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A new approach to assessing carbon fiber/epoxy interfacial shear strength by tensile test of 45° fiber bundle composites: Experiment, modeling and applicability

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ABSTRACT

This work concentrates on the assessment of carbon fiber/epoxy interfacial shear strength by 45° fiber bundle tensile (45FBT) test. The 45FBT samples for three different carbon fiber/epoxy systems were prepared and tested. The multiscale model based on the generalized methods of cells (GMC) was established to simulate the tensile damage process and analyze the interfacial stress state. The interfacial shear strength in 45FBT specimen was calculated. The 45FBT test was compared with the transverse fiber bundle tensile (TFBT) test. The applicability of the 45FBT test was finally discussed.

1. Introduction

The fiber/matrix interface is a vital region which determines, to a great extent, the ultimate strength of the fiber reinforced composites. A growing body of experimental evidence indicates the existence of a three dimensional interphase between the fiber and bulk matrix [1–3]. Though the composition, the structure and the state of stress are complex in the interphase, characterization of interfacial adhesion strength seems to attract the most extensive attention [4]. The assessment of interfacial strength are usually based on the mechanical test of the single filament/resin specimens, i.e., Micro-indentation, fiber pull-out, fiber fragmentation and micro-bond tests have been extensively used in the past few decades [5]. In these testing approaches, the interfacial damage is dominated by longitudinal shear loading and the interfacial shear strength (ISS) can be determined.

Recently, the transverse fiber bundle tensile (TFBT) test has been successfully utilized to estimate the fiber/matrix bonding strength under different interfacial modification conditions [6–11]. Since the failure mechanisms during the tensile procedure of TFBT specimens are much more intricate than the single fiber interfacial tests, many models are created to investigate what is really measured in the TFBT test [11–13]. Higher stress concentration in the normal direction occurs at the interphase. The interfacial normal strength (INS) can be evaluated by the combination of the experimental with analytical results.

It is worth noting that in the TFBT test, the fiber bundle instead of the filament with a diameter of 5–7 μm carefully picked from the fiber tows in the single fiber interfacial tests are directly utilized to prepare TFBT samples, which results in a lower degree of scatter between the experimental values [10]. Besides, the actual distribution of the reinforcing fibers in the matrix can be considered in the TFBT test [12]. The interfacial strength determined from TFBT test should be closer to the interfacial stress state of composite structural level in comparison with the single filament/resin interfacial test.

As a result of the advantages mentioned above, the 45° fiber bundle tensile (45FBT) test was firstly proposed to bridge the assessment of interfacial shear strength and fiber bundle test approach in this work. Like the off-axial tensile test of unidirectional composite, the tensile strength of 45FBT specimen should be more sensitive to the interfacial shear stress. The interfacial shear strength could be assessed in a simpler way by 45FBT test than single fiber interfacial shear test.

Hence, this work aims at evaluating the fiber/matrix interfacial shear strength via 45FBT test. The 45FBT specimens were

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previously prepared with carbon fiber bundles and epoxy resin. The tensile test was conducted and the fracture surfaces were observed. Subsequently, the multiscale model comprised of macro finite element (FE) model and micromechanics model was built to depict the tensile process of the 45FBT specimen. The damage process was simulated based on the failure criteria of fiber, matrix and interphase. The micro interfacial shear stress was compared with interfacial normal and tangential stresses. The fiber/matrix interfacial shear strength was determined by the combination of experimental with analytical results. Eventually, a comparison was made between the 45FBT test and TFBT test. The applicability of 45FBT test approach was discussed.

2. Experimental

2.1. Materials and specimen preparation

The originally received commercial carbon fiber bundles Toray T700S, T800H and T800S were used in the experiment. The epoxy resin was diglycidyl ether of bisphenol A (DGEBA) (WSR618, Wuxi Bluestar Chemical Company) with an epoxide equivalent weight of 185–192 g/eq. The curing agent was JEFFAMINE® D400 polyetheramine purchased from Hustman Corporation with an amine hydrogen equivalent weight of 115 g/eq.

The manufacturing process of the 45FBT specimen was very similar to that of the TFBT sample. A 45° narrow slit was previously cut in the dumbbell shaped mold. The carbon fiber bundle was cut off and then placed in the slit. In order to keep the fiber stretched, both ends of the fiber bundle were fixed to the mold. Then the DGEBA resin was mixed with D400 curing agent. After degassing for 20 min, the resin was poured into the mold. The mold was put under the temperature of 50 °C and vacuum condition for 4 h, which allowed the fiber bundle to be adequately impregnated with the resin in a relatively lower viscosity state before gelation and ensure no air bubbles were left in the specimen. Finally, the fiber bundle and epoxy resin were cured in 3 steps: 75 °C for 2 h, 110 °C for 2 h and 150 °C for 2 h. After the curing process, the 45FBT samples were gingerly demolded (Fig. 1 (a)) and grinded to remove excess resin in the specimen thickness direction. For the purpose of making a contrast, the TFBT samples were also prepared. Since TFBT test was conducted to evaluate interfacial bonding of T700S/epoxy and T800H/epoxy material system in Ref. [13], only T800S TFBT specimens were prepared for testing in this experiment.

Fig. 1 (b), (c) and (d) display the metallographic photos taken in the direction of red arrow in Fig. 1 (a) for T700S, T800H and T800S 45FBT specimens respectively. The oblique section shape of T700S carbon fiber with a circular cross section becomes elliptical. The T800H and T800S carbon fibers are in a 'kidney' shape. The width of the fiber bundle region between the dot lines ranges from 0.25 to 0.35 mm. The carbon fibers distributes more or less uniformly in the fiber bundle section. The average fiber volume fraction V_f can be estimated by the area ratio of the fibers to the whole fiber bundle region based on the examination of 4 samples for each 45FBT specimen. The average V_f values are 61%, 52% and 56% for T700S, T800H and T800S 45FBT samples respectively.

2.2. Test and observation

The tensile tests were conducted on a universal machine (Instron 5565). The tensile force was measured by a load cell with a capacity of 5 kN. The crosshead speed was 1 mm/min. At least 8 effective data of ultimate tensile strength were obtained for each 45FBT specimen. The tensile strength σ_{45FBT} was obtained through dividing the maximum tensile load by the area of the specimen gauge cross section. After the tensile test, the fracture surfaces of 45FBT specimens were observed using the SEM (CamScan JEOL 6010) to explore the failure mechanisms.

3. Analysis

3.1. Macroscopic model

In the present analysis, the macroscopic structural level for 45FBC was discretized by the commercial FE software Abaqus/Standard 6.10. As shown in Fig. 2 (a), the macro model was comprised of the homogenized fiber bundle composite layer with a thickness of 0.3 mm and the epoxy matrix. Apart from the global coordinate system (***XYZ***), a local coordinate system (***123***) was created and assigned to the composite lamina. ***1***, ***2*** and ***3*** represented the fiber longitudinal direction, the transverse direction and the through-the-thickness direction respectively.

The eight-node linear reduced solid elements (C3D8R) were employed in the FE model. Three mesh densities of 800 ($20 \times 10 \times 4$), 3200 ($40 \times 10 \times 8$) and 6400 ($80 \times 10 \times 8$) elements were compared for the composite layer. The results showed that 3200 elements were enough to give accurate local stress and strain distribution. Thus 3200 elements were utilized to mesh the fiber bundle region and 4059 ($41 \times 11 \times 9$) nodes were involved in the thin fiber bundle layer.

One parallel end of the matrix was constrained in ***OY*** direction as the boundary condition while the displacement $\boldsymbol{u_y}$ was applied at the other parallel end to simulate the tensile loading. Besides, it was concluded in Refs. [11] and [12] that the thermal residual stress has a non-negligible influence on ultimate tensile strength of TFBT sample. The residual stress was mainly attributed to the mismatch of the coefficients of thermal expansion α of the carbon fiber and DGEBA/D400 resin [13]. Thus, before the step of tensile loading, the step of thermal cooling from the glass transition temperature (50 °C) to the ambient temperature (20 °C) was also created to calculate the initial thermal stress of the 45FBT specimen.

3.2. Micromechanics model

The micromechanics model based on the Generalized Method of Cells (GMC) [14] was written in a FORTRAN code as the user-defined subroutine of the macro FE model. As shown in Fig. 2 (b), the representative unit cell was partitioned into $N_\beta \times N_\gamma$ subcells in the GMC model. Based on the assumptions of volume homogenization, traction continuity and displacement continuity, the subcell stress $\boldsymbol{\sigma}^{(\beta\gamma)} = \{\sigma_1^{(\beta\gamma)}, \sigma_2^{(\beta\gamma)}, \sigma_3^{(\beta\gamma)}, \sigma_{12}^{(\beta\gamma)}, \sigma_{13}^{(\beta\gamma)}, \sigma_{23}^{(\beta\gamma)}\}$ can be determined by the unit cell overall strain $\boldsymbol{\varepsilon} = \{\varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_{12}, \varepsilon_{13}, \varepsilon_{23}\}$ and the subcell compliance $\mathbf{S}^{(\beta\gamma)} = \{S_{11}^{(\beta\gamma)}, S_{22}^{(\beta\gamma)}, S_{33}^{(\beta\gamma)}, S_{12}^{(\beta\gamma)}, S_{13}^{(\beta\gamma)}, S_{23}^{(\beta\gamma)}\}$. The subcell normal stress $\{\boldsymbol{\sigma}_2, \boldsymbol{\sigma}_3\}$ can be expressed mathematically as

$$\begin{bmatrix} \mathbf{A} & \mathbf{B} \\ \mathbf{B}' & \mathbf{D} \end{bmatrix} \begin{bmatrix} \boldsymbol{\sigma}_2 \\ \boldsymbol{\sigma}_3 \end{bmatrix} = \begin{Bmatrix} \mathbf{c} \\ \mathbf{e} \end{Bmatrix} \varepsilon_1 + \begin{Bmatrix} \mathbf{H} \\ 0 \end{Bmatrix} \varepsilon_2 + \begin{Bmatrix} 0 \\ \mathbf{L} \end{Bmatrix} \varepsilon_3 \tag{1}$$

where $\boldsymbol{\sigma}_2 = [\sigma_2^{(1)}, \sigma_2^{(2)}, \cdots, \sigma_2^{(N_\gamma)}]$ and $\boldsymbol{\sigma}_3 = [\sigma_3^{(1)}, \sigma_3^{(2)}, \cdots, \sigma_3^{(N_\beta)}]$ contain N_γ and N_β unknown normal stresses in the individual columns and rows of the unit cell, respectively; **A**, **B**, **B′**, **D**, **c**, **e**, **H** and **L** are $N_\gamma \times N_\gamma$, $N_\gamma \times N_\beta$, $N_\beta \times N_\gamma$, $N_\beta \times N_\beta$, $N_\gamma \times 1$, $N_\beta \times 1$, $N_\gamma \times 1$ and $N_\beta \times 1$ vectors respectively, whose elements can be expressed in term of subcell dimension and compliance.

Based on the results of subcell normal stress $\sigma_2^{(\beta\gamma)}$ and $\sigma_3^{(\beta\gamma)}$, the subcell normal stress in the longitudinal direction $\sigma_1^{(\beta\gamma)}$ can be calculated as