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Technical Report

Mechanical properties of potentially-smart carbon/epoxy composites with asymmetrically embedded shape memory wires

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A B S T R A C T

Embedding Shape Memory Alloy (SMA) wires in composite structures enables controlling of their mechanical properties. The main aim of this study is to characterize experimentally the mechanical properties of two-layer smart composite structures which are made of one layer of carbon fibers epoxy laminate and one layer of epoxy embedded with SMA wires. A carbon/epoxy layer was first fabricated using vacuum infusion method. Then a SMA/epoxy layer was prepared separately and then laid over the completely cured carbon/epoxy layer using the hand lay-up process. The final structure is smart and has potential of being specifically bent under controlled thermal loading, due to the embedded pre-strained SMA wires. However the temperature was kept constant and there was no thermal excitation of the SMA wires in this experimental study. The configuration of the material constituents through the thickness of the structure renders the cross-section to be unsymmetrical. The specimens were tested in a specially developed unsymmetrical tensile testing machine. From the readings of force from the testing machine and strain gages, the tensile and shear stress–strain relations of the composite materials were obtained. The elastic and shear moduli and also Poisson's ratio of the composite materials were defined and it was observed that, the effective moduli increased with increasing density of SMA wires in the layer. It is concluded that, due to the asymmetrical material variation, finding the mechanical properties via conventional testing machine is not accurate and a special testing machine is needed.

1. Introduction

Using smart materials in composite structures has attracted the attention of many researchers [1–4]. The application of Shape Memory Alloys (SMAs) as a popular smart material in composite structures has been highlighted in robotic, aerospace, medical and many other branches of industry. The advantage of SMA material is remembering the initial shape once they are heated. This phenomenon is repeatable and the initial shape is trainable. During heat treatment two different phases of martensite and austenite are introduced. Transferring between martensite and austenite phases is the basis of the thermo-mechanical behavior of SMA wires [5,6]. The first useful constitutive model to simulate the behavior of SMA was first proposed by Tanaka [7]. The kinetic phase transformation is based on an exponential form between stress and temperature. Tanaka's [7] model is then refined by Liang and Rogers [8] and the kinetic phase transformation was proposed to a cosine form. Brinson [9] introduced two different types of martensite in the model of Liang and Rogers [8]. Brinson proposed a model which has two phases of transformation – a stress induced martensite and a thermal induced austenite.

In the last decade a new method was introduced where composite materials were reinforced by embedding SMA wires in the laminate, to form the new Shape Memory Alloy Reinforced Composite (SMARC). Embedding SMA wires in the composite changes the elastic–mechanical behavior of the material to a thermo-mechanical behavior. One such study was done by Su et al. [10] in which they found the elastic coefficient of material as a function of temperature. SMA wires were embedded concentrically in the composite and the constitutive relation between stress and strain was found for different applied temperature. In another study Zheng et al. [11] calculated the thermo-mechanical behavior of SMA/epoxy and derived the linear stress–temperature relation of SMA/epoxy. Many studies are owed to SMA hybrid composite beams such as vibration analysis, buckling and deflection in composite beams. Asadi et al. [12] analyzed the vibration and post-buckling of Euler–Bernoulli SMA reinforced hybrid composite beams. Post-buckling of Timoshenko SMA reinforced composite beams under uniform heating was investigated by Asadi et al. [13]. The closed form solution to find the deflection-temperature,

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bending moment-temperature and end-shortening-force temperature was proven successful. A new method of fabricating SMA reinforced carbon–epoxy was proposed by Xu et al. [14]. Due to high temperature during fabrication process of carbon epoxy reinforced plastic, the embedded SMA wires contract and loses the pre-strain shape. In order to overcome this shortcoming Xu suggested using cold-worked wires. The interfacial bond between SMA wires and epoxy can be subjected to high stresses when the SMA wires are heated up. These high interfacial stresses may lead to debonding and the release of SMA wires from the epoxy layer. Calculation of the pull-out stresses of SMA wires in the polymer hybrid composite was done by Poon et al. [15] who showed increasing the current in the SMA wires led to faster debonding in the interfacial surface. Axial and shear stresses of SMA wires and composite were calculated by Wang et al. [16] and concluded that the middle length of the wire bears higher axial stress, while the maximum shear interfacial stresses of SMA and composite are high at both ends of the embedded length.

A recent study to find the mechanical behavior of SMA hybrid composite was carried out by Lei et al. [17] who considered the weak interface problem between the SMA and composite. They performed uniaxial tensile tests on the symmetric composite having 1, 3 and 5 SMA wires which were concentrically located in the specimen cross section. A search of related literatures reveals that there is no study on unsymmetrical composite structures under pure tension. The bending-tensile coupling characteristics of composite beams with asymmetrically-located SMA wires have not been studied and this motivates the authors to consider this area of research. To determine the tensile-bending behavior of the unsymmetrical composite beams, a special testing machine [18] was developed for this purpose.

The main focus of this study is on the determination of mechanical properties of the unsymmetrical potentially-smart composite structures without thermal actuation. It is applicable in conditions where the mechanical properties of the structure are needed before conducting a thermal process. In this study, the composite structures were fabricated by bonding one layer of carbon/epoxy with a layer of SMA/epoxy using the vacuum infusion and hand lay-up processes. The unidirectional carbon/epoxy layer was first fabricated using vacuum infusion process and then cured. Consequently, SMA wires which had been heat treated and trained under precise conditions were hand-laid up in a layer of epoxy and left to cure. The two layers were then bonded together to form a smart composite structure. Test specimens were then cut from the structure following the recommendation of the ASTM: D3039/D3039M-08 and tested at constant room temperature. At room temperature the SMA wires completely remain in the martensitic phase. From measured forces and strains the mechanical properties for four types of composite structures with different spatial density of SMA wires were defined and compared. To find the shear modulus of elasticity, specimens with 15° fiber orientation were prepared and tested in off-axis tensile tests.

2. Methodology

2.1. Heat treatment and training of SMA wire

Before being used, the SMA wires need to be heated at a high temperature. The SMA wires were stretched out as straight as possible in a fixture (Fig. 1) which was then placed in a furnace at 750 °C for 30 min (Fig. 2). The fixture with the wires was then taken out of the furnace and left to cool down at room temperature. Austenite start and finish temperatures were found experimentally to be 45 °C and 60 °C. The training of SMA wires was carried out on a tensile testing machine. The SMA wires, each with length of

Fig. 1. SMA wires straightened in fixture.

Fig. 2. Fixture in the furnace.

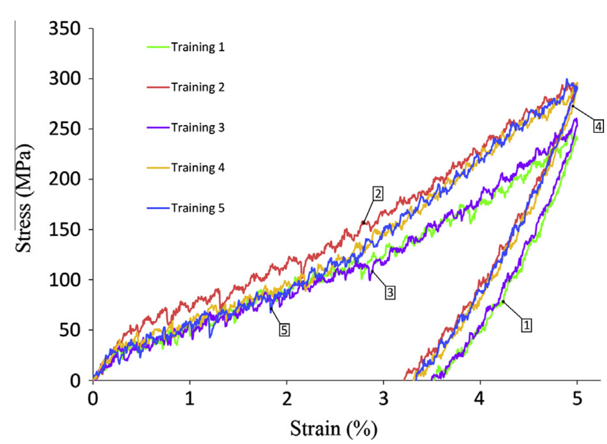

Fig. 3. Training of a SMA wire in tensile test machine.

25 cm and diameter of 0.5 mm, were strained by 5% using the universal testing machine and then released from the testing machine. The wires were then heated again until have regained their initial length. This procedure was repeated 30 times until the SMA wires