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Improving the delamination resistance of carbon fiber/epoxy composites by brushing and abrading of the woven fabrics

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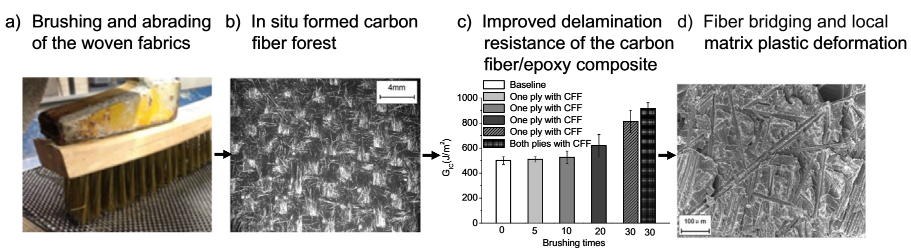
HIGHLIGHTS

- The woven carbon fabric reinforcement was modified by surface brushing and abrading.
- The fabric surface abrading enhanced the delamination resistance of the composite.
- Toughness improvement of the composite is caused by the formed 2.5D fabric structure.
- The fabric surface abrading method is simple, economic, and chemical free.

GRAPHICAL ABSTRACT



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ABSTRACT

To improve the delamination resistance of the carbon fiber/epoxy composite (CF/E), the surface of the woven carbon fabric reinforcement was modified by in situ formed carbon fiber forest (CFF), which acts as novel interleaf in the laminates. The CFF was mechanically fabricated through a simple surface brushing and abrading of carbon fabrics. With the modification of CFF, the mode I interlaminar fracture toughness of CF/E composite laminates could be remarkably enhanced by ~83% with moderate loss of their in-plane tensile strength. Microscopy observation revealed that CFF formed a three-dimensional fiber network in the matrix rich area in the interlayer of the laminates. Mechanism studies indicated that the toughness improvement of the modified CF/E composites mainly originated from the fiber bridging caused by the CFF rooting in the fabrics, displaying similar through-the-thickness reinforcing mechanism to that of the 2.5 dimensional fabric reinforced composites.

1. Introduction

Carbon fibers have been extensively used as reinforcements in the high performance structural component in aircraft, automobile, sporting goods, particular construction and buildings etc, benefiting from their light weight and high specific mechanical properties. The laminated structure of carbon fiber/epoxy composite (CF/E) made them particularly susceptible to fail via delamination and matrix cracking between the plies in such advanced composites [1]. Consequently, lots of techniques were developed to improve the interlaminar fracture toughness of CF/E composites either by toughening the resin [2,3] or by incorporating through-the-thickness reinforcement [1,4]. Although toughened bulk resins exhibit higher toughness value, they only provide limited improvement on the delamination resistance in the CF/E composites in most cases due to the limitation by the carbon fibers [5]. Moreover, some processing problems were inevitably caused by the increasing viscosity of the resin due to the presence of high content of fillers. The methods of utilizing through-the-thickness reinforcements have received considerable attention due to their

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superior toughening ability to the CF/E composites. In the laminates, the bridging (or pinning) by the reinforcements provide direct closure tractions to the delamination cracks. Generally, such reinforcements could be micro-pins (z-pin, stitching, weaving) or nano-pins, including carbon nanotubes (CNTs) and carbon nanofibers (CNFs) [6,7]. However, the fabrication of the reinforcements and control of their alignment in the CF/E composites make the manufacture process to be very complicated and expensive. In addition, the fabrication process of CNTs is energy-consuming, and costly reagents and equipments are always needed [8,9]. Stitching and/or weaving the reinforcement fibers into 2.5 dimensional (2.5D) or even 3 dimensional (3D) fabrics are very effective approaches to improve the mechanical properties of CF/E laminates in the through-the-thickness direction. However, their complicated manufacturing processes make it difficult to be widely utilized in industrial application. For instance, the stitching of the product parts requires access to both sides of them, therefore, the sophistication of the machinery increases with the increasing complexity in the geometry of parts.

In real applications, it is highly desirable to fabricate the advanced CF/E composites with relatively cheap materials and simple manufacturing process. The conventional short fibers (SFs), such as short carbon fibers, short Aramid (or Kevlar) fibers are available more conveniently than their nano-sized counterparts, and thus become ideal candidates for toughening the composites [10]. For examples, the un-bonded non-woven short Kevlar [11,12] fiber veil or/and non-woven short carbon tissues [13,14] was used as interfacial reinforcement for CF/E composites, in which short fibers in the interlayer of composite were random distributed and interlock/intersect each other in the interlayer [15], forming a specific structure close to 2.5D fabric reinforced composites and thus retarding the crack propagation efficiently. Moreover, such a method could be extended to be applied in carbon-fiber aluminum-foam sandwich structures to improve the interfacial delamination resistance effectively [16,17]. The toughening mechanism mainly originated from the bridging effect of randomly distributed SFs, which increase the energy dissipation during the crack propagation [18,19].

The previous experimental and theoretical studies mainly focused on the improvement of the interfacial properties between the fibers and matrix [20–22] by various methods, such as the surface coating of fibers with the sizing agents [23] and/or fillers [24]. For example, attaching CNTs onto fibers have been demonstrated to be one of the effective methods to improve the interfacial properties. It was found that the toughening efficiency of CNTs was influenced by CNTs orientation [24], CNTs-CF interface [25], CNTs length [26], etc. Generally, the roughness of fabric has great effect on the delamination resistance of the fiber reinforced polymer laminates, and woven fabric laminates have been reported to have Mode I interlaminar fracture toughness of 4–5 times larger than that of the laminates made of unidirectional fabrics [27]. However, up to now, there is limited report on the enhancement of the interfacial properties between fabric and matrix in laminates by increasing the surface roughness of fabric directly. In this paper, inspired by the concept of the 2.5D fabrics, fuzzy fabric reinforcements were prepared with a simple fabric surface brushing and abrading method. With this method, the carbon fiber forest (CFF) will be fabricated in situ on the surface of the continuous woven carbon fabrics. In the CF/E composite reinforced with the modified fabrics, the CFF is expected to be distributed uniformly in the epoxy rich area in the interlayer of the laminates and acts as interleaf. Moreover, different from the previous interleaving method with additional materials being put into the interlayer, one of the advantages of our in-situ produced CFF interleaves is that they adhered well to the fabrics as some fibers of them root in the carbon fabrics, which is believed to provide better delamination resistance. This concept to enhance the delamination resistance of the laminate composites by the simple abrading method is quite similar to that by the previously so-called '2.5 D' fabric reinforced composites to some extent. The method presented here is based on our previous work on the SCFs interleaving [15,28], grafting of CNTs forest onto carbon fibers with good bonding [28,29], modifying the surface of the carbon fabrics [26]. And its 'green' manufacturing process is much more cost-effective, chemical-free, and environmental friendly.

2. Experimental

2.1. Materials

The plain woven carbon fibers (Inter-Turbine Advanced logistics Pty Ltd, Australia) were used for the fabrication of the CF/E composites. The epoxy resin system including Araldite-F (diglycidyl ether of bisphenol A, DGEBA) and piperidine, supplied by Sigma-Aldrich.

2.2. The surface modification of carbon fabrics with carbon fiber forest

The carbon fiber forest was fabricated through a brushing and abrading process on one side face of woven carbon fiber cloth, as illustrated in Fig. S1 (see Fig. S1 in supporting information). The carbon fiber cloth (~200 μm in thickness) was evenly placed on the steel pad that was magnetically fixed onto the operating platform of a grinder machine (see Fig. S1(a)), and all edges of the carbon fiber cloth were fixed with double-sided tape (Fig. S1(c)). A copper brush fixed with water-jet component of the grinder machine (Fig. S1(a)) was attached onto the surface of fabric cloth. The copper material was selected as the brush pins to ensure the slight and superficial breaking of carbon fiber bundles in the fabrics, and each copper bundle within the brush comprises of 20 pins (0.8 mm in diameter and 2 cm in length for each pin (see Fig. S1(b and c)).

Before brushing and abrading, the brush pins were inserted into the carbon fiber cloth for 200 μm in depth though rising operating platform with the accuracy of 10 μm. The operating platform in Fig. S1(c) was horizontally moved back and forth at speed of 20 mm/s, which allowed carbon fiber bundles being brushed and abraded in the warp direction (see blue arrows in Fig. S1(a)). The same process was applied in the weft direction of the fabrics (see red arrows in Fig. S1(a)) as well afterwards by rotating 90 degrees around the steel pad centre. Through this method, fuzzy fabric cloths with different amount of CFF were prepared by brushing for 5, 10, 20 and 30 times in each warp and weft direction of the fabrics, respectively.

2.3. CF/E composites preparation

The composites were fabricated from 16 plies of plain woven carbon fabrics and neat epoxy by the hand lay-up method. A 20 μm thick Kapton polyimide film was inserted at the mid-plane of the laminates to serve as the pre-crack to fabricate the specimens for the interlaminar fracture toughness tests.

As illustrated in Fig. S2 (see Fig. S2 in supporting information), one or two plies of CFF modified fabrics were inserted into mid-plane of CF/E laminated composite respectively. The laminates were wrapped with bleeders and release film within a vacuum bag, and vacuumed in a chamber for 30 min followed by curing in a hot-press at 120 °C for 16 h. A pressure of 250 kPa was applied during curing to maintain a uniform laminate thickness and a