Predicting the Stiffness of Biaxial Braided Fiber Composites by Incorporation of Carbon Nano Fiber

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Received: April 2016 Accepted: April 2017

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DOI: 10.22068/ijmse.14.2.53

Abstract: *In this study, carbon nano fibers (CNFs) were mixed into epoxy resin through a magnetic stirrer and again mixed using ultra sonicator. Using hand layup technique, biaxial braided fiber composites were prepared with unfilled, 0.2, 0.5 and 1 wt% CNF. Tensile test and shear test were performed to identify the tensile strength and shear strength of the composites. Fractured surface of the tensile specimens were examined by scanning electron microscopy to identify morphologies of nanoparticles. A discrete three layer model was developed for prediction of the tensile modulus and shear modulus of biaxial braided fiber composites. Theoretical and experimental values were compared. The experimental and theoretical results show that the addition of CNF in the epoxy matrix had significant influences on the mechanical properties of biaxial carbon braided fiber composites. CNF inclusion with braided composite promoted the tensile modulus, tensile strength, shear modulus and shear strength up to 0.5wt% of the biaxial carbon braided fiber composites.*

Keywords: *Biaxial braid, CNF, Mechanical properties, stiffness.*

1. INTRODUCTION

Fiber reinforced plastic composites with braid performs posses light weight, improved delamination resistance, strength, stiffness and mechanical properties, compared to conventional type composites. They have played numerous roles in aerospace, marine, sports, biomedical engineering etc. The mechanical properties of braided composites became important to design and fabrication for such applications. Numerical analyses that can accurately model the braided composites are needed for better designing of structural composites. Keeping this in mind, many researchers have studied and tried to predict the stiffness properties of braided composites. Tao Zeng et al [1] were calculated the Young's modulus and Poisson's ratio of 3D braided composites using homogenization theorem. Shunjun et al [2] were carried out micromechanics based study on a series of single and multiple representative unit cell 3-D FE models and predict the compressive strength of 2D triaxial braided carbon fiber polymer matrix composites. Shawn et al [3] were described a model for predicting the energy absorption characteristics of triaxially braided composites tubes. Cui and Yu [4] were presented two-scale method for identifying the mechanics parameters such as stiffness and strength of composite materials. Xiang and Zhi [5] were suggested a micromacromechanical model of unit cells to analyze the dynamic response of 3D-Braided rectangular plates. Anthony et al [6] were presented a macro-cell analytical model to study the piecewise stiffness distribution and then transformed to give global stiffness properties. With the help of the above approaches, a new model has been developed to predict the stiffness and strength of biaxial braided fiber composites by incorporation of carbon nano fiber (CNF).

Polymer matrix composites with CNF reinforcement have become very admired in structural applications because of its excellent mechanical properties. The benefits of CNF reinforcement in polymer matrix composites are apparent in the form of increased stiffness, strength and so on. CNF has attracted much research interests and are widely used for dispersion in epoxy resin due to the high strength and the larger interface of the polymer- CNF interactions. Momchil et al [7] were showed that addition of 0.25wt% carbon nano fibers results in improvement in tensile modulus and strength compared to syntactic foam compositions that did not contain CNF. Yuanxin et al [8] were infused CNF into diglycidylether of bisphenol A and observed that 22.3% improvement in flexural strength of nano composite. Lan et al [9] were provided an in depth study of mechanical behaviors of CNF/epoxy nanocomposites with various contents of CNFs. Mechanical properties of biaxial braided carbon fiber composite with TiO_2 could be effectively adjusted by adding nanoparticle in different percentage [10]. The current improvements in the fabrication techniques ans sympathetic of their mechanical behaviors contribute to the increasing popularity of braided materials [11]. A mechanical property such as impact strength, hardness and double shear of biaxial braided carbon composite with TiO_2 was improved [12].

However, there are few literatures on the mechanical properties of braided fiber/ epoxy laminates. The purpose of the present work is to develop a numerical model for analyzing the stiffness and strength of braided carbon fiber composites with an amount of unfilled, 0.2wt%, 0.5wt% and 1wt% CNFs. The Tensile strength of braided carbon fiber composites with an amount of unfilled, 0.2wt%, 0.5wt% and 1wt% CNFs were investigated. SEM image was examined for the tensile specimen to identify the morphologies of nanoparticles. Then the experimental results are compared with the predicted stiffness behavior.

2. ANALYTICAL MODEL

In this paper, a new model has been introduced for calculation of the stiffness and strength of braided carbon fiber composites with an amount of unfilled, 0.2wt%, 0.5wt% and 1wt% of CNF. The composite properties of a unit cell have been studied. The unit cell consists of two layers for the bias yarns which are aligned in ±45o and a matrix with different percentage of CNF.

The mechanical properties of each layer were calculated by rule of mixture.

$$V_f+V_e+V_h+V_n=1 \tag{1}$$

$$E_{11}=E_{11f}V_f+E_eV_e+E_hV_h+E_nV_n \tag{2}$$

$$E_{22}=1/((V_f/E_{22f})+(V_e/E_e)+(V_h/E_h)+(V_n/E_n)) \tag{3}$$

$$\upsilon_{12}=\upsilon_{12f}xV_f+\upsilon_exV_e+\upsilon_hxV_h+\upsilon_nxV_n \tag{4}$$

$$G_{12}=G_{12f}xG_e+G_{12f}xG_h+G_{12f}xG_n/(G_{12f}xV_e+G_{12f}xV_h+G_{12f}xV_n+G_exV_f+G_hxV_f+G_nxV_f) \tag{5}$$

$$\upsilon_{23}=\upsilon_{12}=\upsilon_{13} \tag{6}$$

$$G_{23}=E_{22}/2x(1+\upsilon_{23}) \tag{7}$$

In above formulae, Indices f, e, h and n represent fibre, epoxy, hardener and nanoclay respectively, E_{11} - longitudinal modulus, E_{22} - transverse modulus, υ_{12} - longitudinal poisson's ratio, υ_{23} - transverse poisson's ratio, G_{12} - axial shear modulus and G_{23} - transverse shear modulus.

The stiffness matrix (C_{ij}) can be calculated by considering each composite layer made of transversely isotropic material [13].

$$Cij=\begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \tag{8}$$

where,

$$C_{11}=(1-(\upsilon_{23})^2)E_{11}/V \tag{9}$$

$$C_{12}=C_{13}=\upsilon_{12}(1+\upsilon_{23})E_{22}/V \tag{10}$$

[DOI: 10.22068/ijmse.14.2.53]

$$C_{23} = (\upsilon_{23}+((\upsilon_{12})^2 x E_{22}/E_{11}))E_{22}/V \quad (11)$$

$$C_{22} = C_{33} = (1-((\upsilon_{12})^2 x E_{22}/E_{11}))\, E_{22}/V \quad (12)$$

$$C_{44}=G_{23}=E_{22}/(2+2\upsilon_{23}) \quad (13)$$

$$C_{55}=C_{66}=G_{12} \quad (14)$$

where

$$V= [(1+ \upsilon_{23})(1- \upsilon_{23}-2((\upsilon_{12})^2 x E_{22}/E_{11})] \quad (15)$$

The braider angle transformation is given by: [14]

$$T_1=\begin{bmatrix} \cos\theta^2 & \sin\theta^2 & 0 & 0 & 0 & 2\cos\theta\sin\theta \\ \sin\theta^2 & \cos\theta^2 & 0 & 0 & 0 & -2\cos\theta\sin\theta \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & \cos\theta & -\sin\theta & 0 \\ 0 & 0 & 0 & \sin\theta & \cos\theta & 0 \\ -\cos\theta\sin\theta & \cos\theta\sin\theta & 0 & 0 & 0 & \cos\theta^2-\sin\theta^2 \end{bmatrix} \quad (16)$$

$$T_2=\begin{bmatrix} \cos\theta^2 & \sin\theta^2 & 0 & 0 & 0 & \cos\theta\sin\theta \\ \sin\theta^2 & \cos\theta^2 & 0 & 0 & 0 & -\cos\theta\sin\theta \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & \cos\theta & -\sin\theta & 0 \\ 0 & 0 & 0 & \sin\theta & \cos\theta & 0 \\ -2\cos\theta\sin\theta & 2\cos\theta\sin\theta & 0 & 0 & 0 & \cos\theta^2-\sin\theta^2 \end{bmatrix} \quad (17)$$

The stress-strain relation in the global stiffness axes is given as: [15]

$$\{\sigma\} = [T_1]^{-1}\, [C_{ij}]\, [T_2]\, \{e\} \quad (18)$$

Thus, the stiffness matrix of a unit cell in the global coordinate system can be written as:

$$[C]=t^{+\theta}\, [C_{global}]^{+\theta} + t^{-\theta}\, [C_{global}]^{-\theta} \quad (19)$$

where $t^{+\theta}$, $t^{-\theta}$ are specified as the thickness of each layer to the thickness of the laminate. The thicknesses are assumed to be identical.

Then, the compliance matrix is calculated by inverting the stiffness matrix of a unit cell in Eq. (19):

$$[S]=[C]^{-1} \quad (20)$$

The engineering constants of braided composites can be written as: [16]

$$E_x = 1/S_{11},\ E_y = 1/S_{22},\ E_z = 1/S_{33}$$

$$G_{xy} = 1/S_{66},\ G_{yz} = 1/S_{44},\ G_{xz} = 1/S_{55}$$

$$\upsilon_{xy} = - S_{12}/S_{11},\ \upsilon_{yz} = -S_{23}/S_{22},\ \upsilon_{zx} = -S_{31}/S_{33}$$

3. EXPERIMENTAL METHODS

3. 1. Materials and Specimen Fabrication

Biaxial braided carbon fiber sleeves with ±45º, 4” dia, 15.1 oz/square yard, 3k fiber tow, from ACP composites were used as reinforcement. Bisphenol-A-Diglycidyl-Ether (DGEBA), known as LY556 were chosen as matrix material. When DGEBA is united with Hardener HY951 and nanoparticles, it gives a solvent free curing system. Carbon nanofibers – pyrolitically stripped platelets (conical). >98% carbon basis, D x L 100nm x 20-200 µm were obtained from Sigma Aldrich. An epoxy resin of LY556 and hardener HY951 are mixed in the weight ratio of 10:1 and used as the matrix material for neat, 0.2wt%, 0.5wt% and 1wt% carbon nanofiber nanoparticles. The epoxy in a glass bowl was heated at 75ºC to lower the viscosity and the CNF was added. Mixing was conducted in the magnetic hot plate stirrer for 4h at 75ºC. The mixture was subjected to sonication using an ultrasonicator at an ultrahigh frequency for 3h to further disperse the CNF while maintaining the resin temperature at 75ºC using a hot water bath. The mixture was followed by addition of HY951 and the mixture was stirred well to avoid the formation of bubbles. Braid composites were fabricated using hand layup technique. It is followed by a press machine for 24 h at room temperature. The composites were put in an oven with a post cure treatment for 1h at 100ºC. 8layers of biaxial fiber were used to get 3mm

[DOI: 10.22068/ijmse.14.2.53]

thickness of composite material.

3. 2. Tensile Test

Tensile test was performed to determine the stiffness and tensile strength of braided carbon fiber composites with an amount of unfilled, 0.2wt%, 0.5wt% and 1wt% of CNF. A Universal Testing Machine with a gear ratio speed of 2.5mm/min was used to load the specimen, consistent with ASTM D638. The specimens were cut in the dog bone shape with the dimension of 165 x 12.7 x 3mm and gauge length 57mm with radius of 25mm.

3. 3. Double Shear Tests

The double shear strength and shear modulus of the braided composites were measured using Universal Testing Machine according to the ASTM standard method 5616M. The composite specimens with dimensions of 45 x 10 x 3mm were tested. The shear properties were calculated from the tests result. It is compared with theoretical results.

3. 4. Dispersion of CNFs

The dispersion of CNFs was evaluated using Hitachi s3400 scanning electron microscope. To investigate the dispersion of CNFs and to achieve a deeper understanding of the change in microstructure due to CNFs infusion, broken region of tensile specimen was cut with dimension of 10 x 10 mm. The broken surface was observed with the Hitachi s3400 SEM equipment.

4. RESULTS AND DISCUSSIONS

4. 1. Tensile Properties

The tensile modulus and tensile strength from the experiment are presented in Fig. 1 (a) and (b). The stiffness and the tensile strength of the composites were increased by the addition of CNFs up to 0.5wt%. The reason seems that CNFs have high stiffness, strength and bridging effect. However, the stiffness and the tensile strength of the composites were decreased by the addition of CNFs in 1wt%. The reason seems that 1wt% of CNFs were not mixed enough with epoxy resin and forms agglomeration. This shows that high percentage of CNF loading is difficult in the mixing of resin. Due to the above reason, loads were not successfully transferred to the composite material during loading and each ply was fractured individually. The fracture surface of the tensile test specimens are shown in the fig. 2. Fig. 2a indicates the brittle fracture mechanism of neat epoxy resin with biaxial carbon fiber composite. Breakages of fiber were the important failure mode. At tensile strength of 0.103 GPa of neat specimen, fiber breakage was observed vigorously and delamination was also occured. Fig. 2b and 2c composite specimen except 1wt% (fig. 2d) shows improved tensile properties. At tensile strength of 0.245 GPa and 0.269 GPa of 0.2wt% and 0.5wt% composite, the damage of the composite shows ductile nature of the specimen. The significant reduction of 1wt% composite in both failure strength and modulus is linked with a poor dispersion of the high content

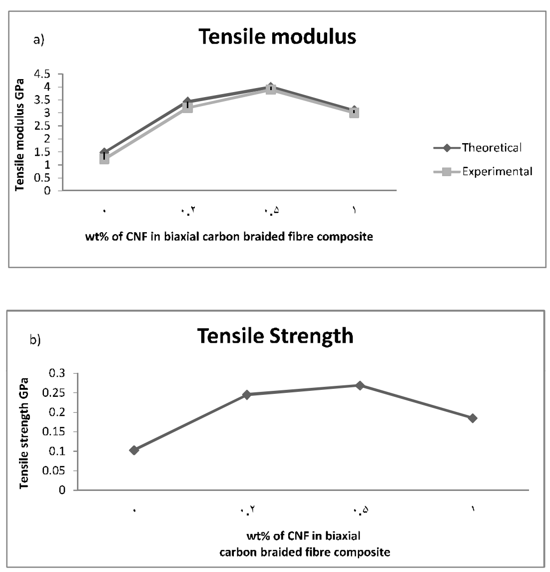

Fig. 1. a) Tensile modulus (stiffness) variation with different wt% of CNF in biaxial carbon fibre composites. b) Tensile strength variation with different wt% of CNF in biaxial carbon fibre composites.

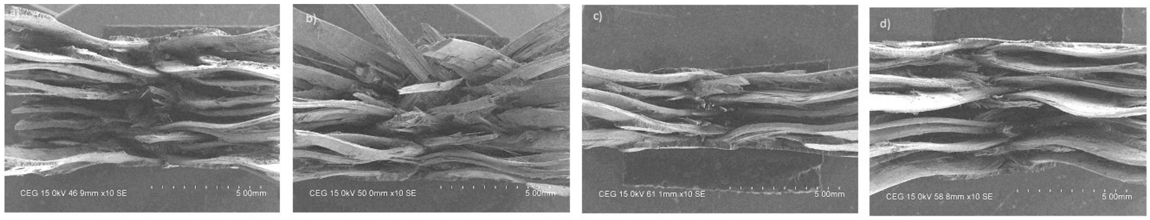

Fig. 2. The fracture surface of the tensile test specimens with a) neat, b) 0.2wt%, c) 0.5wt% and d) 1wt% of CNF in biaxial carbon fibre composites respectively.

level of CNF in the resin shown in Fig. 2d. At tensile strength of 0.185 GPa of 1wt% composite, resin crack and fiber breakage were more. It was observed that an increased viscosity of epoxy due to the addition of high content of CNF made degassing complicate. This allows small void formation and also poor dispersion, agglomeration in the epoxy matrix. Large delamination was observed in the 1wt% of CNFs dispersed composites comparing to the neat, 0.2wt% and 0.5wt%. The reason seems that the CNFs in the composites were aligned in the in-plane direction and it reduced the strength and toughness.

4. 2. Shear Properties

The shear modulus and the shear strength from the experiment are shown in Fig. 3 (a) and (b). The basic parameters affected the shear strength of a quality biaxial carbon braided composite are maximum shear stresses sustainable in the fiber, in the matrix and at the interface. The measured shear modulus and shear strength is agreed well with the predicted. The shear modulus and the shear strength of the composite were increased by the addition of CNFs up to 0.5wt%. The reason seams that proper alignment of biaxial braided fibre and very low void formation during the mixing process. However, the shear modulus and the shear strength of the composites were decreased by the addition of CNFs in 1wt%. The reason seems that 1wt% of CNF were not mixed proper in the epoxy resin and large voids formation by the air trapped adjacent to fibre on the surface of a laminae.

4. 3. Comparison of Tensile Modulus and Shear Modulus with Experimental

The geometrical properties of the biaxial carbon fiber, epoxy resin, hardener and CNF are listed in tables 1 and 2. Table 3 shows the volume fraction of neat, 0.2wt%, 0.5wt% and 1wt% of CNF which is used to predict the tensile modulus and the shear modulus. The geometrical values and volume fractions are applied in the new model to predict the tensile modulus and shear modulus of the composite material. Fig. 1a and 3a are compared the theoretical and experimental

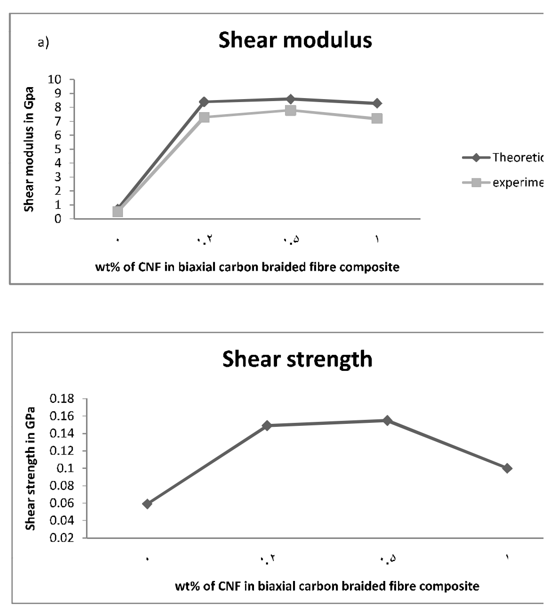

Fig. 3. a) Shear modulus variation with different wt% of CNF in biaxial carbon fibre composites. b) Shear strength variation with different wt% of CNF in biaxial carbon fibre composites.

[DOI: 10.22068/ijmse.14.2.53]

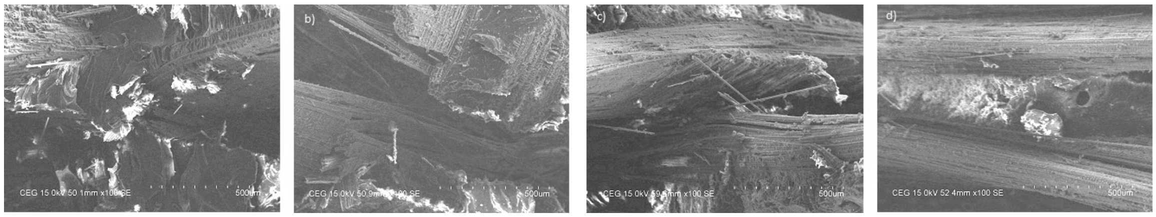

Fig. 4. SEM image a) neat, b) 0.2wt%, c) 0.5wt% and d) 1wt% of CNF in biaxial carbon fibre composites respectively.

results of tensile modulus (stiffness) and shear modulus (stiffness) respectively. The results obtained from the theoretical are nearly in accord with experimental results. The simplicity of this method makes it valid option to predict the stiffness of the composite.

4. 4. SEM Analysis

Scanning electron microscopy image is used to observe neat and dispersion of CNF as shown in Fig. 4. It is quite clear that neat epoxy resin biaxial braided composite shows brittle fracture surface compared to that of the CNF biaxial braided composites. It can be noticed that an ultrasonication at an ultrahigh frequency for 3h led to disperse the CNF uniformly. Only a very few clusters or agglomerations were present in the dispersion of 0.2wt% and 0.5wt% of CNF as shown in fig. 4b and 4c. This shows that the dispersion of the CNF in the epoxy resin is more uniform. But when CNF content is 1wt%, large agglomerations were visible as shown in fig. 4d. The agglomeration can be severe for 1wt% CNF contents due to the reduction of interparticle distances between CNF. As the amount of nanoparticles increases, the inertia of the CNF particles to form agglomeration is also increases. The lack of distribution of CNF is unsettled to that of the epoxy resin and fails to provide proper adhesive force to the fibers. The lower strength could be caused by the formation of CNF agglomeration, poor dispersion and void formation during blending at the high CNF content level. And also, due to lower degree of nanoparticles polymer interaction at higher filler contents. Due to this, interfacial debonding causes during tensile testing and reducing the tensile strength of 1wt% of CNF composite.

5. CONCLUSION

In this paper, the effective tensile modulus (stiffness) and shear modulus are deduced theoretically based on the present model. The effects of CNF loading on the biaxial carbon braided fibre are investigated. The theoretical calculation results are compared to experimental method and excellent results are obtained. The theoretical prediction of the present model shows a good agreement with the experimental data. The different percentage of CNF loading has signicant influences on the stiffness and strength of biaxial carbon braided fibre composites. The stiffness and strength properties in 1wt% were lower than that neat, 0.2wt% and 0.5wt%. This shows that uniform CNF distribution was not easy at high CNF loading. The inclusion of higher CNF (1wt %) content declined the mechanical properties and difficult to disperse, major clustering and entanglement are observed in the SEM images. Moreover, CNF inclusion with braided composite promoted the tensile modulus, tensile strength, shear modulus and shear strength up to 0.5wt% of the biaxial carbon braided fiber composites.

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[DOI: 10.22068/ijmse.14.2.53]