standard and were reshaped as shown in the Figure 2. Tensile cyclic test were performed using Instron Universal Testing apparatus model 600DX equipped with a data acquisition system as depicted in Figure 3. The SMA bar were 200 mm long and the gage length was 50 mm for each specimen respectively. The bars were grip with flat wedges fixtures as demonstrated in Figure 4(a) and Figure 5(a). Extensometer used was 50mm. The above mentioned loading protocol was input using Blue hill 3 software which use strain output to control the movement of the actuator. The specimens were loaded and unloaded with the loading rate of 0.025 mm/min and in compliance to ASTM F2516-07 (Standard Test Method for Tension Testing of Nickel-Titanium Super elastic Materials 2007). The data were automatically stores in the computer for every 1 second interval. The data were then extracted and analyzed.



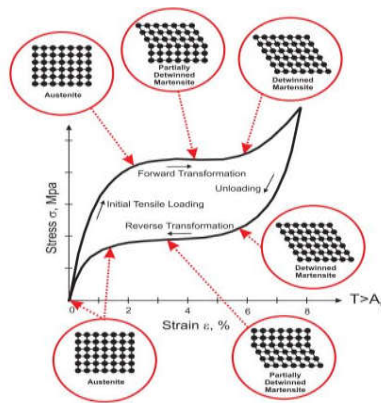
**Figure 3.** Schematics Showing of a Hydraulic Testing Machine for Instron Testing apparatus model 600 DX used for experiment.



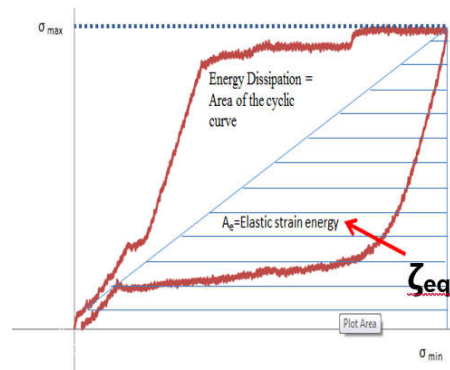
**Figure 4.** (a) NiTi 8 mm, (b) NiTi 12 mm, (c) NiTi 12.7 mm

#### 4. Results and discussion

- (1) Equivalent viscous damping for half cycle,  $\zeta_{eq} = \frac{1}{\pi} \chi \left( \frac{A_{half\ cycle}}{\sigma_{max} \times \varepsilon_{max}} \right)$  where  $A_{half\ cycle}$  stands for the energy dissipated within a half cycle,  $\sigma_m$  and  $\varepsilon_m$  are respectively the maximum of the stress and strain. Figure 7 shows the computation of the equivalent viscous damping ratio for half cycle.



**Figure 5.** Typical stress-strain curve for an SMA undergoing the superelastic effect.



**Figure 6.** Computation of the equivalent viscous damping ratio for half cycle.

(2) Residual strain,  $\epsilon_R$

It can be define as the recovery capacity as the maximum recoverable strain measurement for the material to return to its original undeformed shape upon unloading.

(3) The secant stiffness ,  $E = \frac{\sigma_{max} - \sigma_{min}}{\epsilon_{max} - \epsilon_{min}}$

(4) The secant stiffness ,  $E = \frac{\sigma_{max} - \sigma_{min}}{\epsilon_{max} - \epsilon_{min}}$

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.

4.1 Mechanical properties of the refurbish NiTi alloy

**Table 2.** Tension and compression stress-strain response of the refurbish or reused NiTi in comparison with mild steel.

Refurbish NiTi	Reused NiTi

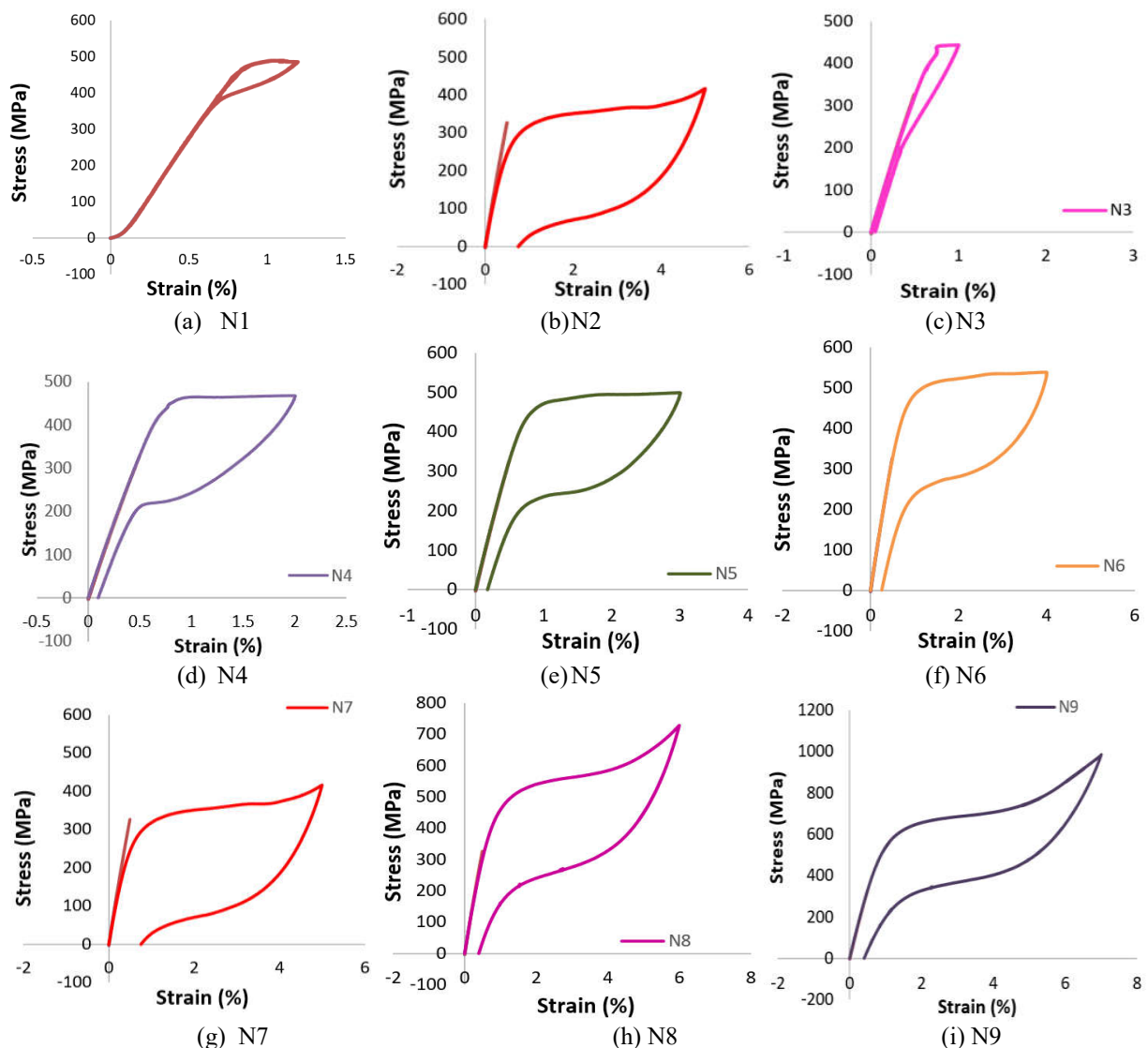


Figure 7. Stress-strain diagram.

The stress–strain responses of the as-received steel and NiTi bar were illustrated in Figure 6(a) and Figure 6(b) and demonstrated that a rounded loading curve with 13 numbers of cycle for as-received and heat treatment wire respectively. The yield point was offset base on 0.2 % forward transformation stress. As a result, the wire is obtained suitable for seismic application despite of the number of cycle is within the range 5-15 N (Debroches 2013). From the curves, it is clear at glance that the stress-strain behaviour of pseudo elastic property for nickel-titanium is temperature dependant. It was observed for all the loading cycles in figure 6(a) that the specimen exhibit superior super elastic with narrow hysteresis and able to recover from plastic deformation. The residual strain for as-received wire during the final loading on stress induced martensitic finish is 8.5%, while residual strain ( $\epsilon_R$ ) was 0.15% corresponding with 98.24% strain recovery capacity.

In comparison, it could be found that the reverse transformation occurs at the higher loading rates but lower stress level at the higher loading rates. As a result, the hysteresis loop for the heat-treated wire is increasing. The stress–strain curve plateau and the ultimate strain increased significantly for heat-

treated sample mainly due to the secondary phases affected by the growth of  $\text{Ni}_4\text{Ti}_3$  and  $\text{Ti}_2\text{Ni}$  precipitates as shown in Figure 5. The permanent strain for the heat-treated sample was approximately 13% corresponding with 98.97% strain recovery.

Figure 8 shows the mechanical quantities of SMA wires as a function of a cyclic number to portray residual strain, energy dissipation, energy viscous damping and elastic modulus or secant stiffness. As seen from the figures, with the increasing of cyclic number, the energy dissipation increasing for both specimens and residual strain for as-received wire, but the residual strain for the heated-treated wire displays a steep decrease until 3% of strain cycle and subsequently for the next 2% cyclic strain it tends to return to its original residual strain before gradually decreasing until the end of cyclic strain. The maximum equivalent viscous damping occurred at around 2% before it start to decreases with the increasing of 2-3 % strain cycles. The secant stiffness of the specimens significantly decreases from 1% to 3% strain before gradually increase from 3-5% and slightly decrease afterwards showing that the degradation of the NiTi wires for both specimens due to fatigue.

## 5. Conclusions

The following conclusion are drawn based on the results from the experimental presented in this study : This study evaluates the cyclic properties of pseudo elastic Ni–Ti shape memory alloys wire to distinguish the effect of heat-treatment wire in terms of cyclic loading number, mechanical properties at ambient temperature, loading history, equivalent damping, energy dissipation, recentering capability and strain recovery were investigated experimentally to assess their potential in view of application for seismic applications. The following conclusion are drawn based on the results from the experimental presented in this study:

1. The tensile cyclic test obtained demonstrated a rounded loading curve based on a 0.2% offset. The as-received NiTi bar exhibited superior pseudo-elastic behaviour with narrow hysteresis through repeated cycling without significant degradation or permanent deformation and in a good agreement with their recentering capability but, decreasing in energy dissipation.
2. The mechanical response of particularly corresponding with the values of stress plateau of NiTi bar increased with the increasing of loading rate. This is due to the formation of martensitic phase upon loading. As a consequence, forward and reverse phase transformations are effected differently as the function of loading, which contribute to wider hysteresis loops and subsequently higher energy dissipation but reduction in recentering capability.
3. The as-received pseudo-elastic Ni-Ti bar is suitable for the earthquake engineering despite of their ability to undergo cyclical strains is 6%, with minimal residual strain, 0.15% which is less than 1%. Therefore, it can significant to be utilising as bracing elements in buildings, and as restraining elements in bridges. However, despite of corresponding values of equivalent viscous damping are too low for pseudo elastic austenitic SMA wire, the heat-treated wire in the martensitic form could be initiatively added because of their wider hysteresis loops can contribute to higher energy viscous damping. Therefore the performance of SMA pseudo elastic wires can be optimize using a hybrid of both austenitic and martensitic form to obtained the recentering and high damping.

## Notation

The following symbols are used in this paper:

$A_f$  = austenite finish temperature

$E_i$  = initial modulus of elasticity

$M_s$  = martensite start temperature

$\zeta_{eq}$  = equivalent viscous damping ratio residual strain

$\sigma_{UL}$  = Unloading plateau stress.

$A_s$  = austenite start temperature

$M_d$  = maximum temperature at which martensite occurs

$\varepsilon_R$  = residual strain

$\sigma_L$  = loading plateau stress



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