Elastic Properties of Green Composites Reinforced with Ramie Twisted Yarn*

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Abstract

This paper suggests a theoretical model to estimate Young’s modulus of green composites reinforced by natural fiber twisted yarns considering a migration structure. First, we made fully green composites using biodegradable resins and ramie twisted yarns to develop a biodegradable material, and then investigated the effect of yarn twist on mechanical properties of green composites. Next, the migration structure of twisted yarn was taken into account and the relation between twist angle and Young’s modulus was discussed by proposing a new reduced stiffness for twisted yarn, in which a twisted yarn was regarded as an orthotropic material with an off-axis angle. The proposed reduced stiffness was verified through comparison between theoretical and experimental results.

Key words: Green Composites, Ramie Twisted Yarn, Twist Angle, Young’s Modulus, Reduced Stiffness

1. Introduction

In recent years, research and development of materials using biomass sources provide opportunity for a sustainable society. A composite consisting of natural fibers and biodegradable resin, so-called the green composite, is one of the most promising materials in developing biomass products1, 2, 3). Some green composite products have already been put to practical uses4, 5). Although, slivers and short fibers are usually used in the green composites as reinforcement, their properties are lower because of their random structure. Additional improvement of their mechanical properties and understanding of their performance are necessary to apply green composites to use something more widely. Therefore, continuous yarns to reinforcement are being required to achieve high stiffness and strength green composites. It is known that a single yarn is formed by twisting natural fibers which are short and hence, non-continuous. For example, the length of a ramie single fiber is 20-200 mm, and that of a flax single fiber is 20-30 mm. Single fibers are

*Received 1 July, 2010 (No. 10-0279)
[DOI: 10.1299/jmmp.4.1605]
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twisted together to produce continuous yarn such as spun yarns. In the past, the mechanics of spun yarn obtained by twisting single fibers was studied in textile engineering\(^6\). Generally, it has been pointed out that amount of twist plays an important role in yarn properties because twist is essential to hold the fibers together in a spun yarn\(^7\). While this mechanism of twist is commonly studied in textile engineering, it is quite unknown in composite engineering. This is due to the fact that most common composites are untwisted yarns. If such yarn twist dependencies are exhibited in composites, then clarification of mechanical properties consisting of twisted yarns is absolutely imperative in order to promote green composites.

The purpose of this study is to propose a theoretical model to estimate Young’s modulus of green composites reinforced by natural fiber twisted yarns considering a migration structure. At first, the effect of yarn twist on mechanical properties of unidirectional green composites was experimentally explored. Next, a theoretical model expressing the relation between twist angle and Young’s modulus was constructed by assuming the twisted yarn as an orthotropic material with an off-axis angle. Theoretical results were compared to the experiment results.

2. Experiment

2.1 Materials

The reinforcement used in this study is a ramie single yarn (No.16, supplied by TOSCO, Co., Ltd.). Five-twisted yarns were produced from ramie single yarns using a twisting machine. The numbers of twists prepared were 1.5, 3.5 and 6.5 / inch. Twisted yarns of 1.5, 3.5 and 6.5 / inch are denoted as ST, MT and LT, respectively. Morphology of these yarns is shown in Figure 1 and the number of twists, twist angle with yarn axis (LD) and fineness of these fibers are shown in Table 1. In Table 1, SY means a single yarn and it is twistless. Two biodegradable thermoplastic resins, Polylactic acid (PLA) emulsion type resin (CP-1000, Supplied from Miyoshi Oil and Fat Co. Ltd. Japan) and cornstarch based resin film (CPR-F3A, supplied by Nihon Cornstarch Co. Japan) were used as matrix materials for the composites. Both resins decompose easily and naturally in soils. Mechanical properties of these resins are provided in Table 2. These properties were obtained from tensile tests. The strain ratio was 0.01/min and the gauge length was 50 mm.

![Fig. 1 Surface morphology of tree kinds of ramie twisted yarns](image)

Table 1 Twist per inch, twist angle and fineness of ramie twisted yarns

<table>
<thead>
<tr>
<th>Yarn type</th>
<th>Twist per inch (/inch)</th>
<th>Twist angle, $\theta$ (°)</th>
<th>Fineness (tex)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SY</td>
<td>0</td>
<td>0</td>
<td>126</td>
</tr>
<tr>
<td>ST</td>
<td>1.5</td>
<td>13.5</td>
<td>543</td>
</tr>
<tr>
<td>MT</td>
<td>3.5</td>
<td>20.9</td>
<td>575</td>
</tr>
<tr>
<td>LT</td>
<td>6.5</td>
<td>41.8</td>
<td>590</td>
</tr>
</tbody>
</table>

Table 2 Mechanical properties of CPR and PLA resins

<table>
<thead>
<tr>
<th></th>
<th>Young's modulus (GPa)</th>
<th>Tensile strength (MPa)</th>
<th>Fracture strain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPR</td>
<td>0.46</td>
<td>17.0</td>
<td>80</td>
</tr>
<tr>
<td>PLA</td>
<td>3.76</td>
<td>28.4</td>
<td>2.0</td>
</tr>
</tbody>
</table>

2.2 Fabrication methods

In the case of PLA resin, ramie yarns were wound around a thin metallic plate, and the PLA resin was pasted onto yarns and dried. Composite specimens were fabricated by applying a pressure of 2.34 MPa at 150°C for 5 min using a compression molding equipment. After 5 min, it was cooled down to near room temperature while maintaining the same pressure. In order to make CPR composites, first, ramie yarns were wound around a thin metallic plate. Next, the yarns were sandwiched between CPR films and hot pressed using the same method used for PLA composites.

2.3 Tensile test

Tensile specimens were cut off from fabricated composites. The longitudinal length along the yarn axis was 100 mm, and their width and thickness were 15 mm and 1 mm, respectively. The gauge length was 50 mm. GFRP tabs were attached with epoxy adhesive on both ends of the composite specimens. A strain gauge was attached at the center of the specimen surface to measure uniaxial strain along the longitudinal direction. Tensile tests of specimens were performed using an Instron-type testing machine (Autograph IS-5000, Shimadzu Co. Ltd., Japan) at room temperature. The tensile speed was 0.5 mm/min to give a strain rate of 0.01/min.

3. Results and discussion

3.1 Relation between mechanical properties and twist angle

Table 3 shows tensile test results for composites. In this table, SY is twistless (zero twist angle), while LT has the largest twist angle with the yarn axis. The data clearly indicate that the normalized Young’s moduli ($E/V_f$) of CPR and PLA composites decrease with increasing of twist angles. Moreover Young’s modulus of PLA composites is higher in all yarn types than that of CPR composites. Regarding tensile strength, its value decreases with an increase in twist angle in both CPR and PLA composites except for SY composites, of which the normalized strengths ($\sigma/V_f$) are slightly lower than that of ST composites. Fracture strains of CPR and PLA composites tend to increase with an increase in twist angle.
3.2 Proposal of two-dimensional off-axis reduced stiffness for twisted yarn

Single yarns in a twisted yarn are oriented along direction of the twist. When the twisted yarn is spread out, it can be regarded as an orthotropic lamina. A fiber orientation angle in the orthotropic lamina learns against an angle $\theta$. In general, stress-strain relation of the orthotropic lamina at angle $\theta$ is expressed as Equation (1) using reduced stiffness.

$$
\begin{bmatrix}
\sigma_x \\
\sigma_y \\
\tau_{xy}
\end{bmatrix} = \begin{bmatrix}
Q_{ij}
\end{bmatrix}
\begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
\gamma_{xy}
\end{bmatrix} \cdots (1)
$$

Where, $Q_{ij}$ ($i = 1, 2, 3$ and $j = 1, 2, 3$) are transformed reduced stiffness, each of them are given from material constants and an angle $\theta$. When only stress $\sigma_x$ works along $x$-axis, Young’s modulus of the lamina can be calculated from this equation. Material constants used in this calculation were obtained from tensile test of SY composites along $0^\circ$, $45^\circ$, and $90^\circ$ directions. These values are shown in Table 4.

<table>
<thead>
<tr>
<th>Table 3 Tensile properties of ramie twisted yarn composites with various twist angles</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Matrix type</strong></td>
</tr>
<tr>
<td>CPR</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
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<tr>
<td>PLA</td>
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</table>

*V_f means fiber volume fraction

<table>
<thead>
<tr>
<th>Table 4 Material properties used in the calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CPR</strong></td>
</tr>
<tr>
<td><strong>Young’s modulus, $E_1, E_m$ (GPa)</strong></td>
</tr>
<tr>
<td><strong>Young’s modulus, $E_2$ (GPa)</strong></td>
</tr>
<tr>
<td><strong>Poisson’s ratio, $\nu_{12}, \nu_m$</strong></td>
</tr>
<tr>
<td><strong>Shear modulus of elasticity, $G_{12}, G_m$ (GPa)</strong></td>
</tr>
</tbody>
</table>
Figure 2 shows a relation between Young’s modulus and twist angle. Perpendicular-axis is normalized by dividing Young’s modulus of SY composites with twist angle 0° by volume fraction \( \frac{E}{V_f} \), because fiber volume fraction of each specimen is different. As shown in Figure 2, both theoretical and experimental Young’s moduli tend to decrease with increasing of twist angle. However, values of experimental results differ from those of theoretical results predicted from Equation (1).

In order to clarify the twisted yarn structure, a single yarn was dyed in blue color, and then a five-twisted yarn combined this single yarn was produced by using a twisting machine. While the blue single yarn was visible periodically along the yarn axis, there were several parts that it was not confirmed in blue. It is highly likely that each yarn waves from the yarn surface to the inner. This means that the yarns have a largest twist angle at the surface, meanwhile, a smallest twist angle at the centre. Therefore, a single yarn orients in a twisted yarn as schematically described on Figure 3. This structure is called the ‘migration’ in textile engineering\(^8\)). If the twisted yarn structure is divided as cylindrical elements with a fine thickness, this yarn may be regarded as plying orthotropic lamina with different angles\(^9\)\(^\text{10}\). Equation (2) was expressed by idealizing relationship between a distance from the center of twisted yarn \( r \) and a distance along a yarn axis \( q \) in the migration structure\(^8\)).

\[
\frac{\partial q}{\partial r} \propto r \quad \cdots (2)
\]

A relationship of \( r \) and orientation angle \( \theta \) is given as follows:

\[
\theta = \tan^{-1}\left(\frac{r}{R \tan \Theta}\right) \quad \cdots (3)
\]

In this equation, \( \Theta \) means the twist angle on the surface of twisted yarn and \( R \) means the radius of twisted yarn. However, when twisted yarns used in this experiment were untwisted, each single yarn in a twisted yarn indicated different lengths. It is found from this result that each single yarn might be not oriented with an ideal twisted angle. In other words, change of \( r \) doesn’t
adjust change of $\theta$. This result also implies that twist angles of some single yarns dramatically change and others slightly change with increasing $r$ in a twisted yarn. It is possible that a relationship between $r$ and $q$ is experimentally determined if distributions of single yarn length could be measured under several yarn twist conditions. In this study, the single yarn twist angle, orientation angle $\theta$ was related to the distance from the center of twisted yarn $r$. This relation was simply given as a function of $r$ using a power law as follows:

$$\theta = \Theta \left( \frac{r}{R} \right)^{\beta} \quad \cdots (4)$$

Where, $\beta$ is a parameter of experimental constant for determination of orientation angle distribution. By considering of the transformed reduced stiffness and the area of each lamina, a new reduced stiffness for twisted yarn is proposed as Equation (5).

$$\begin{bmatrix}
\sigma_x \\
\sigma_y \\
\tau_{xy}
\end{bmatrix} = \frac{1}{2\pi R^2} \int_{0}^{R} \int_{-\pi}^{\pi} Q_y(\theta) e_{xy} \, r \, dq \, dr R \gamma \varepsilon_{xy} \quad \cdots (5)$$

This stiffness is named ‘two-dimensional off-axis reduced stiffness’ for twisted yarn. Once a relation between $\theta$ and $r$ is obtained, Young’s modulus of twisted yarn composites can be calculated numerically through Equation (5). Thus, $\beta$ was decided by fitting the calculated Young’s moduli to the experimental plots of CPR composites using least squares method. As a result, $\beta = 1.87$ was obtained. Figure 4 shows orientation angle distributions for a distance from the center of twisted yarn $r$. These distributions are sort of like averages. The results indicate that the angle, $\theta$ changes largely near to the surface area of twisted yarns.

Next, Young’s modulus of PLA composite was calculated through Equation (5) using $\beta = 1.87$. The result is illustrated by double dashed dotted line in Figure 2. As seen in this figure, the line seems to be fitting the experimental results. That is to say that an assumption of variation in orientation angle as given in Equation (4) is proper to calculate Young’s modulus. It is proved from the results that Young’s modulus can be predicted through two-dimensional off-axis reduced stiffness for twisted yarn.

![Fig. 3 Schematic diagram of orbit of single yarn orientation angle in a twisted yarn](image-url)
3.3 Proposal of three-dimensional off-axis reduced stiffness for twisted yarn

In this section two-dimensional off-axis reduced stiffness for twisted yarn was developed to three-dimensional reduced stiffness. As described earlier if the migration structure in the twisted yarn is stationary along the yarn axis, in other words the yarn axis is the same as the loading axis, Young’s modulus can be calculated through Equation (5) since the orientation angle of each cylindrical element is invariable.

When the twisted yarn leans against the loading axis with an angle $\psi$, the orientation angle of single yarns to the loading axis varies along the circumferential direction as well as the radial one, as shown in Figure 5. Hereinafter, $\psi$ is denoted as off-axis angle, and $\theta$ is an orientation angle to the twisted yarn axis. Therefore, the orientation angles to the loading axis should be considered along the circumferential direction at each cylindrical element. In this case the three-dimensional off-axis reduced stiffness for twisted yarn is suggested as:

$$
\begin{bmatrix}
\sigma_x \\
\sigma_y \\
\tau_{xy}
\end{bmatrix}
= \frac{1}{\pi} \int_0^\pi \frac{1}{\pi R^2} \int_0^R \bar{Q}_{ij}(\phi) 2\pi r dr d\eta \begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
\gamma_{xy}
\end{bmatrix} \cdots \cdots (6)
$$

Where, $\phi$ is the relative orientation angle, which is an angle between the loading axis and single yarn orientation, and $\eta$ shows a variable of angle along the circumferential direction of the twisted yarn, which is divided into a fine element with $d\eta$. As known in Equation (6), the three-dimensional off-axis reduced stiffness is expressed by integration of the two-dimensional off-axis reduced stiffness from 0 to $\pi$. $\phi$ is estimated by geometric relation of a tetrahedral as follows:

$$
\phi = \cos^{-1} \{(\cos \theta(r) \cos \psi + \sin \theta(r) \sin \psi \cos \eta) \} \cdots \cdots (7)
$$

Fig. 4 Relation between normalized distance and orientation angle at $\beta=1.87$
Migration structure excluded and included calculations were carried out. The results are respectively shown in Figures 6 and 7. When the off-axis angle is same as the twist angle, the peak tends to appear, as shown in Figure 6 because the single yarn is oriented along the loading axis. On the other hand, this tendency is not observed in Figure 7 because various relative orientation angles act on the twisted yarn. It is found from Figure 7 that every Young’s modulus tends to be approximately the same, as $\psi$ increases. At 30° off-axis angle, Young’s modulus increases gradually with increasing of twist angle. Thus, an increase in Young’s modulus is expected by choosing an optimal combination of twist angle and off-axis angle.

Figure 8 shows that the theoretical and experimental results were compared at 30° off-axis angle. As can be seen, Young’s modulus of PLA composites is in good agreement with the theoretical results. Thus, it is concluded that Young’s modulus can be predicted through three-dimensional off-axis reduced stiffness for twisted yarn.
4. Summary

In the present study, the relationship between yarn twist and the mechanical properties of green composites using twisted yarns was explained and a new theoretical reduced stiffness was proposed. Young’s modulus of green composites decreases with increasing twist angle. In addition, a relation between twist angle and Young’s modulus was investigated using a reduced stiffness, in which the twisted yarn is assumed as an orthotropic material with an off-axis angle. Consideration of migration structure for single yarns was important for the twisted yarn, and a new theoretical stiffness, called two-dimensional off-axis reduced stiffness, was proposed. Calculated Young’s modulus obtained through the proposed stiffness agreed well with the experimental results. Furthermore, it was also found that Young’s modulus of the twisted yarn composites can be predicted through three-dimensional off-axis reduced stiffness for twisted yarn.

References

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