Effect of Yarn Twist on Young's Modulus of Fully-green Composites Reinforced with Ramie Woven Fabrics

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ABSTRACT

Textile green composites using ramie fabrics and biodegradable resin were developed by hot-pressing for the purpose of applying the composites to various industrial products. Generally, it is said that deformation behavior of woven fabrics is determined by fabric density, crimp angle of yarns, yarn twisting and so on. Therefore, this study focuses on how the yarn twisting affects the deformation behavior and mechanical properties of the textile composites. Results showed that a large number of yarn twists increases Young's modulus of the textile composites, while unidirectional composites reinforced with the same yarns decrease in Young's modulus with increasing the number of yarn twists. This might be related to existence of crimps in the textile composites. To clarify the mechanism, the crimp model analysis based on lamination theory was carried out and its result was discussed.

Key-words: *Green Composite, Woven fabric, Yarn twist, Young's modulus, Biodegradable resin*

1. INTRODUCTION

Today, development of materials technology using biomass is expected for creation of a sustainable society. Especially, the composite consisting of plant-based natural fibers and biodegradable resin, so-called the fully green composite, is much expected for practical use. The authors have developed a textile green composite using biodegradable resin and plain woven ramie fabric, and explored its deformation behavior [1]. Generally, it is said that deformation behavior of woven fabrics is dependent on several parameters such as fabric density, crimp angle of yarns, yarn twisting and so on [2]. On the other hand, it is unknown if such dependencies are exhibited in textile green composites.

This study is thus to explore the effect of yarn twist on Young's modulus of textile green composites. The results showed that a characteristic property different from dry fabrics was newly found.

2. EXPERIMENTS

2.1 Test materials

Folded ramie yarns (No.16, five twists) supplied from TOSCO Co. Ltd. was used as a reinforcing material. On the other hand, a film of cornstarch-based biodegradable resin (Cornpole film CPR-F3A) supplied from Nippon Cornstarch Co. Ltd. was used as a matrix material. Properties of ramie fibers and biodegradable resin were shown in Tables 1 and 2, respectively.

Table 1: Properties of ramie fibers

Density (Mg/m^3)	Cellulose (wt%)	Lignin (wt%)	Hemi-cellulose (wt%)	Pectin (wt%)	Wax (wt%)	Microfibrillar angle (^{o})	Moisture Content (wt%)
1.50	68.6-76.2	0.6-0.7	13.1-16.7	1.9	0.3	7.5	8.0

Table 2: Properties of biodegradable resin

Density ($Mg/\ m^3$)	Melting Point (^oC)	Tensile Strength (MPa)	Fracture Strain (%)	Young's Modulus (GPa)
1.17	68	14.2	81.6	0.46

2.2 Fabrication method

Ramie fabric reinforcements with a plain weave structure were prepared using a manual weaving machine. Some folded ramie yarns were untwisted or further twisted, and used as wefts of the fabric to explore the effect of yarn twist. The fabric made of untwisted yarns is denoted as TL-fabric, of which the number of yarn twist per inch (TPI) is decreased from 3.5/inch to 0.5/inch. The fabric made of twisted yarns is denoted as TH-fabric of which TPI is increased to 6.5/inch. The fabric made of as-supplied yarn is denoted as T-fabric. Fabric density and TPI of yarns of the ramie fabrics used in this study are shown in Table 3. Textile and unidirectional green composites were fabricated using a hot-press machine (mini Test Press-10; Toyoseiki Seisakusho Co. Ltd.). In the former composite, one fabric was sandwiched between two sets of three resin films and pressed at 150^{o}C and 2.33MPa for 10min. In the latter, one yarns-sheet placed unidirectional and one set of three resin films were overlapped and pressed at the same conditions. Subsequently, the composites were cooled down to room temperature under same pressure. Tensile specimens were cut off from the fabricated composites in 15 mm width. The thickness was about 2 mm for the textile composites and about 1mm for the unidirectional composites. Surface of the textile composite is shown in Fig.1. GFRP plates were attached using epoxy adhesive on the both ends of the material. Shape and dimension of tensile specimen is shown in Fig.2. The gage length was 50mm. To explore the deformation behavior of dry yarns, on the other hand, T-, TL- and TH-yarn were cut off in 200 mm width, and GFRP plates were attached using epoxy adhesive on the both ends of these yarns. The gage length was 100mm. To explore the deformation behavior of fabric, T-, TL- and TH-fabric were also cut off in 25 mm width, and 200 mm length. The gage length was 100mm.

2.3 Tensile test

Tensile test of the composites was carried out along their weft directions at room temperature at the crosshead speed of 0.5mm/min using an Instron-type testing machine (Autograph IS-5000; Shimadzu Co.). Tensile tests of the fabrics and their constituent dry yarns were carried out at the crosshead speed of 150mm/min and 12mm/min using a hydraulic testing machine (Servopulser EHF-EB10; Shimadzu Co.).

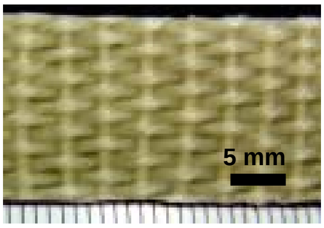


Fig. 1: Photograph of the textile green composite.

Table 3: Fabric density and number of yarn twist of the ramie fabrics used in this study.

	T	TH	TL
Weft (picks/inch)	25	25	25
Warp (ends/inch)	9	8	9
TPI (n/inch)	3.5	6.5	0.5

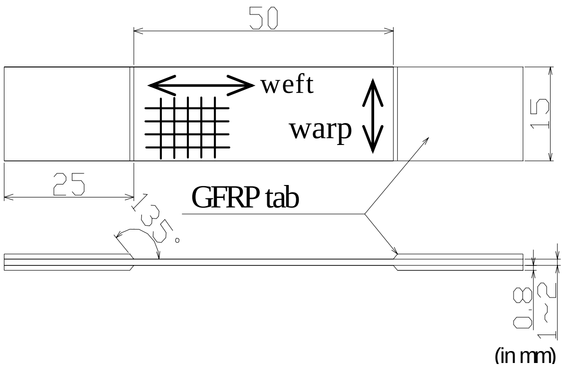


Fig. 2: Shape and dimension of tensile specimen.

3. EXPERIMENTAL RESULTS

3-1 Effect of yarn twist on mechanical properties of yarns and fabrics.

Effect of yarn twist on mechanical properties of the dry yarns was investigated. Typical load-strain diagrams of the T-, TL-, TH4.5- and TH-yarn are shown in Fig.3. In this figure the load is normalized by dividing it by the fineness (tex). The fineness means the degree of the thickness of a yarn, and is defined as fiber weight per 1000m length. If its weight is 1g, the fineness is denoted as 1tex. The value of tex increases with increasing the yarn thickness.

The results show that T-yarn has the highest stiffness, but the stiffness decreases with increasing or decreasing the number of twist from 3.5/inch. It is considered that the yarn stiffness increases to some degree due to inter-fiber friction brought from yarn twisting, but more TPI decreases it with an increase in fiber orientation angle to the yarn axis. Therefore, to obtain a higher stiffness, TPI of 3.5/inch is optimal in this study.

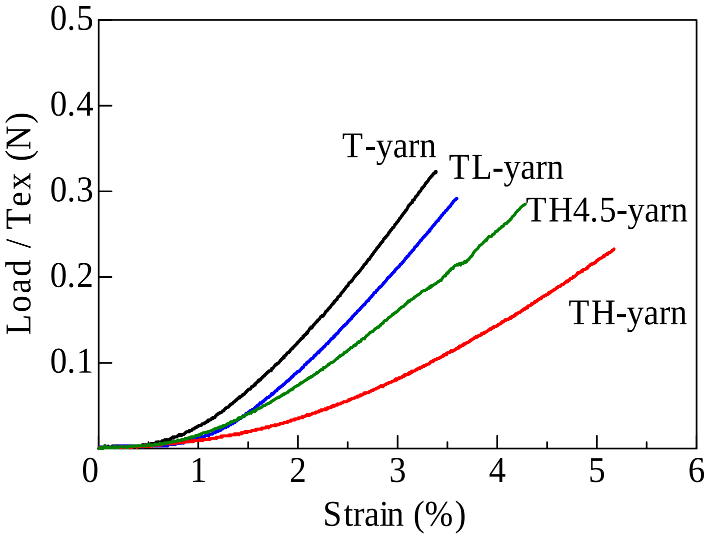


Fig. 3: Typical normalized load strain diagrams of fabric’s constituent yarns

Tensile tests of T-, TL- and TH-fabric were also carried out to explore the effect of yarn twist on their deformation behavior. Typical load-strain diagrams of the dry fabrics are shown in Fig.4. In the figure only initial behavior of the diagram is shown and these loads are normalized by dividing it by the number of longitudinal yarns. Initial slope of T-fabric is more than that of others. Consequently, stiffness and tensile load of the fabrics are increased by an appropriate TPI, and therefore the effect of yarn twist on the deformation behavior of fabrics also shows the same tendency as that of the yarns. Such behaviors mentioned above are quite similar to behaviors discussed in usual textile mechanics [2].

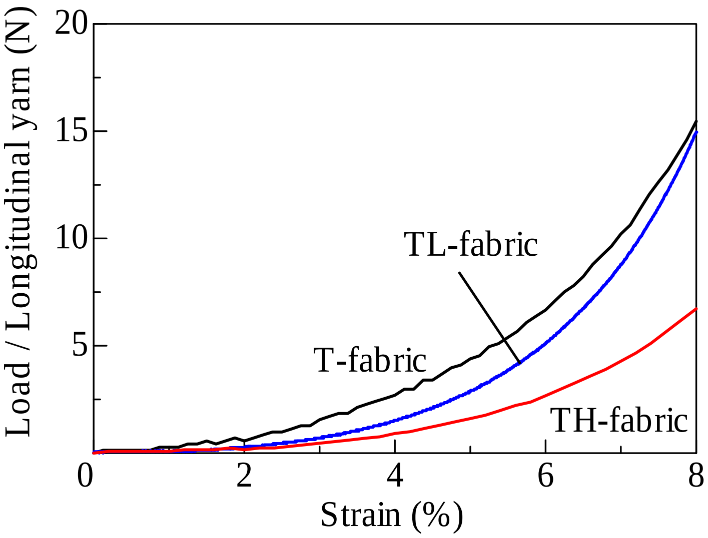


Fig. 4: Typical normalized load-strain diagrams of fabrics.

3-2 Effect of yarn twist on mechanical properties of unidirectional composites.

Effect of yarn twist on mechanical properties of unidirectional composites was explored. Table 4 shows Young's moduli of of T-, TL- and TH-uni. Typical load-strain diagrams of these composites are also shown in Fig. 5. These specimens have almost the same number of yarns but different number of TPI. The results show that the Young's modulus was reduced with increasing TPI. This tendency is different from that of dry yarns mentioned above. This is because the load transfer mechanism works through matrix shear even if the yarns are not twisted. Thus, Young's modulus of unidirectional composites depends on the fiber orientation angle given by yarn twisting.

Table 4: Mechanical properties of unidirectional green composites

	Volume fraction (%)	Young's modulus (MPa)	Tensile strength (MPa)	Fracture strain (%)
TL-uni	47.6	16.9	237.8	1.63
T-uni	42.7	11.72	195.5	2.92
TH-uni	34.8	6.09	104.6	2.06

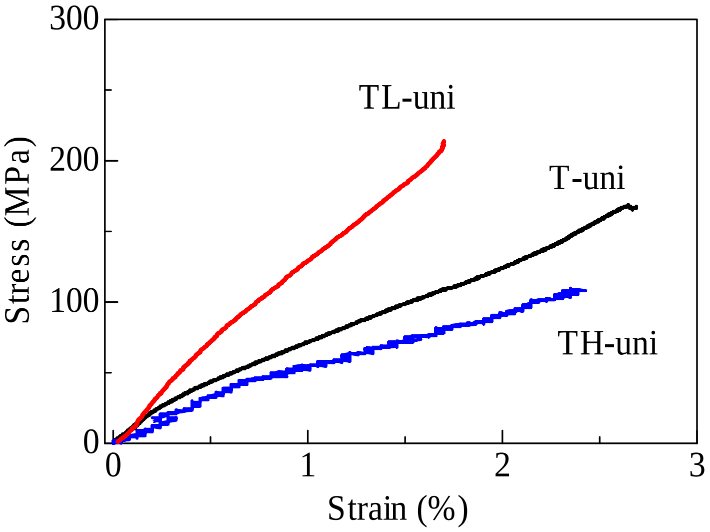


Fig. 5: Typical stress-strain diagrams of unidirectional composites.

3-3 Effect of yarn twist on mechanical properties of textile green composites

Tensile tests of T-, TL- and TH-textile were carried out to explore the effect of yarn twist. The results were shown in Fig.6 and Table 5. These specimens have almost the same fabric density but different TPI. The results show that the Young's modulus and fracture strain were slightly reduced at 0.5/inch. On the other hand, the Young's modulus increased greatly and fracture strain decreased by increasing the yarn twist to 6.5/inch.

Difference between behaviors of the dry fabrics and composite may be related without or with matrix resin. In general, dry yarns between crimps in a woven fabric extend largely as compared to yarns at crimps. Therefore, more TPI deforms the fabric more largely. However resin-included yarns' behavior in a textile composite is related to deformation at crimps as well as that between crimps, because of the load transfer mechanism of matrix resin. As the deformation at crimps is decided by stiffness along the radius of resin-included yarns, such as transverse modulus of elasticity, the increase in the transverse stiffness caused by further twisting restricts reduction in thickness, and results in hardening the composites. Thus, it is considered that such mechanism inherent in textile composites brings an increase in Young's modulus of TH-textile.

Table 5: Mechanical properties of textile green composites

	Young's modulus (GPa)	Tensile strength (MPa)	Fracture strain (%)
TL-textile	3.22	75.2	4.11
T-textile	3.91	74.8	4.28
TH-textile	6.01	75.0	2.83

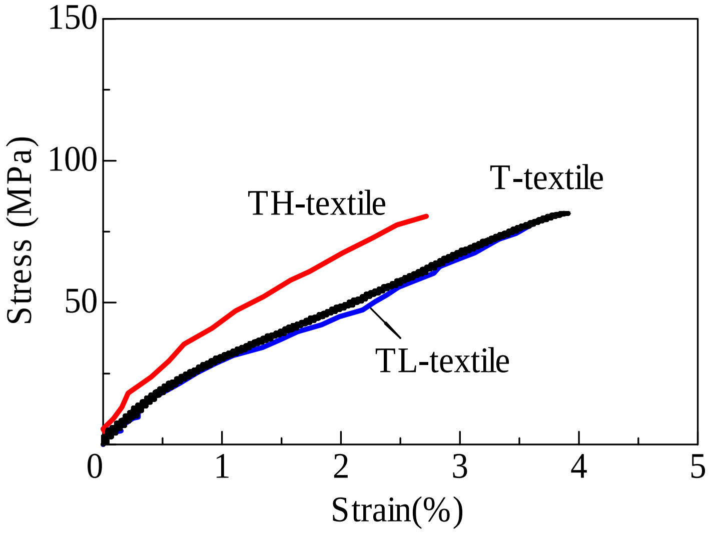


Fig. 6: Typical stress-strain diagrams of TL-, T- and TH-textile.

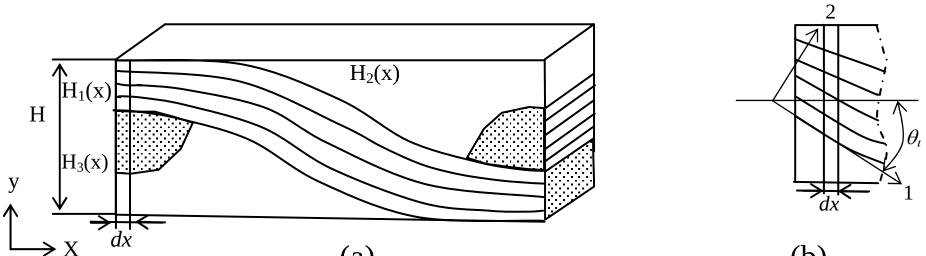
4. DISCUSSION

In the experimental TH-textile showed the largest Young's modulus of all, while TH-uni showed the lowest Young's modulus, and TH-fabric and -yarn also showed the lowest deformation resistance. This is considered to be related with more interaction at crimp portions caused by resin-included yarns. To discuss such an effect of interaction, the crimp model proposed by Ishikawa & Chou [3] may be available. This theory was furthermore developed to three-dimensional analysis by Naik [4], and in recent years, stress analysis of textile green composites has also been studied by 3D-FEM [5].

However, the purpose of this study is not to clarify the effect of yarn twist precisely using complicated computational mechanics methods, but to do it experimentally. Thus, although the model of Ishikawa & Chou is developed two-dimensionally, the present study uses it to understand this phenomenon qualitatively.

4-1 Model

Figure 7 (a) shows the crimp model used for estimation of Young's modulus of textile composites. The composite specimen is divided into a "unit composite" with short length of *dx*, and it is assumed to be composed of linking unit composites each other. One unit composite consists of weft and warp yarns, and resin at crimp portions, or a weft yarn and resin at inter-crimps. These constituents may be regarded as a lamina, in which the weft yarnt has a fiber orientation angle θ_i., as shown in Fig. 7 (b). Thus, the above unit composite may be regarded as a laminated structure, and lamination theory can be applied for each unit composite.



(a) (b)

H: Thickness, $H_1(x)$: Lower configuration of weft yarn,
$H_2(x)$: Upper configuration of weft yarn, $H_3(x)$: Configuration of warp yarn

Fig. 7: Analytical model for fluctuation in fiber orientation of green composites

4-2 Formulation

As easily guessed, each unit composite exhibits different stiffness because of different laminated structure. Therefore, the strains occurring in the unit composites are also different, but the bearing load of each unit composite must be all the same. When the identical load is given to each unit composite as a boundary condition, the whole strain of the composite can be estimated as an average of strains occurring in all unit composites. The relation between the stress components $\{\sigma\}$ and the strain components $\{\varepsilon\}$ of a weft or warp yarn is as follows:

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \end{Bmatrix} = \begin{bmatrix} \overline{Q}_{11} & \overline{Q}_{12} & \overline{Q}_{16} \\ \overline{Q}_{12} & \overline{Q}_{22} & \overline{Q}_{26} \\ \overline{Q}_{16} & \overline{Q}_{26} & \overline{Q}_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \end{Bmatrix} \qquad (1)$$

where, $\overline{Q}_{ij}$ is the transformed reduced stiffness matrix. The fiber orientation angle θ is given from positive rotation of principal material axes 1-2 along the fiber-axis from arbitrary x-y axes. In-plain forces per unit width, called stress resultants, acting on a unit composite are estimated by integrating stress components of first to *n*-th lamina as follows:

$$\left(N_x, N_z, N_{zx}\right) = \sum_{k=1}^{n} \int_{y_{k-1}}^{y_k} \left(\sigma_x^{(k)}, \sigma_z^{(k)}, \tau_{zx}^{(k)}\right) dy \qquad (2)$$

Where, *n*=2 or 3. Bending moments per unit width, called moment resultants, acting on a unit composite are also estimated from definition of moment as follows:

$$\left(M_x, M_z, M_{zx}\right) = \sum_{k=1}^{n} \int_{y_{k-1}}^{y_k} \left(\sigma_x^{(k)} y,\ \sigma_z^{(k)} y,\ \tau_{zx}^{(k)} y\right) dy \qquad (3)$$

Equations (2) and (3) are rewritten as a matrix form as follows:

$$\begin{bmatrix} N_i \\ M_i \end{bmatrix} = \begin{bmatrix} A_{ij} & B_{ij} \\ B_{ij} & D_{ij} \end{bmatrix} \begin{bmatrix} \varepsilon_j^0 \\ \kappa_j \end{bmatrix} \qquad (4)$$

where,

$$\begin{aligned} A_{ij} &= \sum_{k=1}^{n} \left(\overline{Q}_{ij}\right)_k \left(y_k - y_{k-1}\right) \\ B_{ij} &= \frac{1}{2} \sum_{k=1}^{n} \left(\overline{Q}_{ij}\right)_k \left(y_k^2 - y_{k-1}^2\right) \qquad (5) \\ D_{ij} &= \frac{1}{3} \sum_{k=1}^{n} \left(\overline{Q}_{ij}\right)_k \left(y_k^3 - y_{k-1}^3\right) \qquad (i, j) = 1,2,6 \end{aligned}$$

Here, ε_j^0 and κ_j are the strain and the curvature. A_{ij} , B_{ij} and D_{ij} are the in-plain, coupling and bending stiffness, respectively. In this study only the tensile stress resultant along the *x*-axis was given as a boundary condition. In addition, assuming that no bending deformation caused by in-plain loading occurs, another boundary condition, i.e. all components of curvature were set to zero. From the relation between the stress resultant and whole strain, Young's modulus of the textile composite was calculated.

4-3 Material properties

To estimate elastic moduli of the unidirectional ramie yarn-reinforced composite, T-textile specimens were tensile-tested along 0^{o}, 90^{o} and 45^{o} directions, respectively. Table 6 shows elastic moduli of the composite obtained in the test. The composite actually includes some resin rich parts besides the yarn parts, but for simplicity the obtained elastic moduli were regarded as elastic moduli of weft and warp yarns in Fig.7(a).

Table 6: Elastic moduli used in the analysis

E_{11} [GPa]	E_{22} [GPa]	G_{12} [GPa]	ν_{12}
11.7	1.37	0.63	0.40

4-4 Analytical results

Figure 8 shows change in Young's modulus E_c of the textile composite with an increase in transverse modulus. These values were normalized by dividing it by longitudinal modulus E_{11}. The transverse modulus E_{22} was regarded as Young's modulus of the warp, and fixed as a constant in this analysis. Increase in E_{22} and decrease in E_{11} mean that the stiffness of the resin-included yarn increases in radial direction and it decreases in axial direction. In Fig.8, this is corresponding to increasing E_{22}/ $E_{11}$of the x-axis, and therefore this simulates an increase in weft yarn TPI in experiment. As shown in Fig. 8, E_c of textile composites increases first and decreases after a peak as show in an arrow. In other words, twisting for longitudinal (weft) yarns increases Young's modulus of the textile composites to some degree, and decreases if more TPI is given.

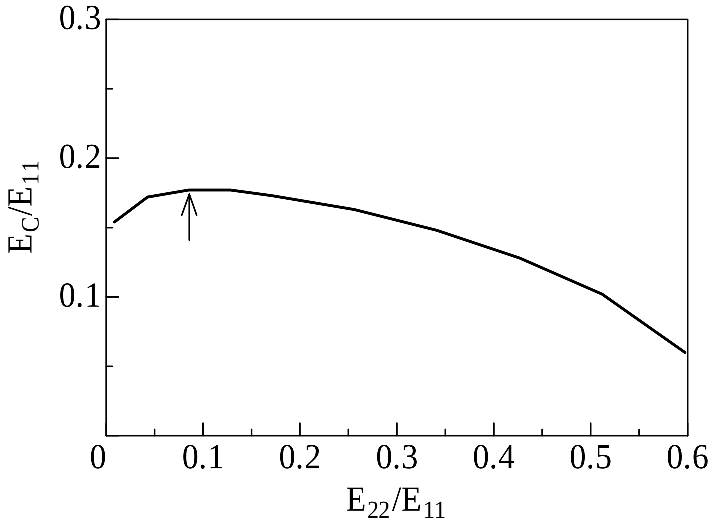


Fig. 8: Relation between E_c/E_{11} and E_{22}/E_{11}

5. CONCLUSION

This study was carried out to explore the effect of yarn twist on Young's modulus of textile green composites. First of all, deformation behaviors of dry ramie yarns and fabrics were explored by changing the number of yarn twists. The results showed that these constituent materials deformed subject to usual textile mechanics. Next, the effect of yarn twists on tensile properties of unidirectional composites consisting of ramie yarns and biodegradable resin was expected. Young's modulus of the composites decreased with increasing the number of yarn twists. On the other hand, Young's modulus of the textile green composites reinforced with same ramie yarns increased with increasing the number of yarn twists. It was considered that this was related to existence of crimps in the textile composites. To clarify the mechanism, the crimp model analysis based on lamination theory was carried out and its result was discussed.

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