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Characterization of superelastic shape memory alloy fiber-reinforced polymer composites under tensile cyclic loading

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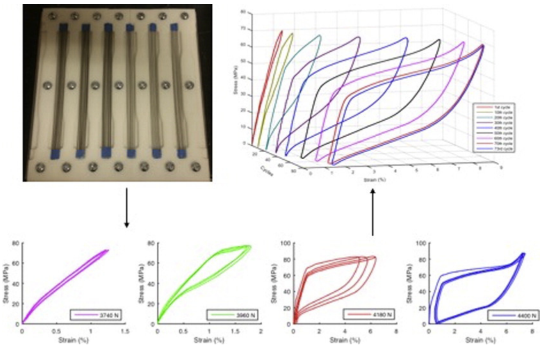
HIGHLIGHTS

- Superelastic NiTi SMA fibers are used to reinforce a thermoset polymer matrix.
- SMA-FRP coupons with three different reinforcement ratios are fabricated using modified hand lay-up technique.
- The uniaxial tensile tests are conducted under cyclic loading protocols at various stress levels.
- Results show that the SMA-FRP composites can recover relatively high strains upon unloading.

GRAPHICAL ABSTRACT



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ABSTRACT

Fiber reinforced polymer (FRP) composites have been increasingly used in engineering applications due to their lightweights, high strength, and high corrosion resistance. However, the conventional FRPs exhibit brittle failure at relatively low ultimate tensile strains, low toughness, and limited fatigue strength. Shape memory alloys (SMAs) are a class of metallic alloys that can recover large strains upon load removal with minimal residual deformations. Besides their ability to recover large deformations, SMAs possess excellent corrosion resistance, good energy dissipation capacity, and high fatigue properties. This study investigates the cyclic behavior of composite materials that consists of a thermoset polymer matrix reinforced with superelastic NiTi SMAs wires. SMA-FRP coupons with three different reinforcement ratios were fabricated using a special-made mold and following a modified hand lay-up technique. The uniaxial tensile tests were conducted under cyclic loading protocols at various stress levels to characterize the behavior of the composite. Low-cycle fatigue properties of SMA-FRPs were also investigated. Microstructural analysis using the scanning electron microscopy (SEM) technique was conducted on fractured surfaces to fully understand the failure mechanism. Results revealed that the SMA-FRP composites can recover relatively high strains upon unloading and exhibit very high failure strains.

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1. Introduction

Over the past decades, there has been a great interest in the use of fiber reinforced polymers (FRPs) in structural applications due to their high strength-to-weight ratio, high corrosion resistance, and good durability [1,2]. Conventional FRPs such as carbon fiber reinforced polymer

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(CFRP) or glass fiber reinforced polymer (GFRP) have nearly linear elastic stress-strain behavior up to rupture and fail in a brittle manner at ultimate tensile strain of 2–4%. As a result, they possess a limited ability to dissipate strain energy. In addition, FRPs have limited creep and fatigue strengths compared to many metallic materials. Therefore, most design codes limit the service stress levels of FRPs to on average of 35% of their ultimate strength [3]. These service stress limits reduce the economic advantages of the FRPs considerably.

Shape memory alloys (SMAs) are a class of metallic alloys that can recover large strains either mechanically (superelastic SMAs) or thermally (shape memory effect SMAs) upon unloading. SMAs possess excellent corrosion resistance, good fatigue properties, and ability to dissipate energy since the loading and unloading trajectories do not coincide and produce a hysteresis loop [4]. Both superelastic and shape memory effect SMAs have been utilized in many applications in different fields including biomedical, aerospace, automotive, and construction. In structural applications, SMAs have mainly been used in the forms of wires, cables or rods. For example, SMA wires have been used in SMA damping systems for tall structures, in seismic isolation systems and in retrofitting historical structures [5–8]. SMA rods have been used in self-centering buckling restrained brace systems for energy dissipation and recentering purposes and in near-surface-mounted applications as an alternative to FRPs for strengthening concrete structures [9, 10]. More recently, SMA cables have been experimentally investigated and found to provide the high strength required for large scale applications, with full recentering ability of strains up to 6% [11].

Several researchers have investigated the use of SMA wires as fiber in epoxy composites. Pappada et al. [12] and Nissle et al. [13] integrated thin superelastic SMA wires into FRPs to suppress propagating of damage in the composite for energy absorption and impact applications. Jang et al. [14] found that incorporating NiTi wires into CFRP composites reduced the tensile strength from 1300 MPa to 1100 MPa, and to as low as 50 MPa, depending on the wires and laminates directions. That was attributed to the fact that material defects were generated in the matrix by embedding the wires, and any increase in the volume fraction of the wires further decreased the tensile strength of the composite. The failure strains of the composite ranged from 0.5% to 1.25%. Sharifishourabi et al. [15] fabricated a smart FRP 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 very low tensile strength of 18 MPa. SMA wires were also used with fiberglass in a GFRP composite to increase the amount of ductility and dissipated elastic energy in the composite [16]. The tensile strength of the composite under cyclic loads was found to be approximately 360 MPa. The test showed that the hybrid GFRP composite with SMA wires was able to sustain 28% of its strength even after the rupture of the fiberglass, and had an enhanced strain capacity of 3.8%, compared to 1.63% failure strain for the neat GFRP specimen. El-Tahan and Dawood [17] developed a self-stressing SMA/CFRP patch using shape memory effect characteristics of NiTiNb SMAs and studied its fatigue performance. They observed only 20% prestress loss after two million loading cycles when the applied fatigue load was below the stress level that initiates debonding of the SMA wire.

The use of SMA wires as the only reinforcing fibers in epoxy matrix to fabricate SMA-FRP composite has also been studied. Payandeh et al. [18] examined the effect of the martensitic transformation of the SMA wires on the overall behavior of the composite. Composites with NiTi wire volume fraction of 6% and 12% were fabricated and tested at different temperatures under monotonic tensile loading. The study concluded that increasing the test temperature enhances the composite mechanical properties, while transformation of the wires upon loading decreases the bond interface between the wires and epoxy. The tensile strength of the composite ranged between 58 and 100 MPa, with failure strain ranging between 2% and 6%. Zafar and Andrawes [19] also fabricated FRP composites reinforced only with SMA wires and tested them under uniaxial tensile loading. The composite specimen was reinforced with seven SMA wires, corresponding to 20.3% fiber volume ratio. Test coupons were loaded at 1%, 3%, 5%, and 7%. The SMA-FRP composite was able to recover the maximum 7% strains with minimal residual deformation of 0.17% and maximum stress level of 105.3 MPa.

This study investigates the mechanical performance of a thermoset epoxy matrix reinforced with superelastic SMA wires under cyclic tensile loading at various stress levels. Superelastic NiTi wires with a diameter of 0.495 mm were used as fibers at three different fiber volume ratios to fabricate SMA-FRPs. A large number of tensile tests, including low-cycle fatigue tests, were conducted to evaluate the characteristics of the developed composites. Microstructural analysis using Scanning Electron Macroscopy (SEM) imaging technique was performed on the fractured surfaces. Results were assessed in terms of ultimate strength, maximum strains, and residual deformations. Dissipated energy, equivalent viscous damping and secant modulus were also calculated for each specimen to provide quantitative comparison.

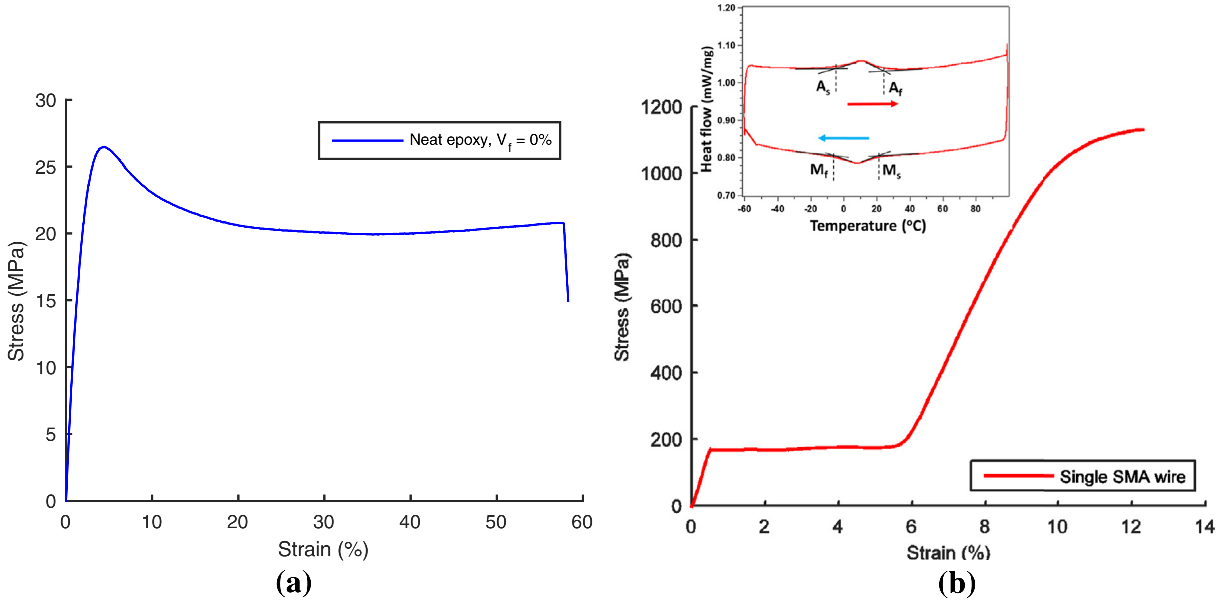

Fig. 1. (a) Mechanical behavior of neat epoxy; (b) Stress-strain curve of single SMA wire and inset curve with DSC analysis results.

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