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Research paper

Correlation of Pseudoelastic NiTi Egineering and True Stress-Strain Curves on the Effects of Nickel Titanium Composition

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Abstract

This research highlights 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 presents 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 evaluated. The NiTi bar used is with weight percentage of Ti-43.98 at. % Ni 56.02 and diameter of 12 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 showed vice versa. Experimental results show potential for the use of SMAs in seismic applications and provide areas for continued research. It was concluded that the as-received pseudo elastic Ni-Ti bar is suitable for use in seismic mitigation despite of their ability to undergo cyclical strains at 6 % which is greater than 5 %, with minimal residual strain of 0.15% which is less than 1%.

Keywords: *Shape memory alloy; Nickel Titanium ratio; Pseudoelastic; Phase Transformation; Engineering and True Stress-strain Relationship*

1. Introduction

Shape Memory Alloy (SMA) is a relatively new class of functional material, exhibiting special thermomechanical behaviours, such as shape memory effect and super elasticity, is developed based on the demands of smart material systems that play an important role in structural application which provides the material that can act as control element or structural member. Different types of SMA are available in the market previously and have been used in the aerospace industry, medical equipment and structural control. Nickel-Titanium (Ni-Ti) is one of the most commonly used type because of its relatively functional properties compared to other smart materials.

However, the development of new material must guarantee that the material possesses enough strength and rigidity to withstand the loads it will experience in its service life whenever it is being used in engineering structure [1]. Hence, a number of experimental techniques have been developed by engineers for mechanical testing of engineering materials subjected to tension, compression, bending or torsion loading.

The mechanical behaviour of cyclic properties of NiTi shape memory alloys for large coupon of 12.7, 19.1, and 31.8 mm bars were studied by [2] to investigate their potential for seismic application.

While the testing(test) on the torsion were conducted by [3]. The influence of different heat treatments on the engineering stress – strain curve was investigated by [4]. The SMA specimens were different in shape (wires and bars with different diameter), have different physical characteristics (alloy composition, thermomechanical treatment and material phase) and subjected to different stress modes (tension, torsion, bending and shear). The cyclic properties of Super elastic Shape Memory Alloy Wires and Bars were investigated by [5].

2. Significance of Research

The fundamental properties of engineering materials along with development of new materials and also quality control of materials for application in design and construction cannot be neglected where the tensile method is the accepted method commonly practiced in order to evaluate the material properties in elastic design.[6]

However, research on the engineering of true stress and true strain for NiTi is limited. Faridmehr et al., in 2014 conducted research on the true stress and true strain of low carbon steel with diameter 6 mm, 8 mm and 10 mm [1] . The aim of this paper is to investigate the engineering and true stress-strain relationships of nine specimens in conformance with ASTM F2516-07 and the (Standard Test Method for Tension Testing of Nickel-Titanium Super elastic Materials 2007) and Standard Test Methods for Tension Testing of Metallic Materials. In this research, the true stress and strain of mild steel rebar and Ni-Ti are compared to determine the mechanical properties in terms of maximum tensile stress and strain, ultimate tensile strength, modulus of young, yield strength, percentage of elongation and percentage of reduction once the specimens were subjected to uniaxial tensile loading.

In addition, NiTi are complex materials and their material behavior depends on a number of parameters. Depending upon the

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alloying elements, SMAs exhibit different behavior in different conditions and are highly sensitive to variation in temperature, phase transformation loading pattern, strain rate and pre-strain conditions. The material behaves differently under different crystallographic changes through shape memory effect or pseudo elastic property. This aspect is important because of one of the barriers for the implementation of SMA for construction and seismic resistance design is because SMAs are extremely sensitive to compositional changes where small changes of the components of SMAs can significantly change the mechanical properties of the material. Therefore, a detailed discussion on the effects of Nickel Titanium composition on the correlation of pseudo-elastic Ni-Ti engineering and true stress-strain curves of SMAs mechanical properties are described.

Previous studies focussed on the cyclical properties, strain rate effects and temperature effects [5]. The research on the true-stress strain, mechanical properties of SMAs, as well as how they vary despite of different Ni-Ti composition ratio and the Austenite temperature is still lacking, and needs to be understood before the potential and effectiveness of SMAs as hybrid steel rebar for seismic mitigation applications can be evaluated.

nomenclature

σ_E	engineering stress	σ_y	yield stress
σ_{TS}	ultimate tensile strength	σ_{TS}	ultimate tensile strength
P	external axial tensile load	σ_T	true stress
ε_E	engineering strain	ε_T	true strain
L_o	original length of the specimen	L_f	final length of the specimen.
A_o	original cross-sectional area of the specimen		
A_f	cross-sectional area of specimen at fracture		

3. Stress-strain relationship

3.1. Definition of yield point and ultimate strength

The Stress-Strain curve relationship under Uniaxial Tensile Loading is shown in Fig 1 and Fig 2 below. Fig 1. shows the stress-strain relationship under Uniaxial Tensile Loading while Fig 2. shows conventional and true stress-strain diagrams for ductile materials.

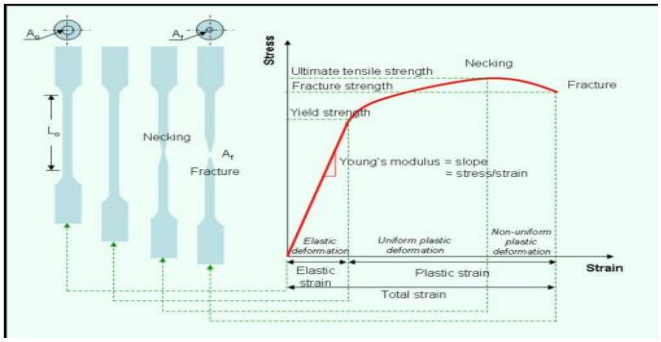
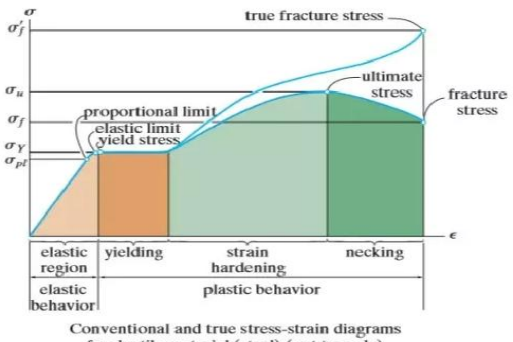


Fig 1: Stress-strain relationship under Uniaxial Tensile Loading



Conventional and true stress-strain diagrams

Fig 2: Conventional and true stress-strain diagrams for ductile material

4. True Stress and True Strain

4.1. Definition of true stress and true strain

Engineering stress and engineering strain (ε), is employed from the original (gauge) dimensions of specimen. Engineering stress (σ) also known as nominal stress is the applied load divided by the original cross-sectional area of a material while engineering strain (ε) is the amount that a material deforms per unit length in a tensile test. True stress (σ_T) is the stress determined by the instantaneous load acting on the instantaneous cross-sectional area where it is the rate of instantaneous increase in the instantaneous gauge length.

True stress (σ') and true strain (ε') are used for accurate definition of plastic behaviour of ductile materials by considering the actual (instantaneous) dimensions. When a structural element is elongated or compressed, its cross-sectional area changes by an amount that depends on the Poisson's ratio of the material. In engineering applications, structural members experience small deformations and the reduction in cross-sectional area is very small and can be neglected where the cross-sectional area is assumed constant during deformation.

The true stress and strain measurement methods were anticipated because of the stress determined using the above definition (as the ratio of the applied load to the undeformed cross-sectional area) seems to be an inaccurate measure for some cases [6]. Fig. 3 and 4 shows the engineering stress vs. true stress measure and curve. At small deformations, the true stress and strain are indistinguishable from the engineering stress and strain. It is noteworthy that in practice, true stress could be much larger than the engineering stress once the strain increases and consequently, the cross sectional of the specimen decreases.

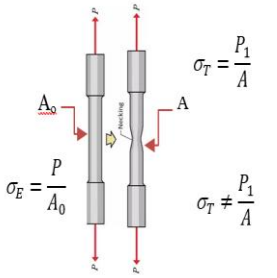


Fig 3: Engineering Stress vs. Strain True Stress Measure

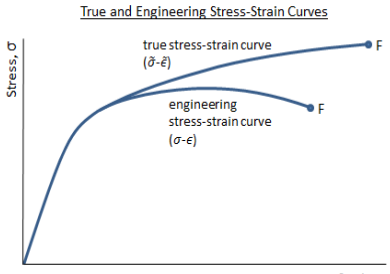


Fig 4. Engineering vs True Stress-Curve

Engineering stress and strain are normally used as fixed reference quantities which distinguishes them by their original cross-sectional area or original length. Such definitions are accurate in most engineering applications due to fixed values of the cross-sectional area and length of the specimen while the loads are applied. However, in other circumstances such as the tensile test, a substantial change in the cross-sectional area and the length of the specimen is expected. True stress and strain for mild steel rebar is significant where stress is calculated by assuming the current cross-sectional area instead of the initial cross-sectional area. The super elastic NiTi is a ductile material that can remember their original length. Hence, the change of cross-sectional area for NiTi seems insignificant due to notch that is not noticed before failure.

5. Experimental Method

5.1 Material

In order to observe the effects of the small variation of NiTi composition on the properties of the material, different compositions of NiTi alloys were systematically compared and studied. Nickel-titanium alloys bar obtained from the manufacturer were classified into two categories that exhibit pseudoelastic alloy and high pseudoelastic NiTi alloys. Pseudoelastic NiTi alloys have a NiTi ratio that are super elastic at room temperature when they are cold drawn and tempered while High Strength Superelastic Nickel alloys have higher NiTi ratio that are super elastic at room temperature with higher super elastic plateau stresses. The bars were treated to some heat treatment process in order to improve the homogeneity level of the microstructure and to alter the shape memory characteristics and the heat treatment process was conducted by the manufacturer to produce super elastic response at room temperature.

The 200 mm long of 12mm diameter mild steel rebar and 7 seven Ni-Ti specimens with different diameter; 8mm, 12mm and 12.7mm and different Austenite Finish (A_f) were pulled until fracture at an elongation rate of 0.25050 mm/min as shown in Fig. 5. Direct tensile test was conducted using the Universal Testing Machine Instron 600DX equipped with a data acquisition system in Strength of Material Laboratory, Department of Mechanical in UTM (Universiti Teknologi Malaysia) as depicted in Fig. 5. Also, the view of the specimen preparation of NiTi bar before and after failure are illustrated in Fig 5a, Fig 5b and Fig 5c for Ni-Ti rebar and Fig 5d and Fig 5e for steel rebar. The testing was done in compliance with the ASTM F2516-07, Standard Test Method for Tension Testing of Nickel-Titanium Super elastic Materials 2007 and Standard Test Methods for Tension Testing of Metallic Materials. Strains were measured with a 25 mm gauge length extensometer and the load was being measured with the internal load cell of the actuator. Bluehill 3 software was used to load protocol, which used strain output from the extensometer to control the movement of the actuator.

Tensile test was conducted through application of longitudinal or axial load at a specific extension rate to a standard tensile specimen with known dimensions, including the gauge length and cross sectional area perpendicular to the load direction, until failure. In order to calculate the stress and strain, the applied tensile load and extension were automatically recorded in the computer for every 1 second interval during the test. The data was then extracted and analyzed.

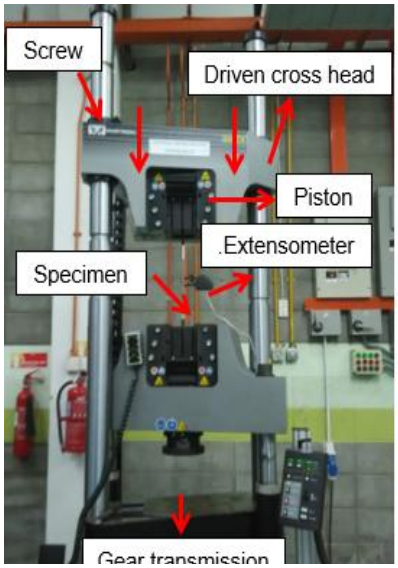


Fig. 5: Universal Testing Machine Instron 600DX used for experiment



Fig. 5(a) **Fig. 5(b)** **Fig. 5(c)**

Specimen preparation NiTi bar before and after failure.



Fig 5(d) **Fig 5(e)**

Steel bar (12mm) coupon before and after failure

6. Result and Discussion

6.1. Mechanical Properties

The ultimate tensile strength (UTS), yield strength or yield point (σ_y), elastic modulus (E) and percentage of elongation ($\Delta L\%$) that were attained during the tension test for all the 9 specimens are tabulated in Table 1 below.

From Table 1, the results of the Ni-Ti with 8 mm diameter bar are significantly influenced by the different Ni-Ti ratio and the Austenite Finish (A_f) temperature. Result shows that even 1 degree of difference in NiTi ratio can contribute to the different properties of shape memory alloy.

Desroches 2004, conducted experimental work on cyclic properties of super elastic shape memory alloy wires and bars where the wire form of the SMAs show higher strength and damping properties compared to the bars. The ultimate tensile load, elastic modulus (E) and percentage of elongation ($\Delta L\%$) attained for 8 mm diameter of Ni-Ti A_f (-6.3) mm is higher as compared to 12 mm diameter of Ni-Ti A_f (-6.3) as shown in Table 1.

According to Desroches, [7], the super elastic properties of shape memory alloys may be ideally suited for applications in seismic resistant design for NiTi in Austenite if the modulus of elasticity is in the range of 30–83 GPa to exhibit super elastic property. While for Martensitic with elastic modulus of 21–41 GPa is suitable for retrofit of structure and exhibit high energy dissipation. Hence, the results of modulus of elasticity obtained in Table 1 shows that all the NiTi used for the experiment has elastic modulus values in between 36-73 GPa showing that all of the specimens have super elastic property that is suitable for seismic resistance design.

The standard deviation of both specimens for Ni-Ti composition is 0.144 and 0.135 which implies that the difference in Ni-Ti composition is insignificant for each specimen. However, the difference in Ni-Ti composition ratio, insignificantly influenced the properties of SMAs such as ultimate tensile load, elastic modulus (E) and percentage of elongation ($\Delta L\%$).

6.2. Tensile Response Results

The engineering and true stress-strain curves of the nine specimens tested for a columned specimen of a mild steel rebar with diameter of 12 mm and the 8 Ni-Ti specimens with different super-elastic alloy phase temperature in Austenite Finish (A_f) are shown in Table 2 and Fig. 6a-j. In this paper, the true and engineering stress-strain relationships between the Ni-Ti specimens and steel rebar were

Table 1: Tensile response result for NiTi with different NiTi composition ratio and diameter of the bars

Specimen	*ϕ (mm)*	*σ_E at maximum load (MPa)*	*ε_E at maximum load (MPa)*	*$(\sigma_E - \sigma_T)/\sigma_T$ (%)*	*σ_T at maximum load (MPa)*	*ε_T at maximum (MPa)*	*$(\varepsilon_E - \varepsilon_T)/\sigma_T$ (%)*	*σ_y (Offset 0.2%)*	*εy (Offset 0.2%)*
Sma-8	8	823.689	7.443	0.76	830.00	7.500	0.76	359.174	1.175
Sma-22	8	1129.184	12.038	10.745	1265.117	11.367	5.574	374.157	0.779
Steel-12	12	559.453	5.625	5.177	590	5.600	0.44	496.843	0.437
Sma-6.3	12	1010.824	10.471	9.478	1116.665	9.958	4.899	457.052	0.866
Sma-6.3	8	1088.339	20.804	17.224	1314.760	18.900	9.152	481.654	0.875
Sma-19	8	771.905	9.414	8.604	844.575	8.997	4.430	666.257	1.109
Sma-9.3	8	601.642	10.183	9.242	662.909	9.698	4.76	426.459	0.806
Sma-25	1	716.019	7.217	6.731	767.696	6.969	3.436	404.219	0.015

Table 2: Engineering and true stress strain result

Samples Temperature (^{0}C)	ϕ (mm)	Length (mm)	Gauge length (mm)	Ni-Ti composition (wt. %)		Modulus Young	Maximum Load	Extension (maximum Load)	Elongation (ΔL%)
				Ni	Ti	(E-GPa)	(MPa)		%
Af -8	8	200	25	56.02	43.98	36.205	41403	10.922	20
Af -22	8			56.17	43.83	64.673	56758	16.573	19
Af -6.3	12			56.02	43.98	68.069	50809	11.481	19
Af -6.3	8			56.02	43.98	71.244	54705	35.020	19
Af -19	8			56.13	43.87	73.984	38800	17.068	20
Af - 9.3	8			55.85	44.15	71.411	17011	7.315	18
Af - 25	12.7			55.80	44.20	44.585	54705	35.991	12.5
σ				0.144	0.135				
Varians				0.021	0.018				
Mean				56.028	44.00				

compared and highlighted with the elastic design properties of machines and structures.

The results demonstrate that the stress-strain curve for tensile stress is completely different to the change in Ni-Ti composition ratio with respect to different Austenite Finish temperature when subjected to static tensile. This can be attributed to the different properties of NiTi including the modulus of elasticity; true yield strength vs strain at 0.2 % offset; yield plateau rigidity; true ultimate strength vs strain; engineering stress-strain at yield and ultimate loads.

All the steel rebar and Ni-Ti specimen behave according to Hookes's Law. Ni-Ti behaves differently, depending on Ni-Ti composition, the Austenite Finish (A_f) and the modulus young, thus, contributing to different Ni-Ti stress-strain curve configuration for each specimen of Ni-Ti. The results of tensile stress and tensile strain at yield value for other specimens are sumarized in Table 2.

As stated by Abdulridha (2013), yielding of the SMA bar was identified as the initiation of the forward transformation phase [8]. Most of the graph show a linear configuration in this "elastic" region until its yield point where the linearity ends except for Ni-Ti A_f (-8) diameter 8 mm. In this case, the yield point along this curve is not easily defined because the Ni-Ti bar demonstrated a rounded loading curve and, thus, did not exhibit a well-defined yield plateau. Thus, according to Y. Zhao et. al (2005), the offset yield point is arbitrarily defined and determined through drawing a parallel line to the elastic portion of the curve, using the value that is commonly set at 0.2 % plastic strain [9].

The yield point was determined using the proof stress method as shown in Fig 7(a). Therefore, the yield point was based on a 0.2 % offset, resulting in the lowest yield stress of 359.174 MPa but the lowest yield stress obtained at 1.175 %. The highest yield stress value attained is 666.257 MPa with 1.109 % strain. For other Ni-Ti, most of the tensile stress at yield obtained is within the range of 404.219 MPa to 481.654 MPa approximately with less than 1 % of strain for Ni-Ti A_f (-6.3), A_f (-9.3) and A_f (-25).

Meanwhile, the tensile stress at yield for A_f (-22) is 374.157 MPa and 0.779 % of strain.

In comparison, the engineering stress-strain tested under monotonic loading at yield for superelastic Ni-Ti A_f (-8) diameter 8 mm rebar is 359.174 MPa. This is lower when compared to mild steel rebar where yielding is at 496.843 MPa as a result of low modulus of elasticity of Ni-Ti as compared to steel. According to the stress-strain curves obtained from the tests in this study, it is evident that the mild steel in Fig.7(i) have a definite yield point.

However, the engineering strain at yield for Ni-Ti as compared to steel is vice-versa. The engineering stress-strain at maximum load obtained for NiTi is higher after the elastic region at 823.689 MPa with 7.443% of strain as compared to steel rebar where the maximum point of stress is 559.453 MPa at 5.625 MPa. This is due to super elastic behaviour of the SMAs that can restore their original shape when the load is applied and their fatigue resistance behaviour. However, the true stress attained is 6.476 % higher as compared to engineering Ni-Ti obtained with 2.593 % difference in strain. While there is 5.177 % of difference for true stress obtained for steel rebar with only negligible difference of 0.044 % for true strain.

According to Faridmehr et al (2014), the strains within the slope of the loading line in the elastic region are totally recoverable and the specimen will return to its original dimensions when the load is relaxed to zero and the gross plastic deformation, which is permanent, will occur on the specimen eventhough the load is returned to zero afterwards, once the load value exceeds the corresponding yield point [1]. This behaviour can be observed for the steel rebar and also other Ni-Ti specimens.

However, for Ni-Ti in Austenite Finish of -22, -6.3 and -25 the phase transformation changes towarsd the second phase, called dwitwinned phase.

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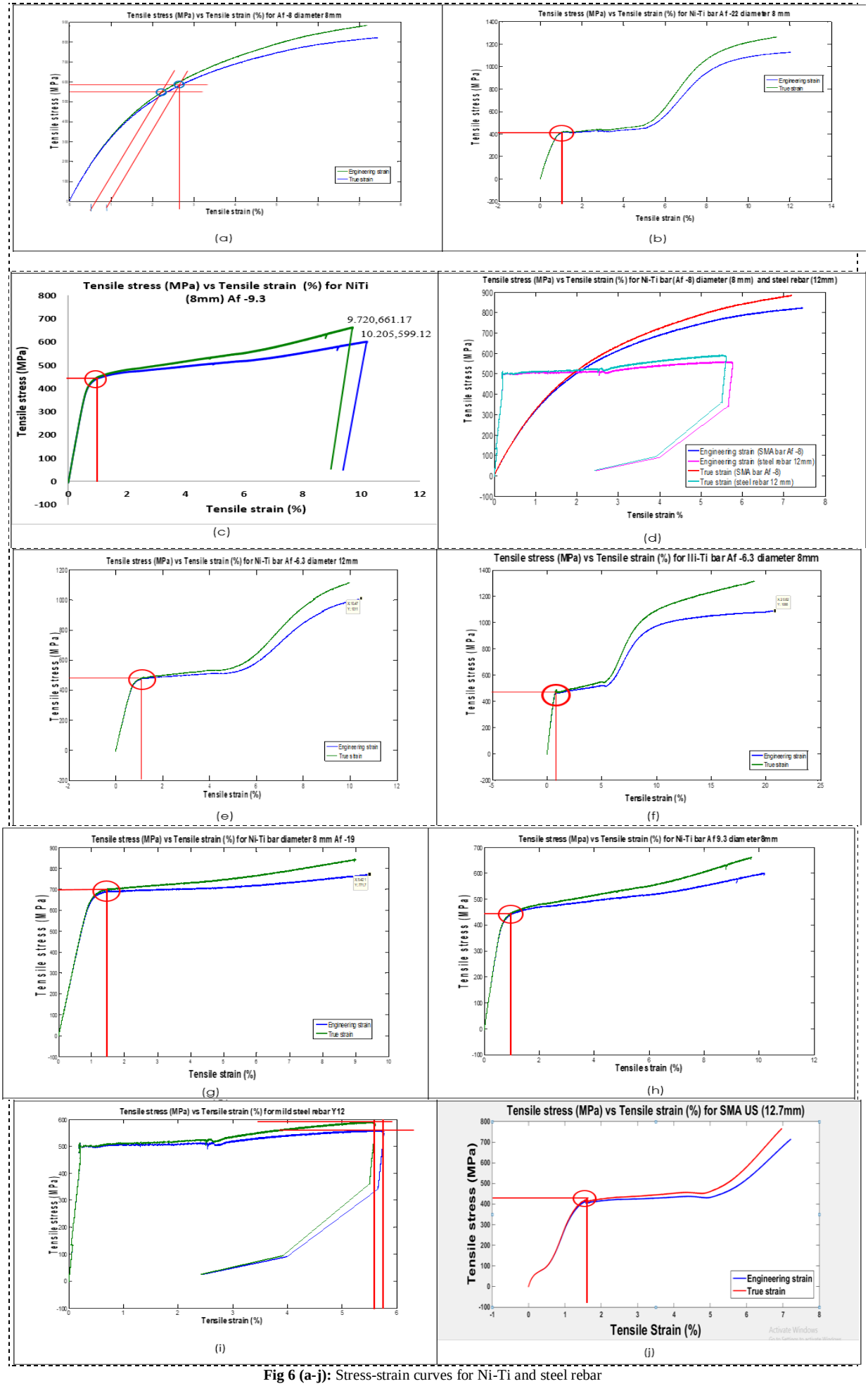

Fig 6 (a-j): Stress-strain curves for Ni-Ti and steel rebar

Afterwards strain hardening was observed and the results showed that the stiffness of the specimens slightly varies at this stage, with specimen Ni-Ti Af (-6.3) diameter 8 mm showed highest stiffness because of the highest result obtained for true ultimate stress at 1314.76 MPa and this is 17.221 % higher than the engineering ultimate stress value; but higher at engineering ultimate strain value until 20.804 % strain with 9.152 % difference with the true ultimate strain value.

In comparison, there were no significant effects when the Ni-Ti of SMA A_f (-6.3) with diameter of 12 mm were compared with the same diameter of steel rebar. The yield stress for Ni-Ti A_f (-6.3) is 457.052 MPa, while the steel rebar is 496.843 MPa which is 8 % higher than the Ni-Ti rebar. However, the Ni-Ti failed at higher true ultimate stress value, which is 1116.665 MPa and 9.958 % of strain. While the ultimate true stress for steel rebar are 590 MPa and 5.6 % of strain. The result also shows the same trend which is 47.16 % difference for the ultimate stress while 43.76 % of strain. The ultimate true strain attained for Ni-Ti shows a similar trend, which is 9.478 % higher than engineering ultimate true strain but 4.899 % smaller than the true maximum strain for Ni-Ti A_f (– 6.3) of 12 mm diameter.

The Ni-Ti bar failed by rupturing at mid-height near the LVDT location without notch is noticed but the steel rebar behaves differently, where the notch is noticed when the ultimate stress and strain is reached. Higher result was obtained for the maximum true stress as compared to the engineering strain. The Ni-Ti A_f (-22) rebar reached an ultimate engineering stress at 1129.184 MPa and approximately 12.038 % strain where higher result was obtained for the ultimate true stress which is 10.745 % higher when compared to the ultimate true stress. While the engineering strain value is 5.574 % higher than the true strain value obtained. The ultimate engineering stress obtained for Ni-Ti specimen A_f -22 is 50.46 % higher as compared to steel while the strain at the ultimate engineering strain is 53.273 % higher than mild steel rebar. However, the tensile stress attained for Ni-Ti Af-22 is 374.157 while 0.779 % for strain at yield. However, the steel rebar failed earlier than Ni-Ti rebar even though their yield point is higher than Ni-Ti because NiTi exhibit super elastic properties to return to their original undeformed shape upon removal of stress and high resistance in fatigue [10].

7. Conclusion

Universal Tensile static test was conducted on nine test specimens made of high strength mild steel and Ni-Ti with a thickness of 12 mm and Ni-Ti 8 mm, 12 mm and 12.7 mm respectively in super-elastic alloy phase temperature at loading rate of 0.25050 mm/min conducted using the Instron Universal Tensile 600DX. The true stress-strain and engineering at yield point obtained for the above graphs were determined through the drawing done at parallel line to the elastic portion of the curve, offset from the 0.2 % strain level**.** The following specific conclusions are drawn:

Based on comparison results of the specimens of Ni-Ti A_f (-6.3) with diameter of 8 mm and 12 mm, the properties of Ni-Ti materials mainly yield strength, extension, young modulus, yielding, true and maximum engineering stress-strain values was significantly increased when the smaller diameter is used.

Ni-Ti property is significantly influenced by the Ni-Ti composition ratio and different super-elastic alloy phase temperature. Regardless of insignificant changes in the NiTi,can significantly change the mechanical properties of the material and potentially leading to undesirable characteristics.

After yielding, all the specimens showed plateau region of 7.443 % until 20.804 % strain which exhibit good potential for seismic resistance design structure as a result of the super-elasticity under tensile strain of up to around 5%. While the steel rebar can only sustain 5 % of the strain.

In addition, the maximum true stress values for NiTi -6.3 diameter 8 mm are almost 17.224 % higher than the maximum engineering stress values while the maximum true strain values are 9.152 % which is smaller than the maximum engineering strain failure values. The true stress obtained are much larger than the engineering stress obtained whenever the strain increases. As a consequent, the cross sectional of the specimen decreased but not significantly decrease for NiTi.

The test results demonstrated that the true stress-strain curve for tensile stress is higher than the results obtained from engineering stress-strain curve that is significantly influenced by different Ni-Ti composition ratio, phase temperature behaviour and diameter. This can be attributed to the differences in: modulus of young, initial elasticity and rigidity; yield strength, strain, and yield plateau rigidity.

Coupon specimens obtained from different locations across the cross section of large diameter bars provided only limited information in terms of the full-scale material properties due to the relatively small volume of material sampled in the highly heterogeneous cross section.

Acknowledgments

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Reference

[1] I. Faridmehr, M. Hanim Osman, A. Bin Adnan, A. Farokhi Nejad, R. Hodjati, and M. Amin Azimi, "Correlation between Engineering Stress-Strain and True Stress-Strain Curve," *Am. J. Civ. Eng. Archit.*, vol. 2, no. 1, pp. 53–59, 2014.

[2] J. Mccormick *et al.*, "Structural Engineering with NiTi . II : Mechanical Behavior and Scaling," no. September, pp. 1019–1029, 2007.

[3] M. Dolce and D. Cardone, "Mechanical behaviour of shape memory alloys for seismic applications 1 . Martensite and austenite NiTi bars subjected to torsion," vol. 43, pp. 2631–2656, 2001.

[4] J. Kłaput, "Studies of selected mechanical properties of nitinol – shape memory alloy," vol. 10, no. 3, pp. 155–158, 2010.

[5] R. Desroches, M. Asce, J. Mccormick, and M. Delemont, "Cyclic Properties of Superelastic Shape Memory Alloy Wires and Bars," vol. 130, no. 1, pp. 38–46, 2004.

[6] I. Faridmehr, M. Hanim Osman, A. Bin Adnan, A. Farokhi Nejad, R. Hodjati, and M. Amin Azimi, "Correlation between Engineering Stress-Strain and True Stress-Strain Curve," *Am. J. Civ. Eng. Archit.*, vol. 2, no. 1, pp. 53–59, Mar. 2014.

[7] R. DesRoches, J. McCormick, and M. Delemont, "Cyclic Properties of Superelastic Shape Memory Alloy Wires and Bars," *J. Struct. Eng.*, vol. 130, no. 1, pp. 38–46, Jan. 2004.

[8] A. Abdulridha, D. Palermo, S. Foo, and F. J. Vecchio, "Behavior and modeling of superelastic shape memory alloy reinforced concrete beams," *Eng. Struct.*, vol. 49, pp. 893–904, 2013.

[9] Y. Zhao, M. Taya, Y. Kang, and A. Kawasaki, "Compression behavior of porous NiTi shape memory alloy," *Acta Mater.*, vol. 53, no. 2, pp. 337–343, 2005.

[10] M. S. Alam, M. Moni, and S. Tesfamariam, "Seismic overstrength and ductility of concrete buildings reinforced with superelastic shape memory alloy rebar," *Eng. Struct.*, pp. 8–20, 2012.