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Strain and damage self-sensing of basalt fiber reinforced polymer laminates fabricated with carbon nanofibers/epoxy composites under tension

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ABSTRACT

This study investigated the strain and damage self-sensing capabilities of basalt fiber reinforced polymer (BFRP) laminates fabricated with carbon nanofibers (CNFs)/epoxy composites subjected to tensile loadings. The conduction mechanisms based on the tunnel conduction and percolation conduction theories as well as the damage evolution were also explored. A compensation circuit with a half-bridge configuration was proposed. The results indicated the resistivity of the CNFs/BFRP laminates and CNFs/epoxy composites exhibited similar change rule, indicating that the conductive networks of CNFs/BFRP laminates were governed by CNFs/epoxy composites. With the increase of strain under monotonic tensile loading, the electrical resistance response could be classified into three stages corresponding to different damage modes. This confirmed CNFs/BFRP laminates have excellent self-sensing abilities to monitor their internal damages. Moreover, stable and repeatable strain self-sensing capacity of the CNFs/BFRP laminates was verified under cyclic tensile loading because the electrical resistance varied synchronously with the applied strain.

1. Introduction

Fiber reinforced polymer (FRP) composites are taking over traditional structural materials in various engineering fields due to their promising properties such as high specific modulus and strength, especially in lightweight structural applications [1–3]. However, FRP composites usually exhibit gradual degradation of mechanical properties during service because the formation of different levels of microscale damage including matrix microcracks, interfacial debonding, delamination and fiber breakage [4,5]. The initiation and propagation of the microscale damage have considerable influence on the durability of FRP composites [6]. Even one small crack in the composites can cause their final failure after experiencing long-term service. Therefore, monitoring of damage initiation and propagation in FRP composites is of significant interest.

In contrast to plenty of researches focused on traditional FRP, such as carbon FRP (CFRP) and glass FRP (GFRP), relatively few researches on the properties of basalt FRP (BFRP) have been undertaken [7–12]. Basalt fiber (BF) has attracted much attention recently due to its good mechanical properties, low water absorption, strong fiber-resin adhesion, excellent tolerability to temperature and environmental actions against to glass fiber and much lower price relative to carbon fiber [13–15]. On account of the above numerous brilliant properties of BF, BFRP has been developed to be a potential substitute for GFRP and CFRP in some engineering fields. For instance, Refai et al. [7] researched the durability and fatigue of BFRP system. The results presented in their study indicated that the durability of BFRP system was not significantly affected after long-term immersion in saline and alkaline solutions, and the fatigue limit of BFRP system was higher than that of GFRP system. The study of Landucci et al. [8] demonstrated that BFRP could be used as reinforcement for novel fire shields due to its high fire resistance. Lopresto et al. [9] investigated the mechanical properties on comparable GFRP and BFRP laminates. The results showed that BFRP laminates, which had larger compressive and bending strength, exhibited better performance compared to GFRP laminates. This suggests possible applications of BFRP in some fields where GFRP are widely applied. The aforementioned studies [7–12] proved that BFRP composites have broad application prospects in many engineering fields. Therefore, the strain and damage monitoring of BFRP composites during their service are in great demand.

Over the last decades, in-situ electrical resistance measurement (ERM) has been regarded as a nondestructive method for strain and damage sensing. Considerable numbers of researches have been performed to study the strain and damage monitoring of CFRP composites

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by using ERM [16–20]. For example, Wang et al. [18,20] studied the static/fatigue damage and dynamic strain monitoring in cross-ply CFRP composites by using direct current measurement techniques. The relative change in resistance $\Delta R/R_0$ was used for strain and damage sensing under static and dynamic loading. However, this method is not available for the electrically insulating GFRP and BFRP composites. Fortunately, with the rapid development of nanotechnology, the advent of carbon nanomaterials, such as carbon nanotubes (CNTs) and carbon nanofibers (CNFs) and graphene, has enable the insulating composites turned into electrically conductive ones [21–23]. In addition, as conductive fillers for FRP composites, nanomaterials can not only improve the mechanical properties of FRP composites, but also endow sensing capabilities to FRP composites [24–28]. For instance, Wang et al. [28] introduced few layer graphene (FLG) into insulating poly styrene-butadienestyrene (SBS) to fabricate the highly sensitive and stretchable strain sensor. Their results reveal that the SBS/FLG fiber based strain sensor possess superior performance, including wide workable strain range (> 110%), excellent sensitivity (gauge factor of 160 at a strain of 50% and of 2546 at a strain of 100%), and durability. Numerous studies have demonstrated that the combination of the ERM technique and conductive networks provided by the carbon nanomaterials surrounding the insulting fibers was an effective technique for monitoring the strain and damage of GFRP composites [29–33]. In the study of Li et al. [29], a small amount of CNT-Al_2O_3 hybrids were introduced into GFRP composites to create an in-situ sensor to monitor the damage initiation and propagation under mechanical loading. Their results suggested that the electrical resistance response could be classified into different distinguished stages to identify various failure modes of FRP composites.

In contrast, relatively few researchers investigated the self-sensing application of strain and damage of BFRP composites [13]. Hao et al. [13] studied the modification of BF using pyrolytic carbon coating for sensing applications. Analysis of the stress-strain curves along with the corresponding electrical resistance of the sample confirmed that BF with pyrolytic carbon coating could be used as a sensor to monitor the damage of composite structures. However, with regard to the growth of conductive fillers on fiber surface, it was most sensitive to the fracture of the loading-carrying fibers while provided less information on the development of cracks in matrix, where the microscale damages were initiated. Therefore, it is worth to study the self-sensing behaviors of BFRP laminates infused with the CNFs/epoxy composites, which can in-situ monitor not only the overall strain and damages of the BFRP laminates, but also the microscale damages of their matrix.

In this study, different contents of CNFs were dispersed into epoxy matrix and infused into basalt fiber fabric to form the conductive networks for strain and damage self-sensing of BFRP laminates. The electrical properties of CNFs/epoxy composites and CNFs/BFRP laminates were investigated first, followed by the description of conductive mechanisms with different contents of CNFs. Secondly, a compensation circuit corresponding to a half-bridge configuration was proposed to eliminate the influence of temperature on electrical resistivity of the specimens. Finally, the electrical resistances of CNFs/BFRP laminates under the monotonic and cyclic tensile loadings were tracked to explore their strain and damage self-sensing abilities.

2. Experimental program

2.1. Materials

Unidirectional woven basalt fiber fabric with surface density of 300 g/m^2 was purchased from Sichuan Aerospace Tuoxin Basalt Industry Co., Ltd., China. Pyrograf-III PR-24-XT-HHT (manufactured by Pyrograf Products, Inc., USA), which are heat treated CNFs with a diameter of 70–200 nm and a length of 50–200 μm, were employed as the conductive nanofillers. The epoxy resin used as the matrix of the nanocomposites was produced by Tianjin Swancor Wind Power Materials Co., Ltd., China. SWANCOR 2511-1A and SWANCOR 2511-1BS, with a ratio of 10:3 in weight or 30:11 in volume, is the main and curing agents of the epoxy, respectively. The epoxy resin has low viscosity, moderate gel time, nice mechanical properties, high heat deflection temperature (HDT), and good wettability to CNFs. The CNFs in the amount of 0.2%, 0.5%, 1.0%, 1.5%, 2.0%, and 3.0% by weight of epoxy resin (i.e., 0.116%, 0.29%, 0.58%, 0.87%, 1.16%, and 1.74% by volume of epoxy resin, respectively) were used in this research. The corresponding CNFs/epoxy composites are called $C_{0.2}$, $C_{0.5}$, $C_{1.0}$, $C_{1.5}$, $C_{2.0}$, and $C_{3.0}$, respectively, in this paper. Similarly, the corresponding CNFs/BFRP laminates are called $L_{0.2}$, $L_{0.5}$, $L_{1.0}$, $L_{1.5}$, $L_{2.0}$, and $L_{3.0}$, respectively. Acetone was used as diluting agent in the amount of 2% by volume of CNFs/epoxy composite. Copper sheet with a width of 5 mm was used as the electrode. The conductive copper paint was used to ensure good contact between the specimens and the electrodes.

2.2. Specimens

In this study, mechanical stirring and ultrasonic treatment were used to disperse CNFs into epoxy matrix. In order to facilitate the dispersion of CNFs, CNFs was put in an oven at 60 °C for 20 min to remove possible moisture in them. The CNFs/epoxy composites and CNFs/BFRP laminates were fabricated by the following procedure (illustrated in Fig. 1): (1) Different amounts of CNFs (0.2 wt%, 0.5 wt%, 1.0 wt%, 1.5 wt%, 2.0 wt%, and 3.0 wt%) were dispersed into acetone by using a mechanical stirrer (Model SFJ-400, Shanghai Modern Environmental Engineering Technology Co., Ltd., China) at high speed (1500 r/min) for 10 min, and then sonicated by Branson 2800 Ultrasonic Cleaner (Model 2510 E-DTH, 100 W 40KHz, Branson Ultrasonic Co., Ltd., USA) for 8 h at about 20 °C to get the CNFs-acetone mixture. The purpose of setting the temperature at about 20 °C was to reduce the volatilization of acetone. In addition, the water temperature was kept around 20 °C by constantly changing the water in the ultrasonic instrument. (2) Heated (at 60 °C for 2 min) SWANCOR 2511-1A was dissolved in the CNFs-acetone mixture via stirring at high speed for 20 min and ultrasonically dispersing at 60 °C for 8 h to get a slurry-like mixture. The purpose of re-use of ultrasonic treatment was to promote dispersion of CNFs in the resin. (3) The mixture was placed in a vacuum oven (Model DZ-2BC, Tianjin Taisite Instrument Co., Ltd., China) to remove acetone and air bubbles. (4) After the mixture was cooled, the curing agent (SWANCOR 2511-1BS) was added and mixed by mechanical stirring at low speed (500 r/min) for 5 min to get the CNFs/epoxy suspension. The purpose of low speed stirring was to create bubbles in the mixture as little as possible. (5) If the CNFs/epoxy composite specimens were to be fabricated, the prepared CNFs/epoxy suspension was poured into silicone molds with dog bone shape. If the unidirectional CNFs/BFRP laminates were to be made, the prepared CNFs/epoxy suspensions were applied into four layers of unidirectional basalt fiber fabrics, and the laminate specimens were made by using wet lay-up technique. (6) All CNFs/epoxy composites and CNFs/BFRP laminates were pre-cured at room temperature for 24 h followed by a post-cure for an additional 24 h at 60 °C. (7) The CNFs/BFRP test specimens with dimensions of 250 × 20 × 1.5 mm were cut from the cured CNFs/BFRP laminates and their surface was polished prior to measurement. The copper sheets were glued at the surfaces of the CNFs/BFRP laminate and CNFs/epoxy composite specimens using a conductive copper paint. The schematic in Fig. 2 presents the dimensions of the specimens and the layout of the electrodes. Moreover, as shown in Fig. 2, the width of the copper electrode is 5 mm. The separations between the two electrodes (gauge length) are 25 mm and 60 mm for CNFs/epoxy composite and CNFs/BFRP laminates, respectively.

2.3. Measurements

2.3.1. Electrical properties

Three samples of each type of CNFs/BFRP laminate and CNF/epoxy