



Fracture behavior and crack sensing capability of bonded carbon fiber composite joints with carbon nanotube-based polymer adhesive layer under Mode I loading

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ABSTRACT

This paper presents a study on the Mode I fracture behavior and crack monitoring of bonded carbon fiber reinforced polymer (CFRP) composite joints with carbon nanotube (CNT)-based polymer adhesive layer. Bonded joints were fabricated using woven carbon/epoxy composite substrates and CNT-based epoxy adhesives. Mode I fracture tests were carried out with double cantilever beam (DCB) bonded joint specimens, and the dependence of the critical energy release rate at the onset of crack growth, i.e., fracture toughness, on the nanotube content in the adhesive layer and the adhesive layer thickness was examined. The electrical resistance of the bonded joint specimens was monitored during the tests. An analytical model based on the electrical conduction mechanism of CNT-based polymers was also employed to describe the electrical resistance change due to crack propagation in the bonded joint specimens, and a good correlation was obtained between the predicted and measured results. The electrical resistance change is found to result in quantitative assessment of crack length based on resistance measurement. It is demonstrated that the bonded CFRP composite joints with CNT-based polymer adhesive layer have improved fracture properties together with crack sensing capability.

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1. Introduction

Aerospace structural components are increasingly being made of composite materials, especially carbon fiber reinforced polymers (CFRPs), due to the combination of high strength, high modulus and low density. While the formability of composites enables the design and processing of larger parts with fewer joints, the use of joints in larger, more complex structures cannot be avoided. There are two main techniques of joining composite components: mechanical fastening and adhesive bonding. Each method has its own advantages and drawbacks. Although mechanically fastened joints remain particularly attractive [1], their major drawback is the local concentration of stresses at the fastener holes which weakens the composites and can often cause premature failure. Moreover, the installation of fasteners (bolts or rivets) results in a large weight penalty. On the other hand, adhesively bonded joints provide many advantages over mechanical fasteners, such as lighter weight, lower life-cycle cost, more uniform stress distribution, smooth surfaces

and greater flexibility in design, and are being pursued as alternatives to mechanical joints in aerospace applications [2]. It is therefore important to understand the mechanical behavior of adhesively bonded joints under a variety of conditions in order to ensure adequate and reliable structural design. In addition, during the service life, many structural components require inspection and evaluation to detect damage that may lead to failure. Since adhesively bonded joints cannot be disassembled easily for periodic inspections, the development of non-destructive, real-time techniques for structural health monitoring (SHM) of such joints is crucial to expanding their applications.

Carbon nanotubes (CNTs) have received a significant amount of attention due to their exceptionally superior physical and mechanical properties compared to conventional materials, and have found many applications including aerospace systems [3]. Of particular interest is the dispersion of CNTs into polymeric materials to form multifunctional, high-performance engineering material systems. Many research works have focused on the use of CNTs as nanofillers in polymers to improve their properties, such as stiffness, strength and fracture toughness [4–6]. Also, theoretical and experimental studies have shown the ability of CNTs to impart electrical

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conductivity to insulating polymers [7]. This is due to continuous conductive networks formed by the nanotubes within the polymer [8–10]. Therefore, CNTs offer a potential route for development of structural and conductive adhesives. Meguid and Sun [11] studied the tensile and shear properties of bonded joints with single-walled nanotube (SWNT)/epoxy adhesives. In the work of Sydlík et al. [12], epoxy-functionalized multi-walled nanotubes (MWNTs) were prepared by multiple covalent functionalization methods and the lap-shear strength of functionalized MWNT/epoxy adhesive joints was discussed. Jakubinek et al. [13] reported the modification of an aerospace grade epoxy adhesive by incorporation of SWNTs and examined the effect on the structural bonding and electrical performances of bonded joints. The resistance of adhesively bonded joints against failure can be quantified by two distinct methodologies; one is based on strength of materials, and the other is based on fracture mechanics. The strength components in the strength of materials approach and the fracture toughnesses in the fracture mechanics approach are considered as material properties. Most of the studies on the mechanical behavior of bonded joints with CNT-based polymer adhesive layer have been focused on the aspects to evaluate their strengths. However, the characterization of the crack behavior in CNT-based polymer adhesive joints and their fracture toughness is also essential because adhesively bonded joints generally contain some sort of imperfections in the form of voids, cracks, etc. which could be induced during the assembly process.

The research works on CNT-based polymers have shown that the existence of electrically conductive nanotube networks brings SHM capabilities to existing material systems [14]. Fiedler et al. [15] first proposed the concept of conductive modification with CNTs as having potential for both strain and damage sensing. Here nanotube networks are acting as sensors, and the deformation or the damage initiation and evolution can lead to changes in the electrical resistance of nanocomposites. There have been numerous studies on this topic [16–20]. The above SHM capabilities can also be exploited in CNT-based polymer adhesive joints. Lim et al. [21] introduced CNTs into a composite substrate as well as an epoxy adhesive, and demonstrated the ability of nanotube networks to sense and distinguish different types of damage in adhesively bonded hybrid composite/steel joints under static loading. Mactabi et al. [22] fabricated aluminum joints using CNT-based epoxy adhesive, and investigated the capability of nanotube networks to evaluate the integrity and predict the residual life of adhesively bonded joints subjected to fatigue loading. Although the technique of CNT-based sensing holds great promise in the field of SHM, interpretation of the electrical resistance response, especially the electrical resistance change due to damage, is still largely qualitative.

In this research, we study the fracture behavior and crack monitoring of bonded CFRP composite joints with CNT-based polymer adhesive layer subjected to Mode I loading. Bonded joints comprised of woven carbon/epoxy composite substrates and MWNT/epoxy adhesives were fabricated, and double cantilever beam (DCB) tests were performed. During the tests, the electrical resistance of the bonded joint specimens was measured. In addition, an analytical model for the electrical resistance response as a result of crack propagation in CNT-based polymers [23,24] was extended to describe the crack induced resistance change of the bonded joint specimens. The fracture properties and crack sensing capability of the CNT-based polymer adhesive joints were discussed based on the obtained results.

2. Experimental procedure

2.1. Material and specimen preparation

In this investigation, joints were prepared using CFRP composite

substrate materials and CNT-based polymer adhesives. The CFRP substrates were made from T300/2500 woven composite laminates with the overall fiber volume fraction of 46% (Toray Industries, Inc., Japan). The fiber reinforcement was a plain weave T300 carbon fiber fabric consisting of two sets of interlaced mutually orthogonal fiber bundles, i.e., warp and fill fiber bundles, and the matrix was the 2500 epoxy resin system. For the adhesives, MWNT/epoxy dispersions with different nanotube contents were supplied by SUMITA Nanotechnology Co. Ltd. (Japan). MWNTs produced via the catalytic carbon vapor deposition (CCVD) process (NANOCYL™ NC7000 series, Nanocyl S.A., Belgium) were used. As stated by the supplier, the nanotubes have a carbon purity of 90%, an average diameter of 9.5 nm and an average length of 1.5 μm . The epoxy system was a bisphenol-F epoxy cured with a modified aliphatic polyamine curing agent (Mitsubishi Chemical Corporation, Japan).

The configuration of a DCB specimen indicated by the ASTM standard D 5528 [25] was used for the Mode I fracture tests. The DCB bonded joint specimen is shown schematically in Fig. 1. The specimen length L and width B were 125 and 20 mm, respectively. The CFRP substrates with thickness h^C of about 1.9 mm were produced from the composite panels made of 8 plies of woven fabric and had warp fiber bundles in the length direction. The superscript C indicates the CFRP composite. The bonding area of the substrates was ground by sand paper, and then cleaned. In order to prepare the adhesives, the curing agent was added to the MWNT/epoxy dispersions and mixed using a planetary centrifugal mixer (AR-100, THINKY Corporation, Japan). The mixtures had MWNT weight fractions of 0.32, 0.65 and 1.3 wt%. After the adhesive preparation, a layer of the adhesive was applied on both substrates. The joint was then assembled and cured for three hours at 80 °C. The adhesive layer thickness h^A was controlled to about 0.6 or 1 mm by inserting polytetrafluoroethylene (PTFE) spacers. The superscript A denotes the adhesive. A PTFE film with thickness of 20 μm was placed at the mid-thickness of the adhesive layer to create a sharp initial crack with length a_0 of about 60 mm. In addition, aluminum end blocks of side length $S = 10$ mm were adhesively bonded to one end of the specimen to enable load application. For electrical resistance measurement, conductive silver paint was applied to the indicated electrode locations on the upper and lower specimen surfaces. The electrode length corresponds to the distance between the initial crack front and the end-edge of the specimen, i.e., the initial ligament length $l (= L - a_0 - S/2)$, and the electrode width was 20 mm ($= B$). For comparative purposes, bonded joint specimens with neat epoxy adhesive layer were fabricated by using the same method.

Electrical conductivity measurements were performed on square specimens (10 mm $\times$ 10 mm) of the T300/2500 woven CFRP

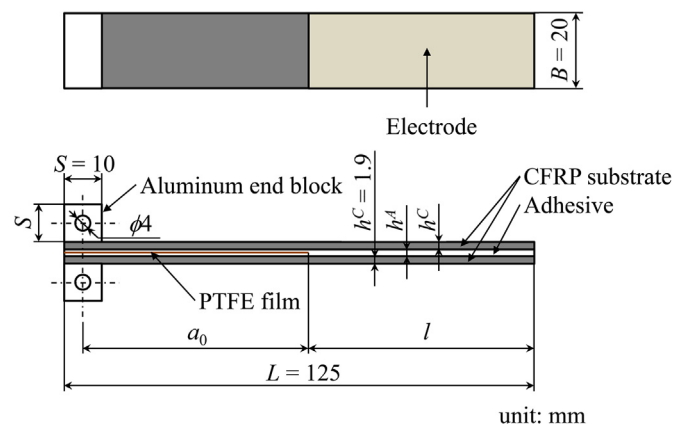


Fig. 1. Schematic of DCB bonded joint specimen.

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