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https://doi.org/10.1002/pc.24751

Effect of Pre-Tension on Tensile Strength of Glass Fibers-Epoxy Composite Reinforced with Shape Memory Alloy Wire

M. Khazaie[1], R. Eslami-Farsani[1], S. M. R. Khalili[2,3]

[1] Faculty of Materials Science and Engineering, K. N. Toosi University of Technology, Tehran, Iran

[2] Faculty of Mechanical Engineering, K. N. Toosi University of Technology, Tehran, Iran

[3] Department of Applied Mechanics, Indian Institute of Technology Delhi, New Delhi, India

Corresponding author: eslami@kntu.ac.ir

Abstract

In this study, the potential of superelastic shape memory alloy (SMA) wire to enhance the tensile strength of a glass fibers reinforced epoxy composite was evaluated. Composite specimens with one embedded SMA wire fabricated with hand-layup method. The specimens were placed under tensile loading (pre-tension) and unloaded before ultimate tensile strength. The pre-tension amounts were 65, 75, and 85% of ultimate tensile strength. After unloading, SMA wire wants to transform to the austenite phase and recover its primary shape and a large amount of compressive stress will be released over the composite specimens. Results show that the ultimate tensile strength for specimen with 75% pre-tension was 32% higher than the composite without pre-tension. This pre-tension has the best effect on ultimate tensile strength and pretension of specimens before ultimate tensile strength leads to higher tensile strength due to the high superelasticity of the SMA wires.

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1. Introduction

Shape memory alloys (SMAs) show two phenomena, superelasticity (SE) and shape memory effect (SME). Both are due to the phase transformations between two crystal structures, austenite and martensite. The phase transformation can be caused by stress or temperature. When the SMA in the austenitic phase is loaded over a critical stress, the austenite starts to transform to martensite, which returns to austenite when it is unloaded. The strain which is recovered is much higher than most metals. This phenomenon is known as SE [1].

Researches on designing the SMA hybrid composites (SMAHCs) show the effects of some parameters like volume fraction of SMA, surface treatment [2], pre-strain of SMA wires [3] and matrix curing process [4]. Several researchers have investigated the use of SMA wires in fiber-epoxy composites. Pappada et al. [5] and Nissle et al. [6] embedded superelastic SMA wires in fiber reinforced polymer composites to avoid propagating of defect in the composite and enhanced mechanical properties such as energy absorption and impact applications.

Kassem Abbas et al. [7] modeled static deformation, dynamic characteristic, and time response of laminated composite plates with SMA sheets. Pazhanivel et al. [8] studied effect of SMA wires on the impact resistance of glass fiber-epoxy composite laminates under different temperatures. It was observed that with the higher temperature, the SMA composite has enhanced damage resistance compared with the glass fibers-epoxy laminates.

Meo et al. [9] investigated the impact damage behavior of carbon fibers-epoxy composite plates embedded with superelastic SMA wires. The results show that in low-velocity impact, embedding SMA wires into composites increase the damage resistance of the composites compared with conventional composites structures. Barrier et al. [10] studied on tensile behavior of hybrid composite SMA wires embedded structures. Khalili et al. [11] studied the effect of some important parameters in low velocity impact of thin-walled hybrid composite plates which are embedded with SMA wires. They studied wire's effect on contact force, torsion and stress and in-plane strain.

Sharifishourabi et al. [12] fabricated a smart composite consisting of two laminated layers of epoxy, one reinforced with unidirectional carbon fibers and the other reinforced with SMA wires. The unsymmetrical specimens reported glass fibers in a composite to increase the amount of ductility and dissipated elastic energy in the composite [11]. The test showed that the hybrid glass fibers-epoxy composite with SMA wires had an enhanced strain capacity of 3.8%, compared with 1.63% failure strain for the conventional glass fibers-epoxy specimen.

El-Tahan and Dawood [13] developed a SMA/carbon fibers reinforced polymer composite using SME properties of SMA wires and studied its fatigue performance. Payandeh et al. [14] studied the effect of the martensitic transformation of the SMA wires on the behavior of the composite. Composites with SMA wire volume fraction of 6 and 12% were fabricated and tested at different temperatures under tensile loading. Results indicate that increasing the test temperature enhances the composite mechanical properties, while loading the wires and transformation to martensite decreases the bond interface between the wires and epoxy. Zafar and Andrawes [15] fabricated fibers reinforced polymer composites reinforced with SMA wires and tested them under uniaxial tensile loading. The SMA-fibers reinforced polymer composite was able to recover the maximum 7% strains with minimal residual deformation of 0.17% and maximum stress level of 105.3 MPa.

As literature shows, many researchers have worked on hybridizing composite structures with smart materials, especially SMA wires and now SMA hybrid composites are well known materials. Nevertheless, still this subject needs more studies. Past researches were focused on SME of the wires to enhance the mechanical properties of composite and most common approach was applying pre-strain to the SMA wires while embedding in the composite specimen. The SMA wires are transformed to the martensite phase and while curing, the wires return to the austenite phase and release compressive stress in the composite specimen. This method may causes much efforts and expenses to fabricate specimens and is less applicable.

In this study, new method of applying pre-strain is introduced, which is applying pre-tension to the SMA composite specimen after embedding superelastic SMA wires. In this method, first the composite specimens were fabricated with embedded SMA wire without any pre-strain. After curing, the specimens subjected to the tensile load which is lower than the ultimate tensile strength and the effect of pre-tension level is evaluated.

2. Experimental

2.1. Materials

The SMA-Glass fibers reinforced polymer (GFRP) hybrid composite which is summarized as SMA hybrid composite (SMAHC) consists of three components: epoxy matrix, woven E-glass fibers and SMA wires. The epoxy matrix and hardener used in this study were EPON 828 (Shell, Inc). The epoxy has a 9:1 resin-to-hardener mixing ratio. The SMA wires were superelastic NiTi wires (G&H, Inc). As shown in Fig. 1, a SMA wire subjected to uniaxial tensile loading and showed linear elastic behavior until a strain of 1.5% and stress of 102 MPa, then exhibited a constant stress criterion until 9.7% strain during phase transformations. Then, a strain hardening behavior was observed, which continued until failure of the wire at a strain of 20% and a stress of 348 MPa. The mechanical tests were performed at room temperature (25 °C). The mechanical properties of SMA wire are shown in Table 1.

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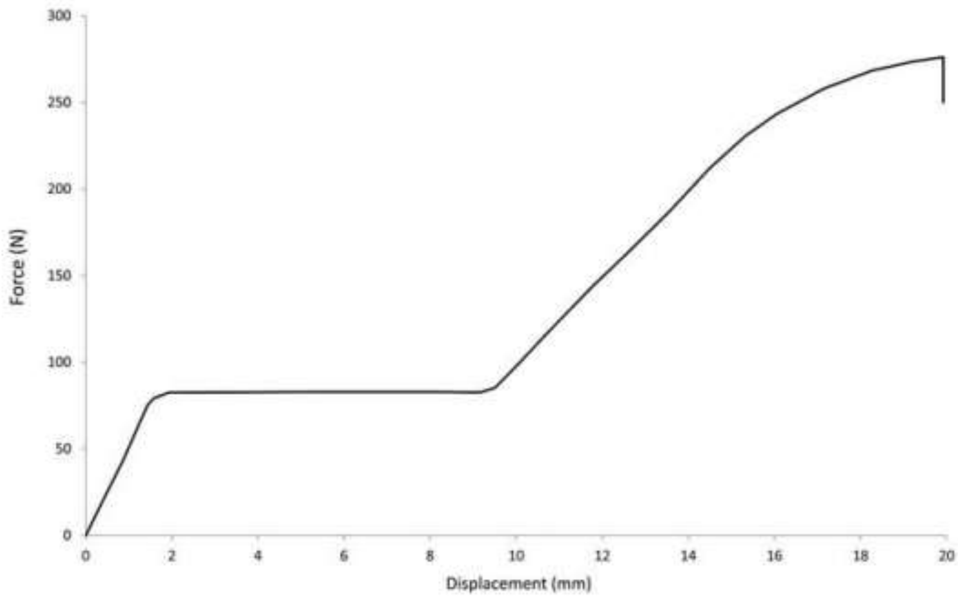

Fig. 1. Force-Displacement curve obtained from single SMA wire tensile test.

Table 1. Mechanical properties of SMA wire.

Property	Value
Modulus of elasticity in martensite phase	27.7 GPa
Modulus of elasticity in austenite phase	70.7 GPa
Poisson coefficient	0.3
Maximum recovery strain	0.067
C_m	8 MPa/°C
C_A	13.8 MPa/°C
Transformation temperatures	9, 18, 34, and 49 °C

In this research, SMA wire with 0.5 mm diameter was used which has most recovery force in circular cross section wires due to the manufacturer's data sheet. More wire's diameter leads to more volume fraction of wire in SMA composite. This may also cause negative effect according to Jang et al. [16] because of weak adhesion between wire and matrix and defect occurred in the matrix.

2.2. Fabrication of Composite Specimens

Six Specimens included one specimen without SMA wire, four specimens with one SMA wire and a specimen with one SMA wire, which had 1.5% pre-strain were fabricated with hand lay-up method. Table 2 shows the codes for specimens and their characteristics. Specimens were fabricated with 6 layers of glass fibers and epoxy resin (45–55 Vol.%). The SMA wire placed between the third and fourth layers.

Table 2. Codes for specimens.

Specimen code	Property
No. 1	GFRP
No. 2	SMAHC
No. 3	SMAHC with pre-tension up to 65% of the ultimate tensile strength
No. 4	SMAHC with pre-tension up to 75% of the ultimate tensile strength
No. 5	SMAHC with pre-tension up to 85% of the ultimate tensile strength
No. 6	SMAHC with 1.5% pre-strain of the SMA wire

2.3. Tensile Test

In this study, the pre-tension on the specimens was chosen as the parameter, therefore, three fabricated specimens were chosen to subject pre-tension on them. First a specimen with one embedded SMA wire placed under tensile loading to obtain its ultimate tensile strength which was 155.33 MPa, then three specimens placed under the tensile loading up to 65, 75, and 85% of obtained ultimate tensile strength. A single specimen with 1.5% pre-strain of the wire was also fabricated to compare the effect of applying pre-tension after specimens fabricated with the applying pre-tension while embedding wires in the specimen.

The cross section dimensions of the specimens for tensile test were 250 × 25 mm at the gauge length according to ASTM D638. Specimens were placed under pressure for 24 h for curing in room temperature. Figure 2 shows some fabricated and cut out specimens for tensile test. Tensile loading test were held by Hounsfield universal testing machine with the test speed of 2 mm/min.

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Fig. 2. SMAHC specimens for tensile test.

3. Results and Discussion

3.1. Results of Primary Tensile Test

Figure 3 shows the force-displacement curve for the specimens without SMA wire and specimen with one SMA wire and Table 3 shows the results of the tensile test.

In the first step, tensile loading was performed on two specimens, one with SMA wire and one without SMA wire to find out the magnitude for ultimate tensile strength for each of them. Each test repeated three times to ensure the results and the standard deviation was 2.08. Results show that embedding SMA wire did not help to improve the ultimate tensile strength of the specimen, this is because of the weak interface between the SMA wire and polymer matrix. Due to the relatively high diameter of SMA wire, bonding between the wire and the matrix was not formed as well and stress concentration appeared around the SMA wire and the ultimate tensile strength was reduced.

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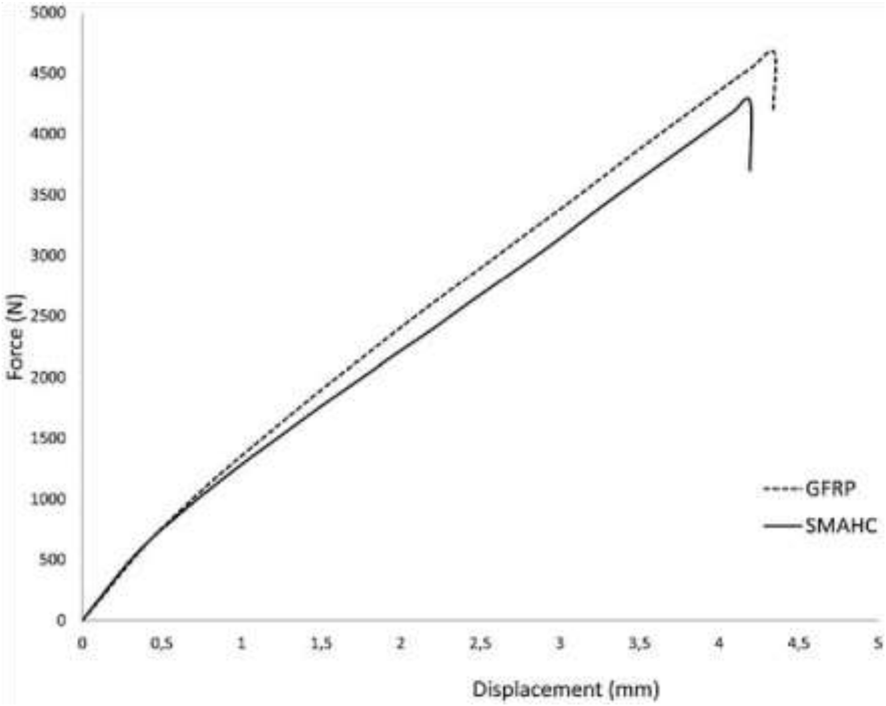

Fig. 3. Force-displacement curve for GFRP and SMAHC.

Table 3. Tensile test results for GFRP and SMAHC.

Specimens	Ultimate tensile force (N)	Max. elongation (mm)	Ultimate tensile strength (MPa)	Max. Strain (%)
GFRP	4,660	4.255	155.33	2.8
SMAHC	4,277	4.5	142.56	3

3.2. Pre-tension of SMAHC Specimens

Three SMAHC specimens subjected to pre-tension. As the Table 3, the ultimate tensile strength for the SMAHC was 142.56 MPa. Thus, the amounts of pre-tensions are 92, 107, and 121 MPa for 65, 75, and 85% of the ultimate tensile strength, respectively. Eq. 1 shows the volume fraction of the martensite phase in transformation from austenite to martensite after applying stress [17].

$$\varepsilon_{A\rightarrow M}=\frac{1}{2}\left\{\cos\left[a_m(\Theta-M_f)-\frac{a_m}{c_m}T\right]+1\right\} \quad (1)$$

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$$a_m = \frac{\pi}{M_f - M_s} \quad (2)$$

In Eq. 1, Θ and *T* refers to the temperature of the room and the subjected stress, respectively. Eq. 1 shows the volume fraction of martensite which expresses whether the subjected stress is enough to force the SMA to transform to the martensite or not. Table 4 shows the martensite volume fraction derived from Eq. 1 for each specimen after applying pre-tension and Table 5 shows the percentage of strain occurred in each specimen while applying pre-tension.

Table 4. Martensite volume fraction for each specimen.

Specimens	Martensite volume fraction
No. 3 (65% pre-tension)	0.49
No. 4 (75% pre-tension)	0.8
No. 5 (85% pre-tension)	0.97

Table 5. Percentage of strain occurred in each specimen while applying pre-tension.

Specimens	Strain (%)
Specimen with 65% pre-tension	1.4
Specimen with 75% pre-tension	1.6
Specimen with 85% pre-tension	2.2

After applying pre-tension, specimens were separated from the fixture and placed again and subjected to tensile force until the failure. Amounts for tensile force, elongation, ultimate tensile strength and strain are shown in Table 6. Figure 4 shows force displacement curve for three specimens.

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Table 6. Tensile test results for SMAHC specimens with 65, 75, and 85% pre-tension.

Specimens	Ultimate tensile force (N)	Max. Elongation (mm)	Ultimate tensile strength (MPa)	Max. strain (%)
65% pre-tension (No. 3)	4332	3.22	144.4	2.14
75% pre-tension (No. 4)	6160	4.18	205.3	2.78
85% pre-tension (No. 5)	3945	2.70	131.5	1.8

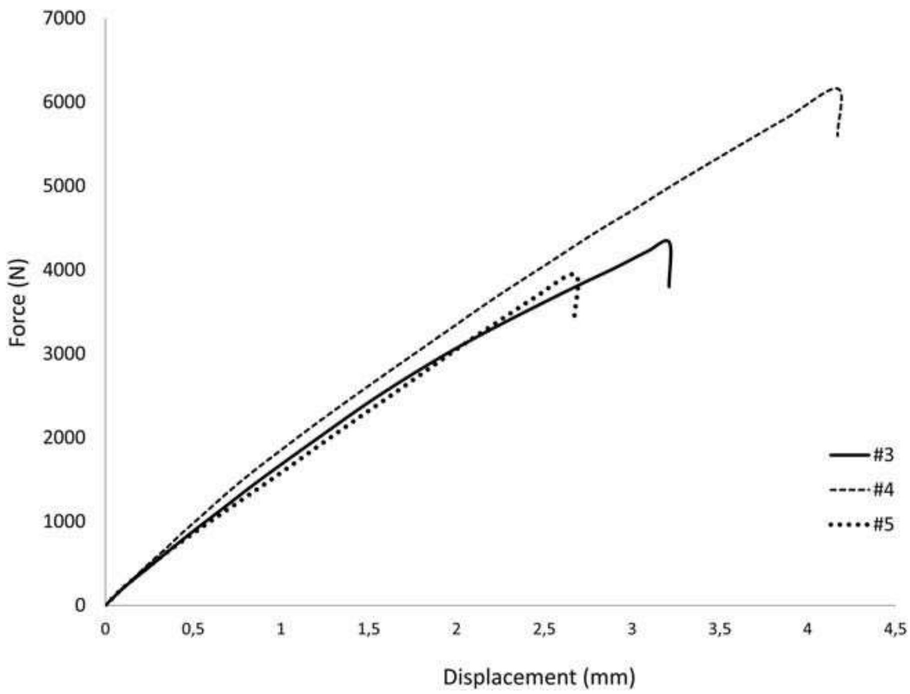

Fig. 4. Force-Displacement curve for SMAHC specimens with 65, 75, and 85% pre-tension.

Based on the results in Table 6, ultimate tensile strength in specimen no. 4 (75% pre-tension) was 205.3 MPa. It is 32% higher than GFRP which was 155.33 MPa and 51% higher than SMAHC which was 142.56 MPa.

When specimen subjected to pre-tension, the embedded SMA wire transform to martensite phase, after unloading the specimen, SMA wire wants to return to the austenite phase and it tends to contract. If this contraction is prevented, compressive stresses are generated and

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released over the specimen. In the next step, when specimens are subjected to the tensile load, a percentage of this force is utilized to overcome the compressive stress. This phenomena leads to the more ultimate tensile strength. Figure 5 is a schematic view of improvement mechanism.

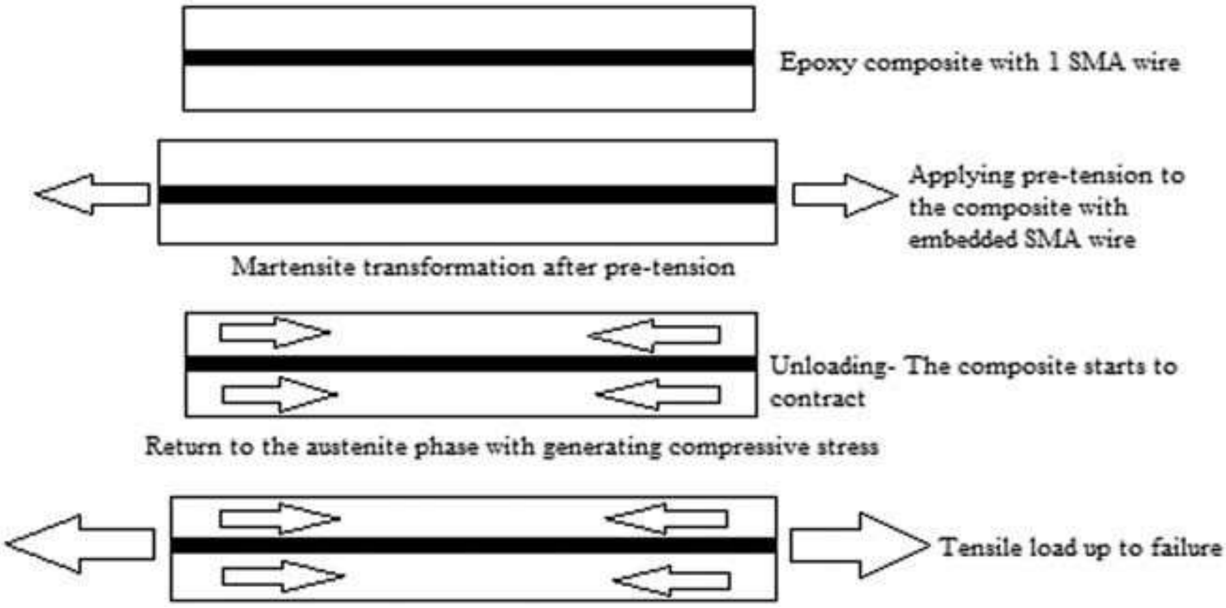

Fig. 5. Schematic diagram for mechanism of improvement of tensile strength.

Amount of pre-tension is a very important parameter. If it is lower than SMA wire's critical stress, the stress which the SMA wire enter to the superelastic zone, which was 102 MPa due to single wire tensile test in Fig. 1, it may not cause the SMA wire to transform to martensite phase and no compressive stress will be released. If the pre-tension amount is too high, the force may exceed the bond strength between matrix and SMA wires and separation between SMA wire and epoxy resin may be happened.

As it mentioned before, in the specimen with 65% pretension, the subjected pre-tension was 92 MPa and according to the single SMA wire tensile test (Fig. 1) the amount of stress which the curve reaches to a plateau area was 102 MPa and also as Table 4 shows, the martensite volume fraction of specimen no. 3 is <50% and the dominating phase in this case is austenite phase, hence, the pre-tension amount is not enough to force the SMA wire to be transformed to the martensite phase because the stress is less than phase transformation critical stress. Also Raghavan et al. [18] in a research on superelastic SMA polymer composite showed that at 1% pre-strain, the stress on the SMA wire, at the time of manufacture, was less than the critical stress for the stress-induced transformation of austenite to martensite, and hence could not have contributed to the reduction in the modulus. In this research in the 65% pre-tension condition, this amount of pre-tension did not force SMA wires to martensitic transformation.

In specimen with 75% pre-tension, the volume fraction of martensite phase after pre-tensioning was 80%. It means that the SMA wire transformed to the martensite phase and after unloading, the SMA wire tends to transform back to the austenite phase and in this process the SMA wire released compressive stress and helped to enhance ultimate tensile strength. The amount of pretension stress in this specimen was 107 MPa, which is more than wire's critical transformation stress.

To determine the presence of SMA wire, an extra test performed on a GFRP specimen (specimen without SMA wire) with 75% pre-tension. The ultimate tensile strength for GFRP with 75% pre-tension was 158 MPa. It was lower than the ultimate tensile strength of SMAHC specimen with 75% pre-tension (205.3 MPa). Figure 6 shows force-displacement curve for GFRP and SMAHC specimen, both with 75% pre-tension.

In 85% pre-strain state, pre-tension stress was 121 MPa which was more than phase transformation critical stress (102 MPa). The volume fraction of martensite phase after pre-tension was 97%, but the ultimate tensile strength is less than specimens nos. 3 and 4 because the pre-tension load destroys adhesion between wire and epoxy. Raghavan et al. [18] proved that with increase in the pre-strain, the modulus of the composite decreased. Figure 7 shows

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the specimen with 85% pre-tension after tensile test. It apparently shows pull-out of wire from matrix.

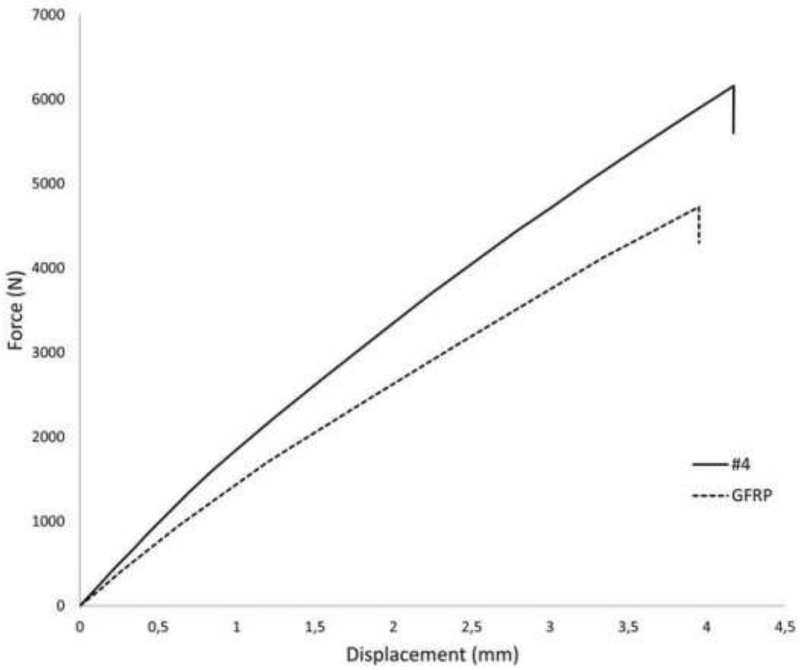

Fig. 6. Force-Displacement curve for SMAHC and GFRP with 75% pretension.

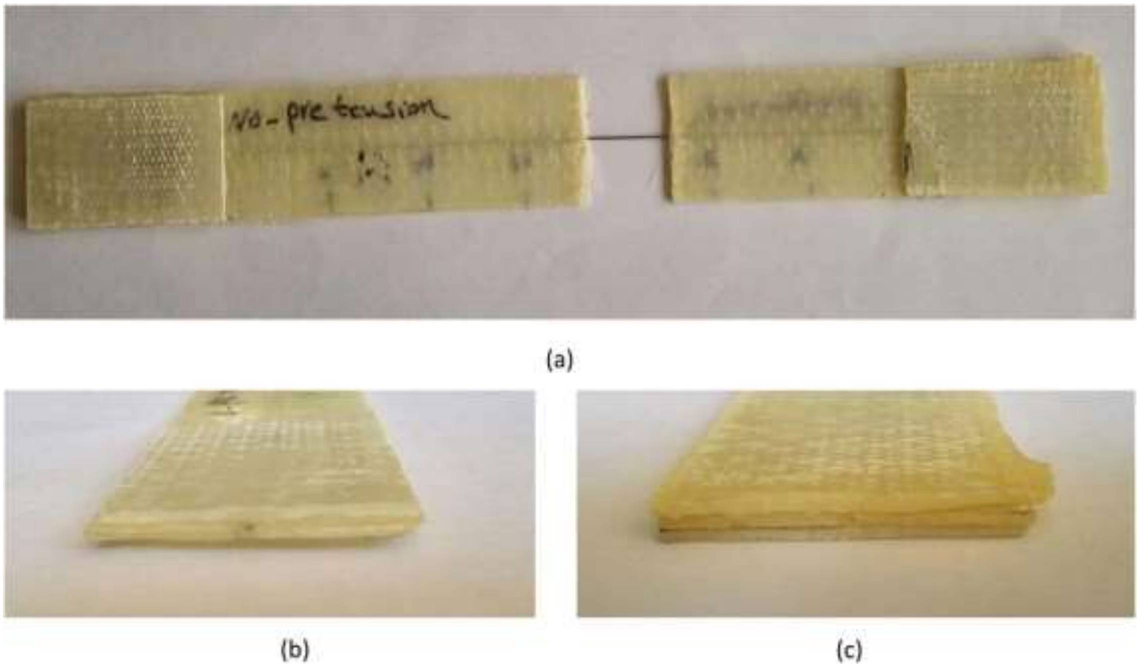

Fig. 7. Specimen with 85% pre-tension after tensile test, (a) top view of specimen, (b) cross section view before pull-out, and (c) after pull-out.

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From this results, it can be noticed that phase transformation critical stress for SMA wire in SMAHC is near 75% of ultimate tensile strength and pre-tension of specimens up to this amount, before tensile loading test, leads to enhanced results in ultimate tensile strength. Comparing to Jang [16], in this research it is shown that pretension of composite specimens after embedding wires instead of pre-tension of SMA wire while fabricating specimen, has more positive effect on tensile strength.

3.3. Effect of Wire's Pre-straining

In the past researches, the pre-tension application method was different from the method used in this research. The pre-tension had been applied while the fabricating process, and the specimens had been cured with the pre-tension [10, 15, 19]. But in this research specimens were cured normally and then the pre-tension was applied to them. For comparison between the pre-tension after fabrication of the specimens and the pre-tension while embedding wire, specimen no. 6 fabricated with 1.6% pre-tension of the SMA wire. 1.6% pre-tension was chosen based on the values in Table 5, as the strain occurred in the specimen no. 4 after 75% pre-tension. Tensile test result of specimen 6 is compared with specimens nos. 3, 4, and 5 in Fig. 8.

The ultimate tensile strength for specimen no. 6 was 161.6 MPa which is less than ultimate tensile strength of specimen with 75% pre-tension (205.3 MPa). This is due to the pull-out occurred between SMA wire and epoxy matrix after applying pre-tension to the SMA wire. Also Teheri-Behrouz et al. [19] showed that applying pre-tension to the SMA wires leads to increase in the area of the debonded zone and also reduces the elastic modulus and it is important to choose correct amount for pre-strain. In this test, it can be resulted that, to have better tensile strength, specimen with no pre-strain of SMA wire will be better.

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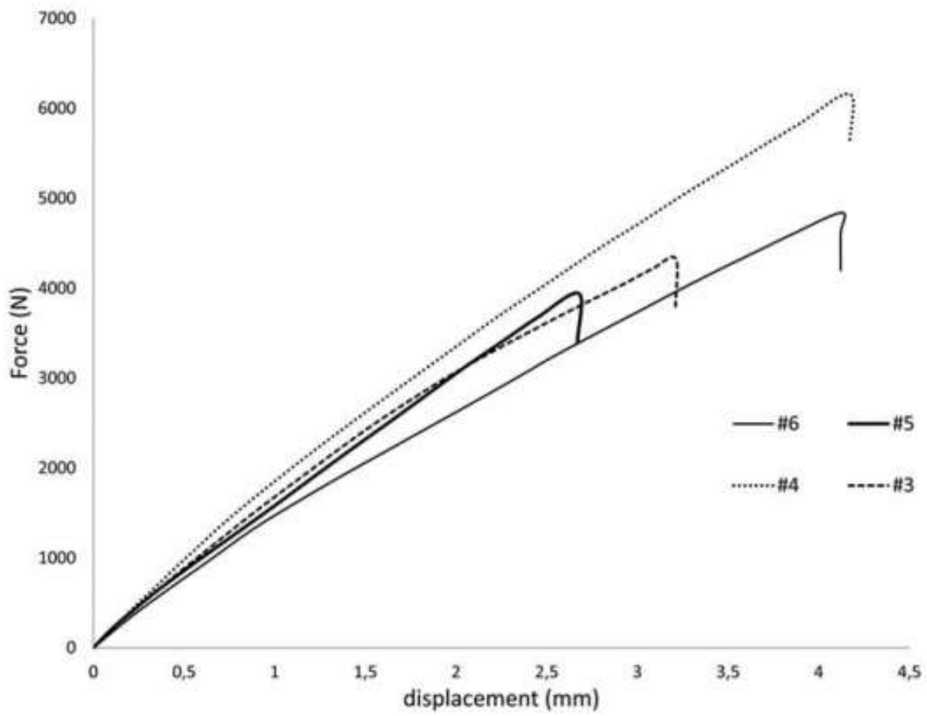

Fig. 8. Comparison of force-displacement curve for specimen with wire's pre-strain with specimens only with pre-tension.

4. Conclusions

In this study, effect of pre-tension on glass fibers-epoxy composite reinforced with SMA wire is discussed. Composite specimens with embedded SMA wire have been fabricated and have been subjected to the pretension up to the 65, 75, and 85% of the ultimate tensile strength and then placed under tensile loading until the failure. The results are as follows:

- Applying pre-tension to the SMA wire hybrid composite causes SMA wire transforms to the martensite phase and releases compressive stress over the specimen. The amount of pre-tension is very important.
- In 65% pre-tensioned specimen, ultimate tensile strength was 144.4 MPa and no significant changes were observed compared with SMA wire hybrid composite without pretension and

glass fibers-epoxy composite. In this condition, pre-tension stress is under SMA wire's critical stress for martensite transformation and tensile strength had no significant progress.

- In 75% pre-tensioned specimen, ultimate tensile strength was 205.3 MPa which is 32% more than glass-epoxy composite and 51% more than SMA wire hybrid composite without pre-tension. In this state, pre-tension of SMA wire hybrid composite before tensile loading test forced the wire transform to the martensite phase and after unloading, SMA wire wants to return to austenite phase and releases compressive stress.
- In 85% pre-tensioned specimen, ultimate tensile strength was 131.5 MPa and no changes were observed compared with SMA wire hybrid composite without pre-tension and glass fibers-epoxy composite. This is due to the fact that high pretension of specimen weakened the bond strength between SMA wire and epoxy matrix and wire pulled out from matrix.
- Results indicate that pre-tensioning the specimens after embedding SMA wires have better effect on ultimate tensile strength than pre-straining the wires before embedding. It is a more comfortable method and also cheaper and more applicable.

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