CFRTP MECHANICAL PROPERTIES SIMULATION BY MORI-TANAKA MODEL AND EQUIVALENT LAMINATE METHOD

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Abstract

Precise simulation of mechanical properties of carbon fiber reinforced thermoplastics (CFRTP) is very important for industrial mass applications. The present work proposes two different simulation approaches to calculate the tensile properties of a randomly oriented strands (ROS) made by water dispersed thin CF/PA6 prepreg tapes (named UT-CTT in this study). One method is the general homogenization Mori-Tanaka model, another one is the de-homogenization equivalent laminate method. To ensure the simulation accuracy, internal structural properties of the material also being studied by X-ray μ-CT and being input to the simulation models. The UT-CTT show outstanding tensile properties as a ROS, and the tensile strength increase with the increase of tape length. The comparison between the simulation results and experimental results indicated that the Mori-Tanaka model have better simulation accuracy in tensile moduli than equivalent laminate method because the continuous laminate overestimating the moduli of discontinuous systems. On the other hand, the Mori-Tanaka mode cannot reproduce the strength-tape length relationship because it neglected the effect of structural irregularity like tape waviness.

1. Introduction

Carbon fiber reinforced thermoplastics (CFRTP) are being used in many automotive applications. The arising CFRTP manufacturing technics are regarded can shorten the production cycle time and saving cost. CFRTP formed with randomly oriented strands (ROS) attracting attentions from both the researchers and engineers because of the high mechanical performance, superior molding ability as well as the good in-plant recycle capability. However, the expanded use of ROS is limited because the computational tools available for industry now are unable to predict the material properties and the manufacturing processes with sufficient accuracy to ensure the reliability and safety for mass applications.

To predict the mechanical properties of CFRTP, especially in the discontinuous reinforcement group like ROS, homogenization methods, e.g. Mori-Tanaka model [1] often be adopted because they can simplify the complex internal geometry of ROS and have considerable computational efficiency. However, the predict accuracy of homogenization methods decrease significantly with the increase of reinforcement volume fraction and aspect ratio which can increase the structural complexity of the material. Recently, a method named de-homogenization was developed and show better prediction accuracy for discontinuous CFRTP. The equivalent laminate method is one famous de-homogenization method, this method regard the ROS as continuous fiber laminates with equivalent orientation distribution [2, 3]. The difference between the modeling processes of homogenization methods and de-homogenization methods is illustrated in Fig .1.

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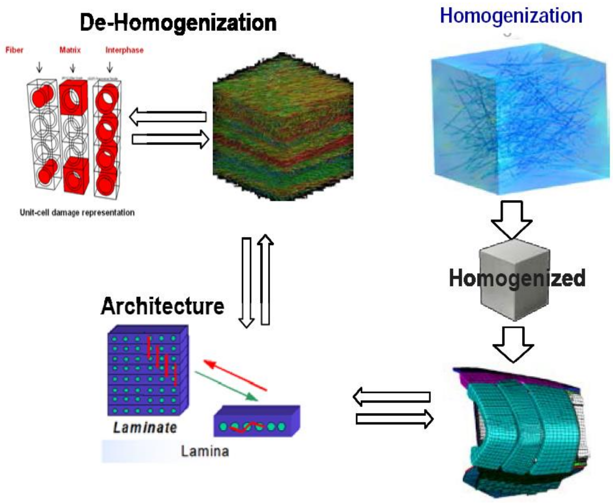

Figure 1. Modeling processes of homogenization and de-homogenization methods [4].

In present study, one kind of ROS made by water-dispersion method was prepared. The tensile and internal structural properties were studied by experiments. Both the general homogenization Mori-Tanaka model and the de-homogenization equivalent laminate method were adopted in this study to simulate the tensile properties and the comparison with experimental values were discussed.

2. Materials and Processes

2.1. Materials

The UT-CTT (ultra-thin chopped carbon fiber tape reinforced thermoplastics), which is a kind of ROS made by water dispersed thin tapes. The UT-CTT is composed of randomly oriented UT-tape (ultra-thin unidirectional prepreg tape). Spread carbon fiber tow (TR 50S, Mitsubishi Rayon Co., LTD.) and Polyamid-6 (PA6, DIAMIRON™ C, Mitsubishi Plastics, Inc.) are used to manufacture this tape. The thin tape thickness (45 μm in average) bring significant scale effect on this material thus the UT-CTT show outstanding mechanical performances. The UT-tapes used in this study are provided by the Industrial Technology Center of Fukui Prefecture and are cut to 5 mm in width and 12 mm, 18 mm, 24 mm and 30 mm separately in length (Fig. 2). The fiber volume fraction (V_f) of UT-CTT is 55% in average and the V_f of UT-CTT in each tape length was measured in detail. Wet-type paper making process was adopted in present research to make the intermediate UT-tape sheets to ensure better tape distribution as well as to diminish structural defects like deformation of tapes and misalignments. The UT-tape sheets are then been dried by vacuum dryer and UT-CTT panels are manufactured under compression molding. The molding pressure is 5 MPa and molding temperature is 270 ℃ on the mold.

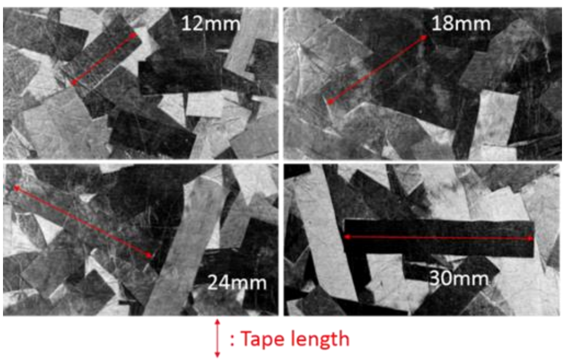

Figure 2. UT-CTT with different tape lengths.

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2.2. Experiments

The V_f of UT-CTT in different tape lengths were measured firstly. The ash test were applied as to calculate the V_f by compare the density and weight change before and after the resin was burned out.

Tensile properties of UT-CTT were verified by experiments. The specimens were cut into 2 mm* 30 mm * 180 mm, and the tensile experiments were conducted using universal test machine with loading speed 5 mm/min. the strains were measured by extensometer and the tensile strengths were measured as the maximum stress until final fracture occurred.

To obtain the elastoplastic performance of the matrix resin, the tensile tests of PA6 used in this study were also conducted. Because The the testing standard JIS K 7113 was applied. After the stress-strain curve of PA6 was obtained, the non-linear part was fitted by the J_2-plasticity model:

$$\sigma_{eq} = \begin{cases} \boldsymbol{C}:\epsilon^e & J_2(\sigma) \leq \sigma_Y \\ \sigma_Y + kp + R_\infty[1 - e^{-mp}] & J_2(\sigma) > \sigma_Y \end{cases} \quad (1)$$

where $J_2(\sigma)$ is the von Mises equivalent stress; σ_{eq} and σ_Y denote the equivalent Cauchy stress and the yield stress, respectively; ϵ^e is the elastic strain; $\boldsymbol{C}$ is the Hooke's operator; and *k*, R_∞ and *m* denote the linear hardening modulus, hardening modulus, and hardening exponent, respectively. The parameter *p* represents the accumulated plastic strain and is expressed as:

$$p = \int \sqrt{\frac{2}{3} d\epsilon_{ij}^p d\epsilon_{ij}^p} \quad (2)$$

2.3. Modeling methods

Two different modeling methods were applied in this study. The first one is the general analytical homogenization method for discontinuous inclusions: the modified Mori-Tanaka model [1]. The other one is the de-homogenization method well used on short fiber composites recently: the equivalent laminate method [2, 3].

The general Mori–Tanaka formulation to describe composites with randomly oriented inclusions was presented by Benveniste as follows [1]:

$$\boldsymbol{E}^{MT} = \boldsymbol{E}_m + V_f\{(\boldsymbol{E}_f - \boldsymbol{E}_m):\boldsymbol{T}\}:[V_m\boldsymbol{I} + V_f\{\boldsymbol{T}\}]^{-1} \quad (3)$$

where $\boldsymbol{E}$ denotes the stiffness tensor, and subscripts *m* and *f* represent the matrix and fiber, respectively. The curly bracket {.} stands for orientation averaging. Tensor $\boldsymbol{T}$ is given by:

$$\boldsymbol{To} = [\boldsymbol{I} + \boldsymbol{S}_m:\boldsymbol{E}_m{}^{-1}:(\boldsymbol{E}_f - \boldsymbol{E}_m)]^{-1} \quad (4)$$

where $\boldsymbol{S}_m$ is Eshelby's tensor, when the matrix is infinite media [5].

On the other hand, in the equivalent laminate method, the moduli of single equivalent layer, like E11 (aligned fiber direction), E22 (transverse to aligned direction), G12 (in-plane shear), and G13 (out-of-plane shear) are calculated by modified Mori-Tanaka model provided by Tandon and Weng [4, 6]:

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$$\boldsymbol{E}_{11}^{MT} = \frac{\boldsymbol{E}_m}{\boldsymbol{1} + \frac{c(\boldsymbol{A}_1 + \boldsymbol{2}\nu_m \boldsymbol{A}_2)}{\boldsymbol{A}}} \tag{5}$$

$$\boldsymbol{E}_{22}^{MT} = \frac{\boldsymbol{E}_m}{\boldsymbol{1} + \frac{\boldsymbol{c}}{\boldsymbol{2A}}[-\boldsymbol{2}\boldsymbol{\nu}_m \boldsymbol{A}_3 + (\boldsymbol{1} - \boldsymbol{\nu}_m)\boldsymbol{A}_4 + (\boldsymbol{1} + \boldsymbol{\nu}_m)\boldsymbol{A}_5 \boldsymbol{A}]} \tag{6}$$

$$\mathbf{G}_{12}^{MT} = \mathbf{G}_m + \frac{\mathbf{G}_m \mathbf{c}}{\frac{\mathbf{G}_m}{\mathbf{G}_{p12} - \mathbf{G}_m} + \mathbf{2}(\mathbf{1} - \mathbf{c})\mathbf{S}_{1212}} \tag{7}$$

$$\boldsymbol{G}_{13}^{MT} = \boldsymbol{G}_m + \frac{\boldsymbol{G}_m \boldsymbol{c}}{\frac{\boldsymbol{G}_m}{\boldsymbol{G}_{p13} - \boldsymbol{G}_m} + \boldsymbol{2}(\boldsymbol{1} - \boldsymbol{c})\boldsymbol{S}_{1313}} \tag{8}$$

where $\boldsymbol{A}$ and $\boldsymbol{A}_i$ are constants depending on the components of the Eshelby tensor and the matrix/fiber properties.

After the moduli of single equivalent layer are obtained, the mechanical properties of the equivalent laminate are calculated by the classical laminate theory (CLT). During the processes, the effect of defects are also considered. The fiber waviness is modeled by assuming the waviness to a sign wave, and using the waviness amplitude of the sign wave as the parameter to calculate the effects [7].

In present study, the general Mori-Tanaka model simulation is running in the mean field modeling software Digimat-MF from e-Xstream engineering, while the equivalent laminate method is analyzed by the MCQ (Material Characterization and Qualification) chopped from AlphaStar.

2.4. Structural analysis

In the general Mori-Tanaka model, the definition of aspect ratio is difficult because the inclusion have multi-scale interphase. In this study, we chose the tape as the basic inclusion and calculated the aspect ratio of the tape based on the definition of 3D aspect ratio generally used in FEM (finite element methods) as the following equation [8]:

$$K_{UT-CTT} = \frac{\sqrt{a^2 + b^2 + c^2} * \left(ab + a\sqrt{b^2 + c^2} + b\sqrt{c^2 + a^2} + \sqrt{a^2b^2 + b^2c^2 + c^2a^2}\right)}{2\sqrt{6}abc} \tag{9}$$

where *a*, *b*, and *c* are the tape length, width, and thickness, respectively.

The orientation distribution of the UT-CTT is measured by X-ray μ-CT. The micro structure, in-plane orientation distribution and out-of plane orientation distribution is illustrated in Fig. 3. In addition, the waviness amplitude is calculated as the half value of the standard deviation of out-of-plane misalignment as shown in Fig. 4.

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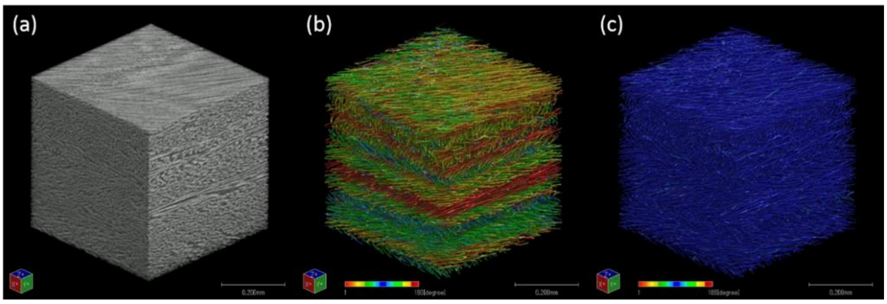

Figure 3. The micro structure (a), in-plane orientation distribution (b) and out-of-plane orientation distribution (c) of UT-CTT

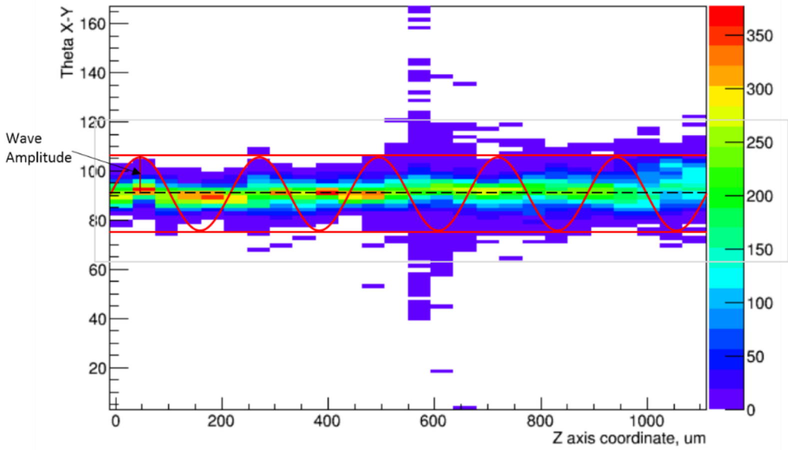

Figure 4. Calculation of the waviness amplitude of UT-CTT. The Color bar is data density; the Theta_XY is the out-of-plane angle.

3. Results and Discussions

The V_f of UT-CTT in different tape lengths calculated by the ash test as well as the equivalent aspect ratio of the tape in general Mori-Tanaka simulation are presented in Table 1. The V_f show subtle difference between each tape length and is regarding caused by the complex interactions during molding processes. The table 1. also indicate the equivalent aspect ratio of the tape is much lower than the aspect ratio of single fiber with same length. Lower aspect ratio will lead to lower mechanical properties in simulation, which support the fact that the multi-scale interphase can generate structural defects in UT-CTT. The mechanical properties of the constituent properties at the fiber and matrix scales are listed in Table 2. and Table 3., respectively.

Table 1. V_f of UT-CTT in different tape lengths.

Tape length (mm)	12	18	24	30
Fiber V_f (%)	52.2	55.1	52.8	53.1
Aspect ratio	212	305	400	497

Table 2. Mechanical properties of the carbon fiber used in this study.

	Young's Modulus E (GPa)	Tensile Strength σ (MPa)	Fracture Strain ε_f (%)	Diameter d (μm)	Density ρ (g/cm^2)
TR 50	240	4900	2.0	7	1.82

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Table 3. Mechanical properties of the matrix used in this study.

	Density ρ(g/cm^2)	Poisson's Ratio v	Young's Modulus E (GPa)	Yield Stress σ_Y (MPa)	Hardening Modulus R_∞ (MPa)	Hardening Exponent m	Linear Hardening Modulus k (MPa)	Equivalent matrix tensile strength σ_m^* (MPa)
PA6	1.14	0.40	3.31	15.0	56	350	160	55

Input the measured data into both the general Mori-Tanaka model and the equivalent laminate model, the simulation results were compared with the experimental values both on moduli and strengths as illustrated in Fig. 5.

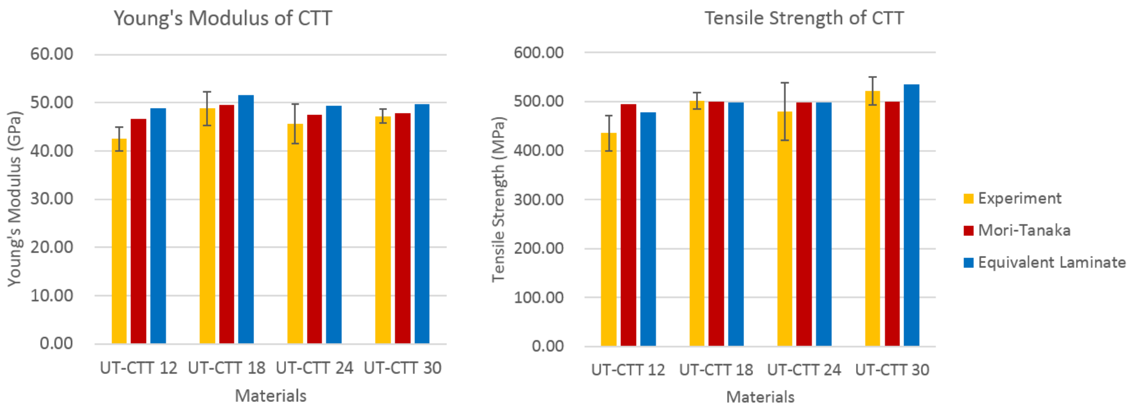

Figure 5. Comparison of tensile properties between experimental results and simulation results.

The experimental results of UT-CTT show high tensile preference compare with general discontinuous CFRTP. Also an increase tendency can be clearly observed in tensile strengths, while although changed can be found in the moduli, but the change of V_f will weaken the change derived from tape length.

The Mori-Tanaka and equivalent laminate simulation both show considerable results comparing with the experimental values. On the other hand, these two methods also show difference in prediction accuracy.

The general Mori-Tanaka model match very good with the experimental values in moduli, the results also predicted the change lead by the change of V_f. While the moduli in equivalent laminate method are higher than the experimental values in all the tape lengths. This result indicate that in prediction of the elastic properties, Mori-Tanaka model can do better job on ROS, and the equivalent laminate method still overestimate the moduli because the method considered the ROS as continuous laminate and the defects as waviness have less effect on the elastic properties.

On the other hand, the Mori-Tanaka model cannot simulate the change of strength caused by the change of tape length but the equivalent laminate method can predict the increase tendency of strength to tape length considerably. The reason of this difference is mainly based on the capability of structural properties definition. In Mori-Tanaka model, only the simple fiber orientation distribution has been considered, while the equivalent laminate method not only counted the fiber orientation, but also considered the defect effects of fiber waviness. Because the internal geometry irregularity have great effect on the fracture propagation of CFRTP, so the equivalent laminate method show better matching with the experimental results.

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4. Conclusions

In this study. The tensile moduli and tensile strengths of UT-CTT in different tape lengths were evaluated both experimentally and analytically. The general homogenization Mori-Tanaka model and de-homogenization equivalent laminate method were used in present research. The results indicated that the Mori-Tanaka model have better simulation accuracy in tensile moduli than the equivalent laminate method because the continuous laminate overestimating the moduli of discontinuous systems. On the other hand, the Mori-Tanaka mode cannot reproduce the strength-tape length relationship because it neglected the effect of structural irregularity like tape waviness.

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