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Manufacturing of electroactive morphing carbon fiber/glass fiber/epoxy composite: Process and structural monitoring by FBG sensors



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ABSTRACT

The aim of this paper is to design and develop a new class of electroactive carbon fiber/glass fiber/epoxy hybrid morphing composite with ability to change its shape in response to external stimuli. Morphing composites are of a great interest for aerodynamic structures to minimize the energy consumption and control the overall system performance. The hybrid asymmetric carbon fiber/glass fiber/epoxy morphing composite developed in this study provides a fine morphing controllability compared to classical morphing and bistable composites. In the conventional morphing structures, morphing ability is bestowed by only directionality of fibers from the same material. Herein, the morphing behavior stems from a mismatch in the coefficient of thermal expansion (CTE) between carbon and glass fibers. Fiber Bragg grating (FBG) sensors are used to monitor the manufacturing process of composites and to shed light on the physics behind the morphing behavior. Direct thermal loads are applied to the composite structure by using a temperature-controlled oven, hence manipulating its shape and in turn studying its morphing performance. Moreover, benefiting from electrical conductivity of carbon fiber reinforcement, the composite structures are provided with self-heating functionality based on Joule heating, which is used as an external stimulus for adjusting the shape of the composite structure.

1. Introduction

Fiber reinforced composites (FRCs) with promising mechanical, physical, chemical properties, light weight, and multi-functionality play a key role in technological advances in aerospace, automotive, energy, and offshore industries [1–3]. One of the attractive functionalities of the FRCs is the morphing capability. Morphing composites are a class of smart materials that can respond to a set of external stimuli and change their shapes if necessary [4]. The inspiration for designing this kind of composites originates from volant animals in nature such as birds where their flexible wings give them capability to control flight posture, minimize energy consumption and control aerodynamic performances in the air [5]. Recently, several attempts have been made to mimic such behaviors and impart morphing capability into the new generation of vehicles and aerodynamic structures [6]. Integration of morphing parts into vehicles enable them to adjust their shapes and improve performance efficiency under service condition [7]. Morphing materials have the potential to replace traditional control surfaces such ailerons and flaps in different vehicles and reduce the weight, cost and complexity of the final structure [8].

An interesting approach to produce morphing FRCs was through formation of bistable structures in carefully designed asymmetric composites with $[0_n/90_n]_T$ or $[+\theta/-\theta]_T$ configurations [9,10] where θ is fiber angle. In these laminates, the thermal contraction of the composite ingredients upon cooling from elevated curing temperatures builds-up locked-in residual stresses which tend to change the laminate shape and create bi-stability [11–13]. The bistable structures jump between different equilibrium states under relatively small bending moment known as the so-called ‘snap-through’ phenomenon [14]. The steep transitions within states, requirement of an external actuation system to initiate the transition, and limited number of equilibrium states are common problems associated with bistable composites. This is mainly due to the fact that in most of the application areas for morphing structures, gradual and controlled transition between states is necessary [13].

Limited controllability of bistable composites have been addressed with two actuation mechanisms namely, integration of piezoelectric patches and shape memory alloy (SMA) in the composite surface or within the structure [13,15]. The piezoelectric actuation uses a fiber-based patch on the surface of FRCs to apply strain on the structure and

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initiate a state transition. The piezoelectric patches provide rapid state change with fine degree of controllability by tailoring the applied voltage while their applications is limited by relatively low strain values that they induce on the structure [16]. Alternatively, SMA induces large forces and strains with relatively slow response time [17]. Attempts have been made to combine the two mechanisms to build an actuation system, referred to as shape memory alloy–piezoelectric active structures, that benefits from the properties of both materials and provide self-resetting bistable composites with capability to reverse the state change [18]. However, these designs are not able to fully address the steep state transition, and fine control of the morphing functionality.

This paper proposes a new hybrid asymmetric carbon fiber (CF)/glass fiber (GF)/epoxy morphing composite that offers fine controllability relative to classical bistable composites made from asymmetric design of the fiber direction in each layer. The morphing capability in the proposed composites originates from the mismatch in the coefficient of thermal expansion (CTE, α) of GF and CF layers in the composite structure. The mismatch in CTE enables the conversion of temperature change into mechanical displacement. The morphing FRCs based on CF/GF hybrids will create a new class of morphing composites without limitations forced by restricted fiber directionality in previously developed bistable FRCs which contains only one fiber type. The morphing composite based on the difference in CTE of layers enables the fabrication of morphing composites with different fiber directions, unique stable states, and fine controllability over morphing performance. It is noteworthy that such design makes it possible to manufacture unidirectional fiber reinforced composites which are of specific interest for a wide range of structural applications due to their outstanding specific stiffness and strength along the fiber direction. In the morphing FRCs based on CF/GF hybrid structure, the higher CTE of GF compared to CF leads to a larger expansion during manufacturing process at elevated temperatures. The build-up stress between layers due to difference in CTE of layers deforms the laminate and creates a curved structure after cooling of the composite to the room temperature. However, in most cases, applying a direct thermal load to morphing composite structure is not a practical solution to control its shape. To address this issue, electrical conductivity of the CF reinforcement is considered as a novel control mechanism [19,20]. Accordingly, Joule (Ohmic) heating where the passage of electric current through a conductive structure releases heat is implemented as a control system to apply required thermal load on the component and control the morphing capability. Joule heating phenomenon in composites reinforced with electrically conductive additives such as carbon nanotubes and carbon fibers has been used for curing and de-icing purposes [20–23]. However, to the best of our knowledge, there is no study which has reported the utilization of self-heating for shape morphing of fiber reinforced epoxy composites. The whole process from composite manufacturing to morphing capability testing was monitored by combination of FBG sensors at different locations and directions to obtain a deeper insight in the phenomena involved in the morphing behavior.

2. Experimental and methods

2.1. Material and composite preparation

The materials considered in this study are uni-directional (UD) carbon fiber/epoxy and glass fiber/epoxy prepreg system supplied by Kordsa Company. Carbon fiber prepreg with dry fabric areal weight of 300 ± 10 gsm is fabricated from DowAksa-A49 12K fibers and epoxy resin of 37 ± 2 wt%. UD Glass fiber prepreg is produced using a fabric with dry areal weight of 330 gsm (283 gsm, 1200 tex glass in 0° ; 37 gsm, 68 tex glass in 90° direction; and 10 gsm 76 dtex polyester stitches) and epoxy resin of 37 ± 3 wt%. The carbon and glass fiber prepreps are two commonly used intermediate materials for various industries and the large difference between their CTEs makes them suitable choices for

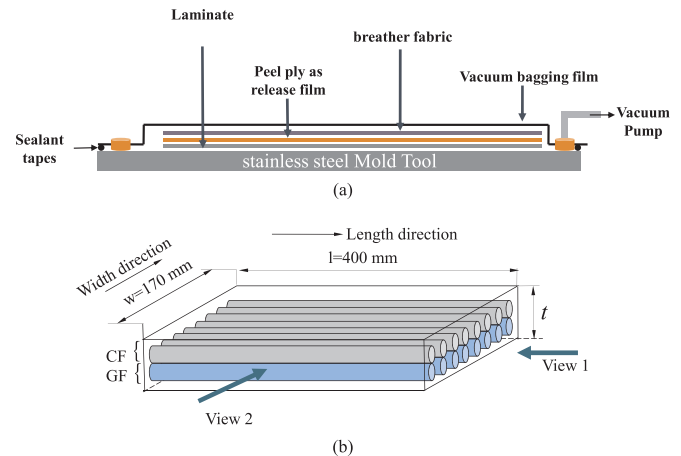


Fig. 1. A schematic representation of (a) composite manufacturing by vacuum bagging technique, and (b) stacking sequence and the placement of CF and GF layers in the morphing composite structure.

developing morphing composites. The epoxy matrix is a toughened resin system curable at 130°C and has Young's modulus of 2.6 GPa, tensile strength of 36 MPa, 2% elongation at break and glass transition temperature (T_g) greater than 130°C (provided by manufacturer). Composites were produced through vacuum bagging method on a heating table as shown in Fig. 1a using a nylon peel ply as release film, 150 gsm breather fabric and METYX-VBF100BT65MIC vacuum bag after applying sealer and release agents on a stainless steel mold surface. The prepared laminates for morphing tests consist of single layers of UD GF and CF prepreps with dimensions of 170 mm in width $\times$ 400 mm in length, where UD fibers were aligned along the length of specimen as seen in Fig. 1b. Prior to curing, the laminates were debulked under vacuum for 30 min to remove entrapped air from lay-up and to consolidate the laminates. Next, the mold was heated to 130°C for 3 h and kept under vacuum until cooling to the room temperature. The manufacturing of morphing composites with and without FBG has been realized at least two times to ensure the repeatability of experimental results. Additionally, sole CF and GF laminates were manufactured separately using two layers of each prepreps for determining CTE, and mechanical characterization of individual prepreg type.

2.2. Characterization methods

The CTE of the matrix material was determined by using METTLER TOLEDO - Thermomechanical Analysis (TMA) in the temperature range of 0 – 200°C with temperature ramp of $10^\circ\text{C}/\text{min}$. Mechanical tests were conducted using Instron 5982-100 kN Electromechanical Test System (UTM) with 100 kN load cells, with a constant cross-head speed of 2 mm min^{-1} in accordance with ASTM D5083-02 standard for at least three specimens of a given laminate. The strain measurements during tensile test were performed by using KYOWA KFG350 Ω Biaxial, $0^\circ/90^\circ$ foil strain gauges. Nikon-LV100ND optical microscope was used to study the cross section of specimens, hence determining the thickness of each layer and detecting imperfections in the composites if there is any. The cross section of specimens was polished using Struers polishing system with SiC papers of #320, #500, #1000, #2400 and #4000, in the given order, to achieve a smooth surface for microscopic analyses. The CTE of solo glass fiber and carbon fiber composites in longitudinal and transverse directions were measured following the procedure given in reference [24] by using KYOWA KFG350 Ω uniaxial strain gauges attached to the surface of each specimen while recording a temperature using a K-type thermocouple. Both strain gauges and thermocouples are interrogated with National Instrument data logger system with a LabVIEW interface.

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