Nonlinear Characterization of a shape memory alloy NiTi fiber-reinforced composite plate subject to static loading

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Abstract

In this manuscript the design process of a SMA wire-reinforced hybrid composite (SMAHC) plate is introduced in detail. The influence of various parameters on the overall behavior of the SMAHC plate is dis-cussed. These parameters include: the mechanical behavior of the constituents (i.e. the host composite and SMA), the SMA volume fraction, the temperature dependent loading effects and the fabrication process. For that, a series of SMAHC plates were fabricated and tested under monotonic loading condition. The characteristics curves and formula for assessing the effect of the SMA at different temperatures are presented. It would be demonstrated that the embedment of SMA wires could improve the overall structural response of the host material in terms of stiffness and strength at elevated temperatures. Also capability of the one dimensional constitutive models in predicting the macroscopic stress–strain behavior of SMAHC plates is verified experimentally.

1. Introduction

Among the various types of structural reinforcement, the use of SMA within composite structures is an interesting subject due to the many applications of composite materials in various industries. Numerous applications use the characteristic of greater stiffness induced in NiTiNOL alloys upon their transformation into the austenite phase. Many researchers[1–5] have proposed theoretical and numerical models to investigate the effect of SMA reinforcement in composite structures subject to different loadings; however, few of them have addressed this issue from a practical perspective.

The research into experimental characterization of shape memory alloy reinforced hybrid composite (SMAHC) is still continuing. Turner et al.[6], Turner[7-8] and Davis et al.[9], developed a manufacturing method for fabrication of SMAHC beams and characterized their behavior under thermo mechanical loading. Their manufacturing method is very similar to the manufacturing method presented herein. Han et al. [10] used SMA springs for the reinforcement of epoxy columns under buckling. They proposed analytical, numerical and experimental methods to show how SMA springs could be used to enhance the buckling behavior of epoxy columns. Subsequently, Han et al.[11] presented their method on enhancing the stability of composite plates by embed-ding SMA wires within the plate. In their process, SMA wires were activated by applying DC current.

2. Motivation

The material behavior of the SMAHC plates under monotonic loading are described and compared under the ambient and elevated temperatures. The one dimensional constitutive equation for SMAHC structures and rule of mixture (ROM) formula, are presented and verified experimentally. Finally, modifications for an improved performance design and production process are recommended.

3. Scope And Objectices

The focus of this research is therefore more on the reinforcing attribute of SMA wires when incorporated within woven glass/epoxy composites.

4. Maroscopic Behavior Of Sma Hybrid Composites

Fig. 1 schematically illustrates the macroscopic behavior of a SMAHC plate in terms of its stress–strain behavior under mechanical loads and isothermal conditions, as a function of its boundary conditions.

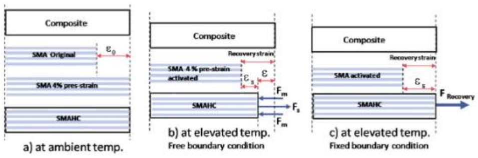

Fig. 1.Structure of a SMAHC plate and its constituents.

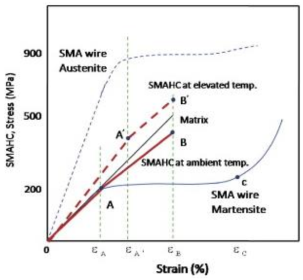

Fig. 2.Schematic stress–strain curve of the SMAHC plate and its components at ambient and elevated temperatures.

In Fig. 1a a SMAHC is shown at ambient temperature. In this case the SMA wires are elongated in the martensite phase before being embedded in the matrix (the word "matrix" hereafter refers to the host laminate composite). Fig. 1b and c show the same SMAHC at an elevated temperature (i.e. at fully austenite phase) under free and fixed boundary conditions, respectively.

In Fig. 2 curves 0–*A*–*B* and 0–*A′*–*B′* are representative stress–strain curves of SMAHC plates under ambient and elevated temperatures, respectively.

A. SMAHC behavior under the ambient temperature

Under the ambient temperature, as illustrated by curve 0–*A*–*B* in Fig. 2, the slope of the stress–strain curve could be constant up to the detwinning stress of SMA wire (point *A*). After this point, because of the martensite detwinning under almost constant loads, Young's modulus of the SMA wires reduce to their lowest value (say, to 5% of their elastic portion), which results in reduction in the stiffness of the SMAHC plate. After point *A*, the stress in both matrix and SMAHC increases until failure occurs at point *B*.

B. SMAHC behavior under elevated temperatures

In order to calculate the magnitude of the compressive strain on the host material, the SMAHC plate could be heated, while held in a free–free boundary condition as shown inFig. 1b. By considering the equilibrium of forces across the cross section along the SMA wires direction, one would obtain:

5. Application Of The Rule Of Mixture(Rom)

In order to evaluate the mechanical properties of a SMAHC based on its constitutes, the standard rule of mixtures micromechanics relation is used in this work [12]. It should be mentioned that ROM is valid only if the stress–strain relationship of the constituents is linear. In this research, as explained earlier, a bilinear stress–strain relation is considered for the SMA wires in both the fully martensite and austenite phases; therefore the ROM should be applied separately for each phase of the material. On the other hand the SMAHC plate would have a bilinear stress–strain behavior.

6. Experimental Investigation

A systematic experimental investigation was performed in two stages. In the first stage the mechanical properties of the SMA wires and prepreg composite plates were evaluated at the ambient and elevated temperatures. In the second stage, an experiment was designed and performed on SMAHC plates, also at ambient and elevated temperatures, to establish: (a) the accuracy of the ROM for predicting the longitudinal modulus of elasticity of the SMAHC; (b) the integrity and accuracy of Eq.

A. SMA wire testing

The stress induced martensite plateau that was observed in the wires tested at the ambient temperatures could not be observed in the stress–strain curve of the wires tested at elevated temperatures of 100 °C (see Fig. 3).

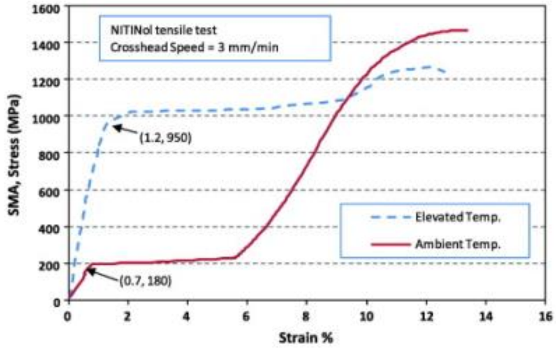

Fig. 3.Stress–strain response of NiTiNOL wires as received at ambient (28 °C) and elevated (100 °C) temperature .

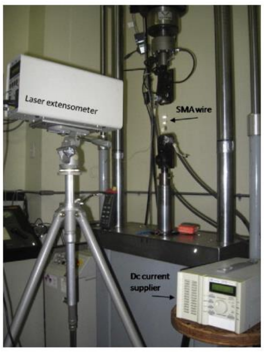

Fig. 4.Tensile test setup of SMA wires at activated temperatures (i.e., resistive heating).

Length of the SMA wires was approximately 400 mm and special gripping fixtures, as shown in Fig. 4, were used to perform the isothermal test on SMA wires.

A representative curve showing the wire's stress variation as a function of time is shown in Fig. 5.

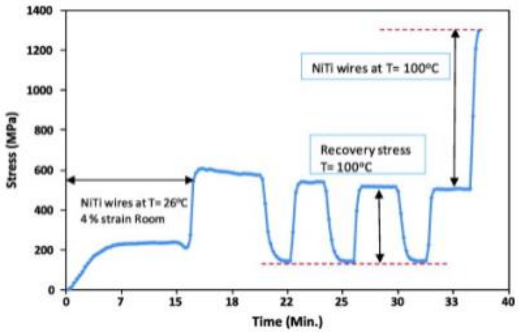

Fig. 5.Recovery stress measuring in NiTiNOL wires at 4% pre-strain and elevated temperature (100 °C).

B. Laminated composite testing

Typical intact and failed specimens are shown in Fig. 7 ; Fig. 13, respectively.

C. SMAHC specimen preparation

The SMA wires were pre-strained using an in-house designed rigid steel frame with movable rods as shown in Fig. 6. The assembly was subjected to the oven cure cycle recommended by the vendor (heating rate of 2 °C/min, ramped to 135 °C, held for 120 min at that temperature and cooled down to room temperature) and the resulting consolidated plate produced within the manufacturing frame is shown in Fig. 6.

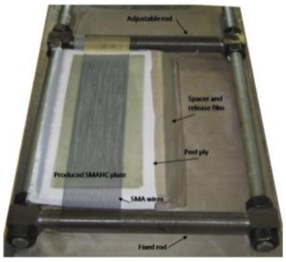

Fig. 6. The rigid adjustable frame and SMAHC plate after curing.

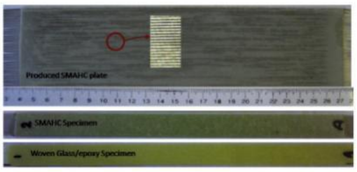

Fig. 7. A consolidated SMAHC plate and typical specimens machined from plates with and without SMA wires.

A two part heat resistant adhesive from Huntsman, Inc. (TX, USA) with the commercial name of Araldite 2014 was used for tabbing the tensile specimens according to ASTM D 3039, as shown in Fig. 7 ; Fig. 9. A total of five specimens were tested for each temperature under monotonic tensile loading.

D. SMAHC specimen testing and discussion

In order to evaluate the reinforcing effect of the SMA wires on composite materials, three sets of tests were performed on the fabricated SMAHC specimens. These were (i) scanning electron microscope analysis; (ii) monotonic tensile testing; and (iii) induced strain measurement.

1. Scanning electron microscopy analysis

The good bond quality between the wires and host matrix of the intact specimens can be observed through the SEM images illustrated in Fig. 8 ; Fig. 9. The good adhesion is evident by the presence of large resin clusters around the wires (see Fig. 8a). Fig. 8b further illustrates the perfect bond and lack of any voids in the interface of the SMA wire and matrix. Fig. 9 is a representative micrograph, showing a typical longitudinal cross section of one of the SMAHC specimens. As seen in the magnified image of Fig. 9b, there is no evidence of any gap or crack within the longitudinal interface region. In contrast to the intact specimens, the SEM micrograph (shown in Fig. 10), prepared from the surface of a failed specimen under monotonic tensile loading, reveals the presence of a micro-crack between the SMA wires and host matrix. Fig. 11 shows the uniform spacing of the SMA wires within the matrix.

In addition, the SEM image illustrated in Fig. 12 shows a relatively lower magnification of the transverse cross-section of the SMAHC; the uniform distribution of the SMA wires within the host matrix is evident. In the image, the darker regions surrounding the wires indicate the presence of pure resin deposited between the SMA wires during manufacturing of the SMAHC plates. The volume fraction of the SMA wires in the SMAHC specimen is evaluated to be between 6% and 7%.

Obtained results from the SEM observations exhibited uniform distribution of SMA wires inside the host material and verified existence of appropriate bonding qualitatively in SMA–composite interface.

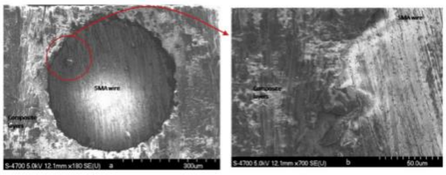

Fig. 8. Representative micrographs of an intact specimen with different magnifications.

2. Monotonic tensile testing of the SMAHC specimens

The strain was measured using an Instron extensometer with 25 mm gage length. Fig. 12 shows the tensile response of the SMA reinforced and un-reinforced specimens at the two different temperatures. As seen, the SMA reinforcement improved both the stiffness and the ultimate strength of the SMAHC coupons tested at the elevated temperature compared to those at the ambient temperature. The comparison of the experimental results (i.e. at ambient and elevated temperatures) and the theoretical results obtained by using Eqs.(5), (8) ; (10) are also illustrated in Fig. 12.

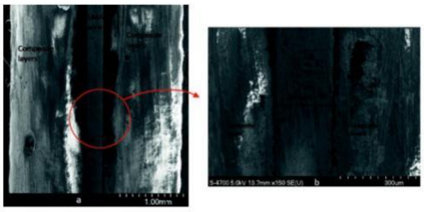

Fig. 9. SEM micrographs showing a plane cut along the axial direction.

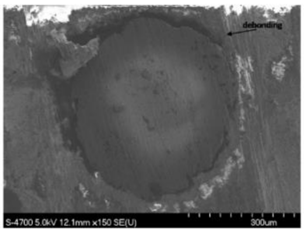

Fig. 10. SEM image of a specimen failed under tensile loading.

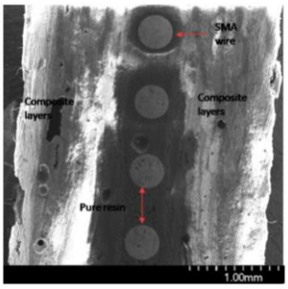

Fig. 11. Uniform distribution of the SMA wires in the transverse cross section of the SMAHC specimen.

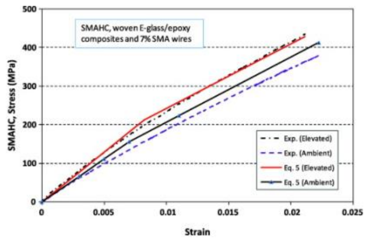

Fig. 12. Stress–strain behavior of SMAHC plates under ambient and elevated temperatures.

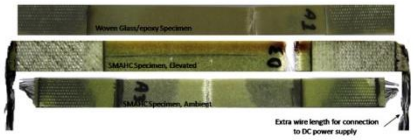

Fig. 13. Typical failed non-SMA reinforced composite specimen, and SMAHC specimens tested under ambient and elevated temperatures.

The wires followed the regime shown in Fig. 3. Fig. 13 shows a typical failed laminate composite (i.e. un-reinforced with SMA) and SMAHC specimens under the ambient and elevated temperatures.

3. Induced strain measurement

Finally, as it has been shown in Fig. 12 and Table 2, the stiffness and load capacity of the SMAHC could be enhanced by appropriate activation of the SMA wires at elevated temperatures.

7. Conclusion

(1)Considering the observations made in this research, the use of SMAHC could be considered viable in applications where elevated temperatures could significantly degrade the stiffness of the host conventional polymeric composites, thus significantly influencing their intended performance.

(2)The results showed that one can safely use the ROM for estimating other mechanical properties by knowing the characteristics of the constituents. It was also observed that the stress and strain predicted by the use constitutive equation derived based on the one-dimensional model could produce results with acceptable accuracy in comparison to the experimental data. Therefore, this equation, along with the ROM, could be effectively used as a “rule of thumb” for predicting the macroscopic behavior of SMAHC systems.

(3)SMA wires can be incorporated as reinforcement in host materials like composites and polymers that have relatively lower stiffness/strength than SMA (those measured at the austenite phase). Such reinforcement could significantly compensate the host materials’ degradation due to exposure to elevated temperatures. However, their application in structures that have inherently comparable stiffness/strength would not lead to appreciable enhancement.

(4)The shape memory effect (martensite–austenite transformation) is believed to be the main reason for mitigating stiffness and strength degradation in SMAHC plates at elevated temperature.

(5)The level of pre-strain of SMA played as important role in enhancing the strength of the SMAHC; in fact, in the austenite phase, higher pre-strains produced higher induced compressive stress in the matrix, which in return produced higher strength for the SMAHC. However, it should be noted that the higher pre-strain may also induce an excessively large magnitude of initial tensile stress on SMA wires, thus adversely influencing the overall strength and ultimate strain capacity of the SMAHC plates.

(6)A residual tensile strain remained in the SMA wires because of the constraints provided by the host material (e.g. during manufacturing), which could in turn cause an increase in the activation temperature of SMA wires. Therefore, a readjustment of the vendor suggested activation temperature is recommended.

(7)It is concluded that selecting a suitable pre-strain activation temperature is very important; this temperature would differ from one application to another.

Acknowledgements

This work is supported by the National Natural Science Foundation of China（No. 11602066） and the National Science Foundation of Heilongjiang Province of China (QC2015058 and 42400621-1-15047), the Fundamental Research Funds for the Central Universities.

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