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# Mechanics of Advanced Composite Structures

journal homepage: <http://MACS.journals.semnan.ac.ir>

## Compression Analysis of Hollow Cylinder Basalt Continuous Filament Epoxy Composite Filled with Shape Memory Wire

S.M.R. Khalili <sup>a</sup>, M. Rajabpour <sup>b\*</sup>, M.R. Jafarinezhad <sup>c</sup>, R. Maher <sup>c</sup><sup>a</sup> Center of Research for Advanced and Smart Materials and Structures, K.N Toosi University of Technology, Tehran, Iran<sup>b</sup> Young Researchers and Elite Club, Semnan Branch, Islamic Azad University, Semnan, Iran<sup>c</sup> Faculty of Engineering, Postgraduate School, South Tehran Branch, Islamic Azad University, Tehran, Iran

### PAPER INFO

#### Paper history:

Received 2016-12-23

Revised 2017-01-26

Accepted 2017-02-08

#### Keywords:

Shape memory alloy

Basalt

Compression

Hybrid composites

### ABSTRACT

This paper presents an experimental investigation into the compression behavior of shape memory alloy hybrid composites (SMAHC) subjected to quasi-static loading as it relates to the rotation effects of shape memory wire in basalt continuous filament (BCF) direct roving epoxy composite. Two types of BCF direct roving reinforced epoxy composite specimen were prepared: one type was filled with shape memory wire and the other type had no shape memory wire. Compression strengths of two specimens per type are analyzed. Specimens were prepared by hand layup at room temperature for curing. For a composite specimen, four-layer BCF direct roving reinforced epoxy composite was prepared. The effect of shape memory wire on the maximum load bearing capacity of resultant specimens after quasi static damage was experimentally investigated. Results of compression testing for two specimens per type of BCF and SMAHC showed that composite specimens with four layer BCF direct roving reinforced epoxy composite has higher load capacity than SMAHC specimens with rotated wire between second and third layer. The weak interface between shape memory wire and the matrix may be due to incompatibility of materials.

DOI: 10.22075/MACS.2017.1817.1095

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## 1. Introduction

Composite materials are increasingly used in construction and in the aerospace and automotive industries because they are lightweight, strong, and corrosion-resistant. In addition, their anisotropic properties can be controlled [1]. The high specific stiffness and strength characteristics of composites have increased their application in various engineering structures over other engineering materials [2]. However, there is a growing demand to create "smart" composite materials that can sense, actuate, and respond to the surrounding environment. Shape-memory alloys (SMAs) are metallic alloys that can undergo reversible martensitic phase transformations as a result of applied thermomechanical loads, and they are capable of recovering from permanent strains when heated above a certain transformation temperature [3]. SMAs possess sensing and actuating functions and potentially control the mechanical properties and responses of their hosts

as a result of their unique inherent shape-memory effect and pseudoelasticity characteristics [4]. When integrated into structural components, they can potentially perform sensing, diagnosing, actuating, and repairing/healing functions, thereby enhancing the performance characteristics of their hosts. Amongst the commercially available SMAs, nickel-titanium (NiTi) alloys are most widely used because of their excellent mechanical properties and superior material characteristics. Their shape-memory performance, good processability, notable corrosion resistance, cyclic stability, wear resistance, and biocompatibility allows them to be used in the biomedical field [5]. Sanusi et al. [6] present a concise review of NiTi SMA applications in composite materials and the ways in which their performance characteristics can be improved. Zhao and Zhang [7] investigated thermomechanical properties of a composite asymmetrically embedded with an SMA layer. They found that the beam deflection depends on the thickness of the SMA layer and the moment gener-

\* Corresponding author. Tel.: +98-23-33664385 ; Mob: 09126834075

E-mail address: [mortezarajabpour@yahoo.com](mailto:mortezarajabpour@yahoo.com)

ated by the SMA. They established that the thicker the SMA layer, the stiffer the composite beam and, hence, the smaller the composite beam deflection as a result of mechanical load.

A literature review revealed that Angioni et al. [8], investigated impact-damage resistance and damage-suppression properties of SMAs in hybrid composites. Lei et al. [9] presented simulation and analysis of shape memory alloy fiber reinforced composite based on a cohesive zone model. Dong et al. [10] used SMA springs to store elastic energy and obtain a larger deformation than was possible by using SMA wires in a changeable wing skin. A soft morphing actuator capable of a twisting motion using a pair of SMA wires was investigated for a twist morphing wing [11]. Also, soft composite actuators, into which smart materials and anisotropic materials are embedded together in an elastomer, were presented with a coupled in plane/bending/twisting deformation of the structure [12]. Smart soft composites (SSC) are characterized by their composition of anisotropic materials that exert an influence on actuation as both a scaffold and woven type. The performance characteristics of each type of SSC was evaluated, and multiple applications have been presented [13–16].

Rodrigue et al. [16] investigated a smart SMA-based soft composite structure capable of multiple modes of actuation. Their actuator combines four SMA wires embedded in a soft matrix in which one or two SMA wires can be activated to induce the actuator into bending mode, twisting mode or a combined bending-and-twisting mode of actuation. Han et al. [17] present a woven type of smart soft composite consisting of SMA wires and glass fiber-reinforced composite that was fabricated and applied to the rear spoiler of a 1/8-scaled radio-controlled car. Their smart soft composite is capable of actuating either symmetrically or asymmetrically. SMAs provide multiple advantages, such as a high force-to-weight ratio that makes them favorable for a considerable range of applications [18,19]. Fusible alloy embedded in the matrix has also been used to realize soft actuators capable of shape retention [20]. Anisotropic layers embedded in the matrix have been used to couple the bending deformation with a twisting motion [21]. Further, anisotropic properties can help induce actuators in a multitude of deformation types [22,23], but the orientation of the fibers limit movement in other modes and other actuation directions. Experimental modeling and active shape control of hybrid composite structures actuated by SMA wires were presented by Yang et al. [24]. Hybrid composite structures were established by attaching the SMA actuators on the surface of a graphite/epoxy composite beam and plate by bolt-joint connectors. For faster and more accurate

shape/deflection control of the hybrid composite structure, feed-forward and proportional integral derivative feedback controllers were designed and applied to the hybrid composite structure. Roh et al. [25] investigated thermo-mechanical responses of SMA actuators and their applications in shape adaptive structures with strip SMA actuators. The thermo-mechanical behavior of NiTi SMA ribbons was experimentally and numerically investigated by Roh and Bae [26]. Bodaghi et al. [27] investigated modeling and active shape/stress control of laminated beams subjected to static loading with an integrated/embedded shape memory alloy (SMA) layer. Also, the Euler-Bernoulli beam theory and von Karman geometrically non-linearity were utilized to describe displacement and strain fields of laminated beams consisting of SMA and elastic layers.

With the development of new manufacturing technologies and processing, shape memory alloy hybrid composites (SMAHC) have generated strong interest within practical engineering fields as a candidate for intelligent composite or smart structure. Therefore, it has considerable potential for uses as a protective structure in aeronautical engineering, or as an energy-dissipation structure in shipbuilding engineering. An appropriate bilinear macroscopic mechanical behavior for shape memory alloy (SMA) was shown during the process of loading. Shape recovery and stiffness enhancement characteristics of SMA can be effectively used to mitigate stiffness and strength degradation of structures when subjected to higher temperature or displacement. However, the utilization potential of hybrid composite was often limited by the weak interface between the SMA fiber and the matrix due to the incompatibility of the materials. Thus, it was essential to investigate the macroscopic mechanical behavior and interfacial properties of SMAHC. Recently, many researchers have investigated the macroscopic mechanical responses of SMA reinforced composites subjected to various loading conditions via experimental testing, finding that embedding SMA can improve the overall structural response of the host materials in terms of stiffness and strength [28–32]. Fathollah et al. [28] assumed the interfacial bonding between the SMA fiber and matrix was intact, and they evaluated the mechanical properties of SMAHC plate based on a standard rule of mixtures micromechanics relation. The effect of superelastic SMA fiber on the low-velocity impact properties of carbon fiber reinforced composite was observed through instrumented impact testing [29]. It was suggested that SMA fiber's contribution to the higher impact performance of the hybrid composite is attributable to its energy-absorbing capability and the high reversible force that acts as a healing force. Raghavan et al. [30] evaluated the potential of superelastic SMA fibers to

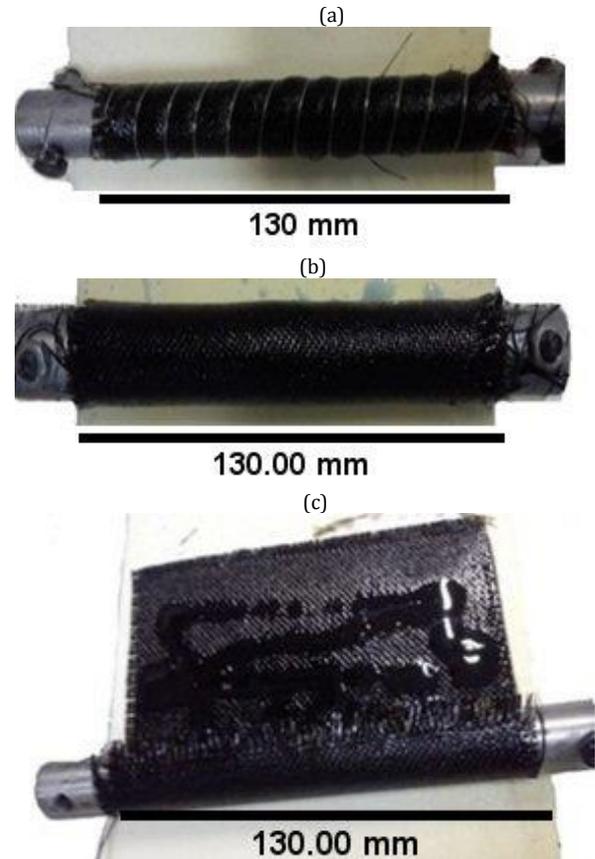
enhance the damping capacity and toughness of a thermoset polymer matrix and observed appreciable improvement in the damping, tensile, and impact properties of the polymer matrix due to reinforcement with superelastic SMA fibers.

This research presents an experimental investigation into the compression behavior of SMAHC subjected to quasi-static loading as it relates to the rotation effects of shape memory wire in BCF direct roving epoxy composite. Two types of specimen were prepared: BCF direct roving reinforced epoxy composite filled with shape memory wire and BCF direct roving reinforced epoxy composite without shape memory wire. Compression strengths of two specimens per each type were analyzed. The research is novel, because it investigates utilizing SMA wires in hollow cylinder composites to observe the compression behavior of SMAHC for possible application in such fields as aerospace, automotive, the military, and the nuclear and medical industries. SMAHC's notable features—it is lightweight, strong, corrosion-resistant, and strong, in addition to having controllable anisotropic properties—are not mentioned in previous research, as seen in the literature review. Experimental research about the effect of SMA wires in cylindrical composite, especially in hollow cylinder composites, is a new topic.

## 2. Materials and Experiments

### 2.1. Specimen manufacture

In this study, the polymer used as a matrix was Unsaturated Polymer Resin ML-506, which can be cured at ambient temperature. The hardening agent was methyl ethyl ketone peroxide (MEKP). The resin was mixed with hardener at a volume-fraction ratio of 1:1%:0.3%. The reinforced material used was woven BCF direct roving, and the surface density was  $350 \text{ g/m}^2$ . The SMA fiber was superelastic Ni-Ti alloy wire. Considering the influence of fold around SMA fiber, the wire diameter was 0.5 mm so as to minimize local distortion. To investigate the effects of a weak interface on the macroscopic mechanical behavior of SMAHC, a series of basalt continuous filament/resin hybrid composite laminates was fabricated. In the SMAHC specimen, shape memory wire rotated between the second and third layer with 1 revolution per 1 cm. For preparing this specimen, first and second layers were manufactured, and in the next step, the shape memory wire rotated on the second layer. The final step entailed manufacturing the third and fourth layers on the shape memory wire and fixing the two wires, as shown in Figure 1 a-c.

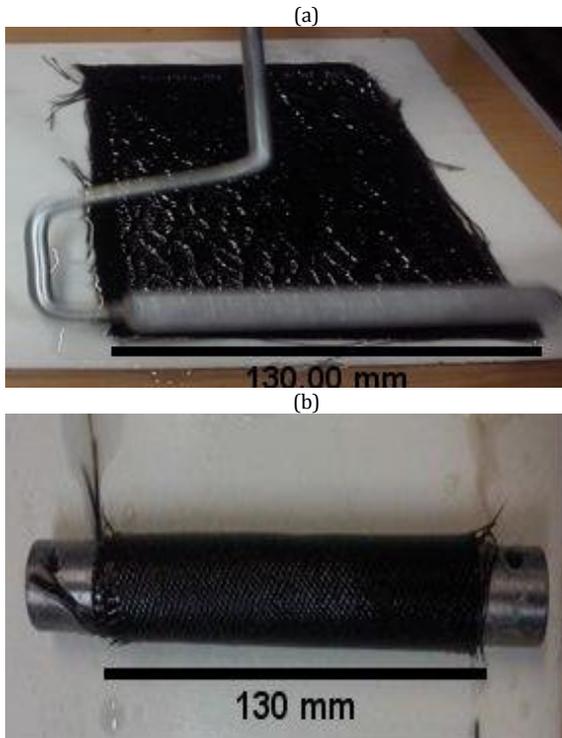


**Figure 1.** SMAHC specimen manufacturing: (a) first and second layers manufactured; (b) shape memory wire rotating on second layer; (c) third and fourth layers manufactured

In the composites specimen, four-layer BCF direct roving reinforced epoxy composite was prepared, as shown in Figure 2 a-b. It should be noted that after manufacturing the initial specimens, two additional SMAHC specimens and two composite specimens were created.

### 2.2. Interface analysis

It has been confirmed that the interface between SMA fiber and the matrix played an important role in determining the effective response of SMA reinforced composite, because it was the medium through which stress transfer occurs [33,34]. Due to the materials' incompatibility, there may be weak interfaces between SMA fiber and hybrid matrices. Fathollah et al. [28] and Zhou and Lloyd [35] observed this phenomenon in their experiments; however, they did not consider the consequence of a weak interface in the mechanical properties of composite.

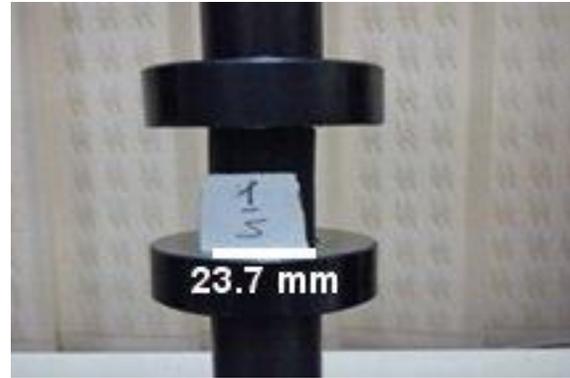


**Figure 2.** Four layer BCF direct roving reinforced epoxy composite specimen manufacturing: (a) the resin was mixed with BCF; (b) rotating of BCF and resin

### 2.3. Compression test

To evaluate the effects of SMA on the macroscopic mechanical properties of SMAHC, compression tests of SMA basalt hybrid composite specimen and composite specimen were carried out using a servo-electric testing machine. The standard utilized was ASTM (D5449/D5449M-93) Standard Test Method for compressive properties of polymer matrix composite cylinders. The test setup is shown in Figure 3. As mentioned earlier, after manufacturing the initial specimens two additional specimens for SMAHC and two composite specimens were created.

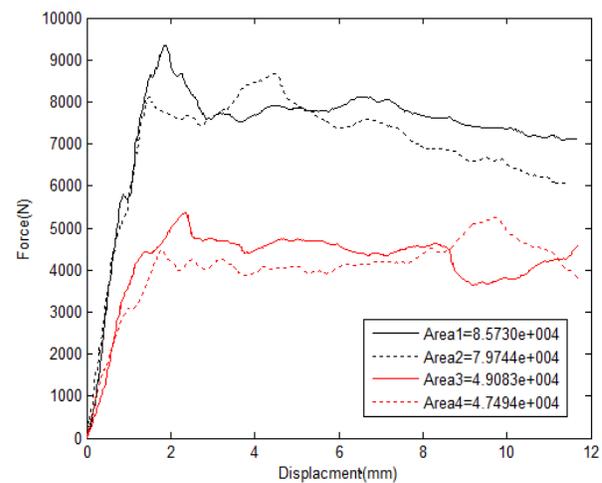
The final dimensions of the SMAHC and composite specimens were: length = 41.5 mm; inner diameter = 20.2 mm; outer diameter = 23.7 mm; and thickness = 3.5mm. For all specimens,  $l/d = 2$  is constant. Tests were performed at ambient temperature ( $293.5 \text{ K} \pm 1 \text{ K}$ ) on two specimens per type. The cross-head speed was 2 mm/min.



**Figure 3.** Setup for compression tests

## 3. Results and discussion

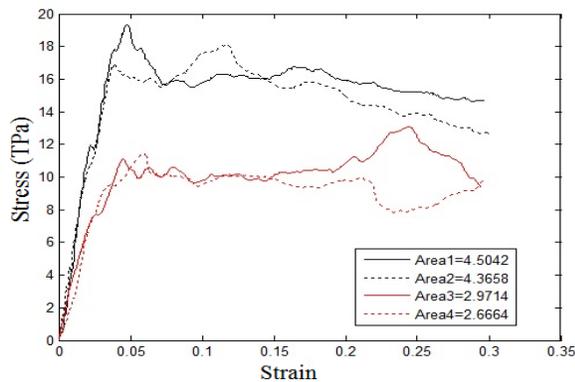
For appropriate understanding of the results, force-displacement and SMAHC stress-strain curves and composite specimens were considered. Figure 4 shows the representative curves of macroscopic force-displacement for four specimens and the area under the curve for each specimen for BCF direct roving reinforced epoxy composite (black line and dashed line) and shape memory wire hybrid composites (red line and dashed line) under compression, respectively. It should be noted that solid lines represent the first specimen, and the dashed lines represent the second specimen for BCF direct roving reinforced epoxy composite and shape memory wire hybrid composites specimens.



**Figure 4.** Force-displacement for four specimens and surface under curve for each specimen. The solid black and dashed lines represent the composite specimens, and the solid red and dashed lines represent the SMAHC specimens

Figure 5 shows the representative curves of macroscopic stress–strain for four specimens and the area under the curve for each specimen for BCF direct roving reinforced epoxy composite (black line and dashed line) and shape memory wire hybrid composites (red line and dashed line) under compression. As above, the solid line represents the first specimen, and the dashed line represents the second specimen for BCF direct roving reinforced epoxy composite and shape memory wire hybrid composites specimens.

It should be noted that compression failures in the specimens started from the maximum stress in the stress–strain diagram test. Also, buckling is a mathematical instability, leading to a failure mode. Buckling is characterized by a sudden sideways failure of a structural member subjected to high compressive stress where compressive stress at the failure point is less than the ultimate compressive stress that the material is capable of withstanding. Thus, a compression test was implemented, and there was no buckling. Results of the compression test showed that composite specimens with four layer BCF direct roving reinforced epoxy composite had a maximum load of about 9453 N and 8717 N respect to 12 mm displacement, and shape memory wire hybrid composites with rotated wire between the second and third layer had a maximum load of about 5215 N and 5363 N respect to 12 mm, as presented in Table 1.



**Figure 5.** Stress–strain for four specimens and surface under curve for each specimen. The solid black and dashed lines represent the composite specimens, and the solid red and dashed lines represent the SMAHC specimens

**Table 1.** Results of compression test for composite and SMA hybrid composite

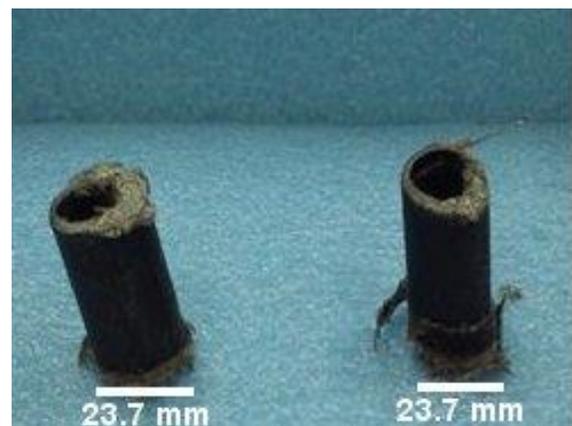
Type specimens	Specimen 1	Specimen 2
Composite	9453 N	8717 N
SMA hybrid composite	5215 N	5363 N

As shown above, SMA hybrid composite specimens tolerate lower force than do composite specimens. The weak interface between the shape memory wire and the matrix, noted in Section 2.2, may be attributable to the incompatibility of materials generating some micro-cracks in hybrid composite's region of increasing of strain; the micro-cracks caused the degradation of stiffness. The composites specimen with four-layer BCF direct roving reinforced epoxy composite has a maximum stress of about 19.7 MPa and 17 MPa, and SMAHC with rotate wire between second and third layer has maximum stress of about 10.8 MPa and 11 MPa, as shown in Table 2.

It is known that when fiber-reinforced material fails, it may be due to fiber fracture, fiber-matrix interfacial debonding, or any combinations of them. (Compression test procedures for composite and SMAHC specimens were presented in Figure 3.) This test was repeated for two specimens per type of composite and shape memory alloy hybrid composite. Typical failure morphologies of each type are shown in Figure 6. When the longitudinal strain of hybrid composite is increased to the ultimate strength, the basalt/resin matrix will gradually damage. Meanwhile, the interfacial shear stress of SMA fiber and normal stress were subjected to the external load together. Then the interface between the fiber and basalt/resin matrix began debonding gradually, pulling out the SMA fiber from the hybrid composite.

**Table 2.** Results of stress compression test for composite and SMA hybrid composite

Type specimens	Specimen 1	Specimen 2
Composite	19.7 MPa	17 MPa
SMA hybrid composite	10.8 MPa	11 MPa



**Figure 6.** Failure morphologies of composite specimen (left) and SMAHC specimen (right)

Note that it has been confirmed that stress concentration would occur near the cross-head around the SMA fiber, due to the non-uniformity of the hybrid composite. This would lead to SMA fiber fracture during the loading process, as seen in Figure 6. In addition, with the increase of longitudinal strain, the weak interface gradually debonded because of strain incompatibility along the interface, causing the basalt/resin layers to fracture and the hybrid composite to lose the load capacity, as seen in Figure 6. Therefore, the results indicate that the macroscopic fracture behavior of hybrid composite would be changed due to the effect of the SMA fiber and the weak interface. As stated earlier, it can be concluded that the overall mechanical properties of SMAHC were changed owing to the embedding of the SMA fiber. The rupture elongation increased, but the ultimate strength decreased. While the weak interface can be observed between SMA fiber and the matrix due to the discrepancy in materials compatibility, it will enhance the effect of the composite, especially the Young's modulus of the hybrid composite. The influence of the weak interface can be compensated by following these steps:

- (a) Take the SMA in longitude position of hollow cylinder and increase the number of shape memory wires.
- (b) Utilize a chemical method to enhance the adhesion between the SMA fiber and the matrix.
- (c) Provide a mechanical improvement, such as scratching the surface of the wire.

Results of other research shows that in most conditions, adding SMA fiber increased the mechanical behavior of shape memory alloy hybrid composite. For example, Hongshuai et al. [34] investigated this by adding SMA fiber in composites, improving the ultimate strength by 3.4% for the 3 SMA fiber composite uniaxial tensile tests of SMA fiber, glass/resin matrix and hybrid composites. The dimension of the SMAHC specimen was  $200 \times 26 \times 3.5$  mm. Also, by increasing the SMA fiber numbers, Young's modulus of the hybrid composite increased. Other research results [20] show that the highest stiffness of an SMA-based smart soft composite structure actuator is more than eight times that of its lowest stiffness. As mentioned earlier, SMA fiber improved the mechanical behavior of smart composite structures, but in this work, with material, geometry, and test condition, it was found that SMAHC structures are weaker than composite structures.

As mentioned earlier, the topic of this paper is novel. Many researchers investigated different parameters of hybrid composites. The material, geometry of composite rotating wire, and loading in the present research is new, and we can say that the results are also novel and worthy of further research.

#### 4. Conclusions

This paper presents an experimental investigation into the compression behavior of shape memory alloy hybrid composites (SMAHC) subjected to quasi-static loading as it relates to the rotation effect of shape memory wire in basalt continuous filament (BCF) direct roving epoxy composite. Two types of BCF direct roving reinforced epoxy composite specimen were prepared: one type was filled with shape memory wire and the other type was not. The strength of two types of specimens were analyzed. For all specimens,  $l/d = 2$ . Based on the experimental analysis, the following observations can be drawn:

(a) A weak interface was present between SMA fibers and the matrix due to material incompatibility. The first two layers were manufactured, followed by the shape memory wire being rotated on the second layer and, finally, third and fourth layers were manufactured. It should be noted that rotation of shape memory wire between the second and third layers has no appropriate mechanical properties for a compression test.

(b) The overall stiffness of composite specimens is more appropriate than shape memory alloy hybrid composite. Ultimate force of basalt continuous epoxy composite for the two specimens was 9453 N and 8717 N, while for basalt continuous epoxy composite filled with shape memory wire, it was 5215 N and 5363 N with 12 mm displacement. Similarly, the ultimate stress for the two basalt continuous epoxy composite specimens was 19.7 MPa and 17 MPa, while for basalt continuous epoxy composite filled with shape memory wire, it was 10.8 MPa and 11 MPa.

(c) The influence of the weak interface should be considered in designing an intelligent composite structure in the following steps: Take the SMA in longitude position of hollow cylinder and increase the number of shape memory wires. Then, utilize chemical and mechanical methods to enhance the adhesion between the SMA fiber and the matrix.

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