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Mode I and mode II interlaminar fracture toughness of CFRP laminates toughened by carbon nanofiber interlayer

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Abstract

Interlaminar fracture toughness for mode I and II deformation were investigated for carbon fiber (CF)/epoxy laminates toughened by a carbon nanofiber/epoxy interlayer. Vapor grown carbon fiber (VGCF) and vapor grown carbon nanofiber (VGNF) were chosen as the reinforcement for the interlayer. To illustrate the effect of the interlayer on the fracture toughness of the laminates, several types of carbon fiber reinforced plastics/carbon nanofiber (CFRP/CNF) hybrid laminates were fabricated. Each laminate was composed of unidirectional carbon/epoxy prepregs with carbon nanofiber varying the interlayer thickness. Mode I interlaminar fracture toughness was evaluated by a standard double cantilever beam (DCB) test. Mode II interlaminar fracture toughness was evaluated by an end notched flexure (ENF) test using a three point bending test. The experimental results of the DCB test confirms that the mode I interlaminar fracture toughness for hybrid laminates is about 50% greater than the base CFRP laminates. Furthermore, the results of the mode II fracture toughness test confirms that the interlaminar fracture toughness for hybrid laminates is 2–3 times greater than base CFRP laminates. In addition, the results revealed the recommended range of CNF interlayer thickness is between 100 and 150 μm (approximately 20 g/m^2 carbon nanofiber area density). The difference in the effect of the interlayer fracture properties under mode I and II deformation was discussed on the basis of fractographic observations derived from scanning electric microscope.
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1. Introduction

Over the past few decades, fiber reinforced plastics (FRP) have been developed as the foremost material for products in fields such as mechanical, electrical, architectural, and structural engineering. Carbon fiber reinforced plastic (CFRP) has especially attained a prominent position in use as structural materials for aeronautical and space engineering. Application in this industry requires further reduction in weight to satisfy the demand for higher fuel efficiency. In the Boeing 787 project, the overall weight was reported to have considerably decreased owing to the adoption of CFRP for the main wing and fuselage [1].

When considering delamination growth in view of fracture mechanics, interlaminar fracture toughness still plays an important role in damage propagation of CFRP [2]. Therefore, a number of experimental and analytical techniques have been proposed to estimate the fracture toughness for mode I [3–6], mode II [7–10], mixed mode [11] and dynamic deformations [12–14] with several combinations of carbon fiber and matrix resin.

Previous attempts to improve the interlaminar fracture toughness of CFRP laminates has shown a variety of useful results. Namely, a certain level of toughening technique has already been achieved by inserting an interleaf (interlayer) between the CFRP prepregs [15–18]. T800H/3900-2, with a heterogeneous interlayer consisting of fine thermo plastic particles, has shown high compressive strength after impact (CAI). In contrast, ionomer interleaved CFRP laminates

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have shown higher toughness under mode II deformations [19].

Since discovery of the carbon nano tube in the 1970s [20,21] and the publication in Nature clarifying the structure of the carbon nanofibers [22], carbon nano tubes and carbon nanofibers have received a great deal of attention in the aeronautical, biological, electrical and mechanical sciences, and engineering fields. Due to CNF's superiority in electrical conductivity, MWCNT or vapor grown carbon fiber 'VGCF' has established a strong presence in the storage battery field as the conductive filler.

In addition, carbon nano tubes and fibers have been applied as the toughening filler of the structural material for resin or metal based composites [23,24]. They are suitable for this application as they also have excellent mechanical properties such as elastic moduli, strength, fracture toughness, and flexibility compared with the traditional carbon fiber which are based on polyacrylonitrile (PAN).

In this study, we implemented an alternative way to increase the interlaminar fracture toughness of CFRP laminates by inserting carbon nanofibers between the CFRP prepreg sheet. VGCF was employed as reinforcement for the interlayers for mode I and II fracture toughness tests. In addition, VGNF was applied for mode II tests. Mode I and II interlaminar fracture toughness of the composite was evaluated by double cantilever beam (DCB) and end notched flexure (ENF) tests using unidirectional CFRP beam specimens, respectively.

The experimental results showed that the interlaminar fracture toughness of the CFRP/CNF hybrid laminates are superior to base CFRP laminates, and optimum thickness of the CNF interlayers exists. The difference in the effect of the interlayer fracture properties is discussed with reference to fractographic observation results derived from a scanning electric microscope.

2. Experimental procedure

2.1. CFRP specimens

Mode I and II specimens of CFRP laminates were made by an autoclave AA-1710-048-M (APC Aerospecialty Inc.) in the laboratory. The specimens are composed of carbon/epoxy unidirectional prepreg seats TORAY P3052S-22 as shown in Table 1 and carbon nanofiber interlayers. Vapor grown carbon fiber 'VGCF' and vapor grown carbon nanofiber 'VGNF' (SHOWA DENKO K.K.) were used as reinforcement for the interlayer (see Fig. 1). The specifications of the VGCF and VGNF are shown in Table 2.

Table 1
Specifications of unidirectional CFRP prepreg P3052S-22

Carbon fiber	T700S
Diameter of carbon fiber (μm)	7
Matrix (epoxy resin)	#2500
E_L (GPa): Young's modulus for fiber direction*	97.8
E_T (GPa): Young's modulus for the transverse direction*	7.1
G_{LT} (GPa): Inplane shear modulus*	3.3
ν_{LT}: Inplane Poisson's ratio*	0.35

* Measured data in our laboratory.

The carbon nanofiber reinforcement was inserted between prepregs in the middle layer of the CFRP specimens to an area density between 10 and 30 g/m^2. After making a paste of the carbon nanofiber with a small amount of solvent (ethanol), the CNF paste was applied by hand on a pair of CFRP prepregs using a metal roller. After volatilizing the solvent on the prepreg sheets, the two parts of prepregs are fixed together. By this process, a CNF interlayer of 50–200 μm thickness is naturally formed by the fusion of CNF and epoxy resin which leaks into the interlayer during the production process. Here, we have to note that thickness and Young's modulus of the CFRP prepreg adjacent to the CNF interlayer can vary slightly as related to the resin exuding.

Since the current method used to create the CNF interlayer is very primitive, there are problems which have to be solved in the future to improve the quality of the interlayer. However, the data spread of the experimental results, fracture toughness of the specimens and thickness of the interlayer was confirmed as being not a large factor in the present study.

In order to estimate interlaminar fracture toughness of the hybrid composite, the change of the Young's modulus of the CFRP prepreg layers should be considered. It was

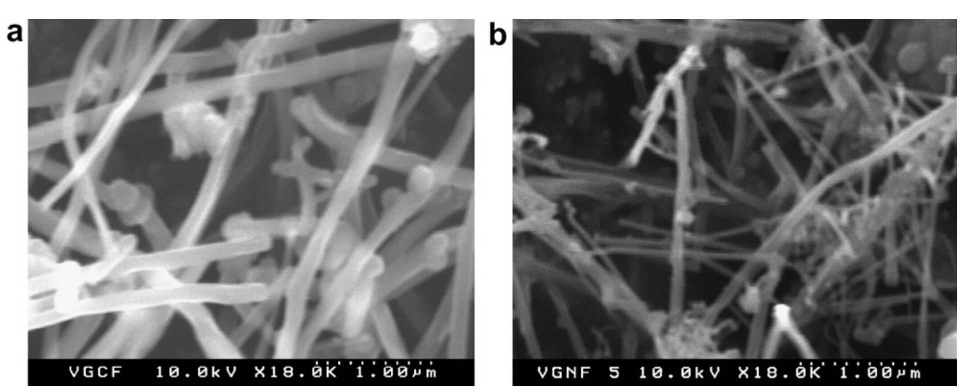

Fig. 1. Scanning electron micrographs of VGCF (a) and VGNF (b).

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