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Evaluation of carbon fiber/epoxy interfacial strength in transverse fiber bundle composite: Experiment and multiscale failure modeling

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ABSTRACT

This work aims at calculating the fiber/matrix interfacial strength in the transverse fiber bundle (TFB) composite. The TFB specimens made up of carbon fiber bundles and epoxy resin were prepared and tested. The multiscale failure analysis based on the Generalized Method of Cells (GMC) was presented and the progressive damage progress of TFB composite under transverse tensile loading was simulated. Interfacial debonding was experimentally and theoretically proved to be the dominated failure mechanism in the TFB test. The interfacial normal strength could be determined by the combination of the experimental and analytical results.

1. Introduction

Recently increasing efforts have been devoted to characterize the adhesion between the fiber and the surrounding polymer matrix using the transverse fiber bundle (TFB) test [1–4]. The TFB specimen in a dog-bone shape medially contains a fiber bundle which is perpendicular to the transverse loading direction. The tensile strength of the TFB specimens under transverse loading were found quite sensitive to slight changes in the interface [3,4]. The TFB test can provide a simple and quick approach for the assessment of fiber–matrix adhesion in fiber-reinforced composites [4].

TFB tensile strength σ_{TFB}, however, is not simply equal to the fiber/matrix interfacial strength. Theoretical analysis is necessary for establishing a quantitative relation between the TFB tensile strength and fiber/matrix interfacial strength. A three-dimensional finite element (FE) model comprised of macro, intermediate and micro models was built by Rosso and Váradi [5] to investigate what was really measured in the TFB test. Zhang et al. [6] established a plain FE model to figure out the fiber/matrix interfacial bonding strength. Two limitations may exist in both FE models: (1) the failure load of the TFB test was directly assigned to the TFB sample in the FE models and no failure initiation or damage propagation was simulated; (2) the fiber and matrix were assumed to be perfectly bonded due to the complexity of applying any interface elements. Two- or multi-scale approaches based on the solution of microscale boundary condition problems are very efficient and suitable for characterizing the effective constitutive behavior of micro-heterogeneous materials [7]. The multiscale approach can overcome the limitations mentioned above.

Therefore, a combination of reliable experimental approaches and efficient numerical analysis is still urged for determining the actual interfacial strength in the TFB test. This work concentrates on providing valid result of the interfacial strength of the TFB composite under transverse loading via multiscale analysis. To begin with, the carbon fiber/epoxy TFB specimens were prepared and tested. The fracture surfaces were examined by the scanning electron microscope (SEM) to explore the failure mechanisms. Afterwards, the macroscopic structural level for the TFB composite was discretized by the FE method using Abaqus/Standard. And the Generalized Method of Cells (GMC) reformulated by Pindera and Bednarcyk [8] was implemented as a special subroutine to calculate the micro stresses. Apart from the fiber and matrix, a discrete interphase was included in the repeating unit cell (RUC) of the GMC micromechanics model. The progressive damage process of the TFB composite was simulated on the basis of the interphase and matrix failure criteria. Interfacial debonding was experimentally and theoretically proved to be the dominated failure mechanism. The interfacial normal strength was determined by the correlation of experimental and analytical results. Furthermore, the effects of interphase stiffness and thickness on the calculated interfacial normal strength were investigated.

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2. Experimental

The commercial Toray T800H and T700S carbon fiber bundles composed of 6000 and 12,000 single fibers respectively were used in the experiment. The diglycidyl ether of bisphenol A (DGEBA, Dow Chemical Company) with an epoxide equivalent weight of 185–192 g/eq was mixed with curing agent D400 (Dow Chemical Company). The sample dimensions of type IV in ASTM D638 [9] were selected for both the resin and TFB specimen.

Since the TFB samples are cured in an open mold, the impregnation process is very critical to the final quality of TFB specimen. The fiber bundle was naturally impregnated with the resin before gelation [1,2,5,6]. In this experiment, the carbon fiber bundle was impregnated with the epoxy resin on an automatic impregnation apparatus (Fig. 1(a)) before specimen preparation. The fiber bundle was drawn through the resin bath and the squeezing rollers to ensure adequate resin impregnation. The excessive resin was then removed by the wiper rollers. The well impregnated bundle was finally wound onto the winder frame.

Subsequently, the impregnated fiber bundle was employed to prepare the TFB specimens. Firstly, a length of fiber bundle was cut down and stretched directly. The stretched bundle was placed in the middle narrow slit of the mold and kept under tension. The degassed resin was then casted into the mold. TFB samples were finally cured in 3 steps: 75 °C for 2 h, 110 °C for 2 h and 150 °C for 2 h. After being demolded (Fig. 1(b)), the specimens were milled on the surfaces using sandpapers to reduce surface roughness, which ensured the cross-section in the middle of the gage length only contain the fiber bundle.

Fig. 1(c) and (d) shows the specimen cross-section image taken along the direction of the arrow displayed in Fig. 1(b) by an optical microscope (Leica DM4000). Due to the impregnation process before specimen preparation, the carbon fibers between the dot lines distribute relatively uniformly compared with former results [1,5]. The widths of fiber bundle between the dot lines are about 0.25 mm and 0.20 mm for T800H and T700S TFB specimen respectively. The average fiber volume fraction V_f equals the area ratio of all the fibers to the whole bundle region. The average V_f of the T800H/epoxy TFB specimen is estimated to be approximately 34% while that of the T700S/epoxy TFB sample is about 40%.

The TFB and bulk epoxy tension tests were conducted on a universal test machine (Instron 5565) using a 5 kN load cell. The cross-head speed was 1 mm/min. The elongation of specimen during tension was accurately measured by the extensometer with a gauge length of 25 mm. More than 8 measurements for each different test were implemented to compensate for the problem of relatively scattered results [2]. The fracture surfaces were examined by the SEM (CamScan CS3400) to explore the failure mechanisms.

3. Analytical

3.1. Macro modeling

The commercial finite element software Abaqus 6.9 was utilized to carry out the FE-calculations. Fig. 2(a) provides an overview of the TFB tensile specimen. The carbon fiber bundle in the middle section was modeled as a thin homogenized composite layer with a nominal thickness of 0.25 mm. The composite layer and epoxy matrix were assumed to be perfectly bonded. Because of the implementation of symmetry boundary conditions in *OX*, *OY* and *OZ* directions, only one eighth of the TFB specimen was created. The reduced integration solid elements (C3D8R) were employed to mesh the TFB part. Finer meshes (Fig. 2(b)) were used in the composite layer to ensure the accurate macro stress and strain fields.

The residual stress has a non-ignorable effect on the failure of TFB specimen [5,6]. It can be seen in Fig. 3 that the glass transition temperature T_g of the DGEBA/D400 system is about 50 °C, which is lower than the curing temperature at the final step (150 °C). For the fiber reinforced composite cured above T_g, the residual stress is developed neither during the curing reaction nor during cooling from curing temperature to T_g, but during cooling from T_g to the room temperature [10]. The residual stress is mainly ascribed to

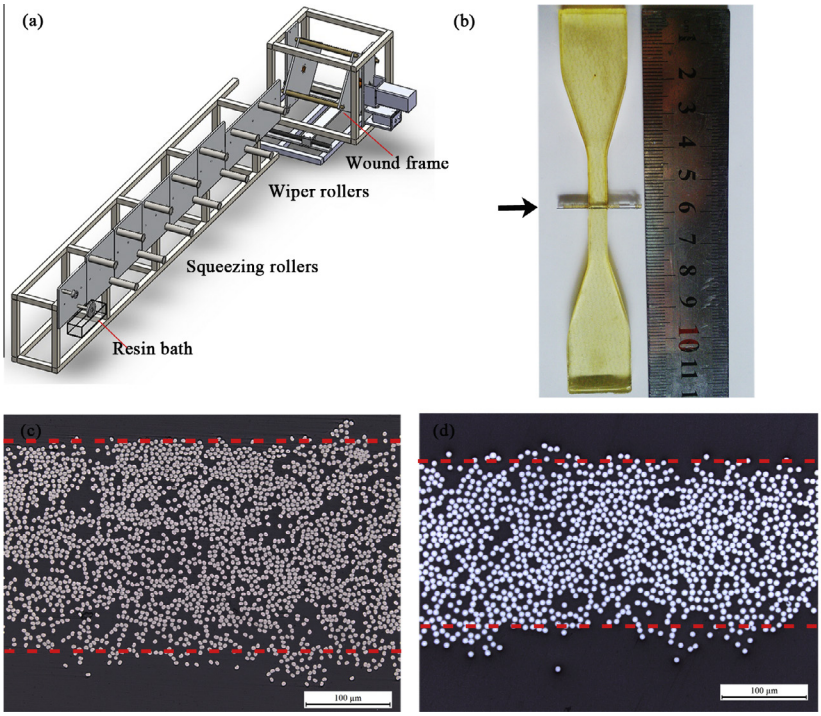

Fig. 1. Automatic impregnation apparatus (a), demolded TFB specimen (b) and optical microscopy photos for T800H/epoxy (c) and T700S/epoxy (d) TFB samples.