1 Introduction

Braided fabrics are one of typical textiles along with woven fabrics and knitted fabrics. The schematic image of braided fabrics was shown in Fig.1. Braided fabrics were composed of a lot of yarns which oriented diagonally called braiding yarns (BY). And yarns called middle-end-yarns (MEY) can be inserted into braiding yarns along the longitudinal direction. As materials for braiding yarns and middle-end-yarns, various kinds of fibers, such as glass fiber, carbon fiber and aramid fiber, can be used. One of the important features of braided fabrics is the capability to change the orientation angle of braiding yarns called braiding angle (at ±θ degrees to longitudinal direction). Braiding angle can be changed freely as shown in Fig.2. In addition, another unique feature of braided fabrics is the continuity of all fibers. All fibers are continuously oriented from one end to the other end and subjected to forces evenly. Therefore braided fabrics have been expected to be excellent preforms for reinforcements of composite materials with excellent mechanical properties, and it enables to produce excellent structural parts according to various kinds of requirements.

However it is very difficult to design braided composites according to requirements. In previous study, it was clarified that the internal structure of braided composites depended on four internal structural parameters in Fig.3 (braiding angle, distance between braiding yarns, area and cross-sectional shape of fiber bundles of braiding yarns). These parameters have the interrelationship with each other. For example, in the case of popular plain-woven fabrics, the orientation angle of yarns and the distance between yarns are constant. While, in the case of braided fabrics, when braiding angle is changed, the distance between braiding yarns, the area and the cross-sectional shape of fiber bundles of braiding yarns are also changed automatically. Therefore it’s very difficult to design braided composites and the practical realization has been delayed in comparison with other textiles.

The purpose of this study is to clarify the interrelationship between internal structural parameters. In order to clarify the interrelationship, braided fabrics were fabricated on a tapered tubular mandrel with constant braiding angle to control distance between braiding yarns. In order to estimate the interrelationship between internal structural parameters quantitatively, cross-sectional observation was conducted and internal structural parameters were quantified. From these results, the interrelationships were mathematized and data bases for investigation were obtained. As the result, numerical models for braided composites with or without middle-end-yarns were constructed to predict internal structural parameters. Based on the result, the prediction method of internal structural parameters of braided composites with thermoset resin was proposed.
2 Method

2.1 Materials

As materials for braided composites, two types of prepreg yarn which were impregnated with epoxy 38 wt% were used. One with the filament number of 12000 was called type “12k” (T700-12-RC38%-SX3: JX Nippon oil & Energy). The other with the filament number of 6000 was called type “6k” (T700-6-RC38%-SX3: JX Nippon oil & Energy). The carbon fiber properties for prepreg yarn were shown in Table 1.

2.2 Fabrication

A braiding machine was used to fabricate braided composites. The machine was shown in Fig.4. The braiding machine is mainly composed of two mechanism; carrier moving mechanism and take-up mechanism. Braided fabrics were fabricated by rotating bobbin carriers with prepreg yarns (carrier moving mechanism) and by pulling the mandrel with braided prepreg yarns (take-up mechanism). Braiding angle was decided by the relative speed of the rotating speed and the pulling up speed. One layer of braided fabrics was prepared on a tapered mandrel with 1m length and the diameter was changed from 30 to 100mm. The mandrel was shown in Fig.5. 48 bobbins for braiding yarns and 24 bobbins for middle-end-yarns were used for a fabrication. The braiding angle was constant with 45 or 65 degrees. Preforms were wrapped with PET tape with 25mm width and cured in an oven at 130°C for 2 hours and 150°C for 2 hours. After that, braided composites were removed from the mandrel. The braided composites were shown in Fig.6.

<table>
<thead>
<tr>
<th>Type of material</th>
<th>filament number</th>
<th>Tensile strength</th>
<th>Young's modulus</th>
<th>Elongation percentage</th>
<th>Tex</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>T700</td>
<td>6000</td>
<td>4900</td>
<td>230</td>
<td>2.1</td>
<td>400</td>
<td>1.8</td>
</tr>
<tr>
<td>T700-6k</td>
<td>12000</td>
<td>4900</td>
<td>230</td>
<td>2.1</td>
<td>800</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Fig.3 Internal structural parameters.

Fig.5 Tapered tubular mandrel.

Fig.6 Tapered tubular Braided composites.
2.3 Experimental procedure

In order to investigate the interrelationship between internal structural parameters, three specimens were fabricated from different combinations of braiding yarns and middle-end-yarns as shown in Table 2. Specimens were named depending on combinations of BY and MEY. For example, the specimen was called “T-12k-6k” when the filament number of braiding yarns was 12000 and that of middle-end-yarns was 6000.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Filament number</th>
<th>Braiding yarns</th>
<th>Middle-end-yarns</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-12k-none</td>
<td>12000</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>T-12k-6k</td>
<td>12000</td>
<td>6000</td>
<td></td>
</tr>
<tr>
<td>T-12k-12k</td>
<td>12000</td>
<td>12000</td>
<td></td>
</tr>
</tbody>
</table>

Cross-sectional observation was conducted in order to quantify internal structural parameters as follows: Specimens were cut along a braiding yarn at each inner diameter (30, 40, 50, 60, 70, 80, 90, 100mm) as shown in Fig. 7. Each cut specimen was embedded into thermoset resin. The cross sections were polished and observed using an optical microscopy (PME3: Olympus Corporation). Internal structural parameters were quantified from the images.

Fig. 7 Points where specimens were cut.

2.4 Quantification

Calculation methods to quantify internal structural parameters were described below. Distance between braiding yarns $L$ was calculated as follows:

$$ L = \frac{\pi D \cos \theta}{N_{BY} / 2} $$

where $D$ is diameter of mandrel, $\theta$ is braiding angle, and $N_{BY}$ is number of bobbins for braiding yarns.

In order to estimate cross-sectional shape of fiber bundles of braiding yarns quantitatively, aspect ratio of fiber bundles cross-section was defined. Aspect ratio was calculated by dividing minor axis by major axis as follows:

$$ \text{Aspect ratio} = \frac{A_S}{A_L} $$

where $A_L$ is major axis and $A_S$ is minor axis of fiber bundles of braiding yarns.

Additionally, gap between braiding yarns was defined as Gap and calculated by subtracting major axis from distance between braiding yarns as follows:

$$ \text{Gap} = L - A_L $$

Gap between braiding yarns causes a decrease in mechanical properties of braided composites and affects the appearance of products. Therefore gap between braiding yarns also should be considered.

In this study, the relationships between distance between braiding yarns and major axis or aspect ratio of fiber bundles of braiding yarns or gap between braiding yarns were investigated.

3. Results

3.1 Observation results and interrelationship between internal structural parameters for braided structure without middle-end-yarns.

First, in order to clarify the interrelationship between internal structural parameters of braided composites, a braided structure without middle-end-yarns “T-12k-none” was investigated. Cross-sectional photographs of “T-12k-none” ($\theta=65$ degrees) in diameter of (a) 30mm, (b) 60mm and (c) 90mm were shown in Fig. 9. Each fiber bundle of braiding yarns was assumed as elliptical shape respectively. As shown in these photographs,
with increasing the diameter of mandrel corresponding to distance between braiding yarns as shown in equation (1), cross-sectional shapes of braiding yarns tended to flatten and thickness of a layer of braided composites was decreased. Additionally, gap between braiding yarns was increased with increasing the diameter of mandrel.

In order to estimate the observation results quantitatively, the relationships for “T-12k-none” between distance between braiding yarns and major axis or aspect ratio of fiber bundles of braiding yarns or gap between braiding yarns were investigated. The relationship between aspect ratio and distance between braiding yarns for “T-12k-none” was shown in Fig.10. Each data point was represented by a solid square for 65 degrees or an open square for 45 degrees. Aspect ratio was decreased with increasing distance between braiding yarns. Regardless of the difference in braiding angle, each data seemed to be continuous and on a same curve. In this trend, both aspect ratio and distance between braiding yarns should have a minimum and positive value geometrically. Therefore distance between braiding yarns converged on a certain value with increasing aspect ratio, and aspect ratio also converged on a certain value with increasing distance between braiding yarns. From this trend, the relationship between aspect ratio and distance between braiding yarns was approximated by a fractional function. The approximate expression \( F(x) \) was given by:

\[
F(x) = \frac{a}{(x - b)} + c
\]

where \( F(x) \) is aspect ratio, \( x \) is distance between braiding yarns, \( a \) is proportional constant, \( b \) is the minimum distance between braiding yarns and \( c \) is the minimum aspect ratio. This expression meant that \( x \) converged on \( b \) with increasing aspect ratio and \( F(x) \) converged on \( c \) with increasing distance between braiding yarns. First, \( b \) was determined when neighboring braiding yarns were contacted with each other and the maximum aspect ratio was 1 \( (A_L=A_S) \) as shown in Fig.11. Then \( b \) was equal to major axis and minor axis of fiber bundle of braiding yarns. In other words, \( b \) was equal to the diameter of fiber bundles of braiding yarns. Therefore, \( b \) was given by:

\[
S_{BY} = \frac{\pi A_L^2}{4} = \frac{\pi A_S^2}{4} = \frac{\pi b^2}{4}
\]

where \( S_{BY} \) is area of a fiber bundle of a braiding yarn. After \( b \) was calculated as above, \( a \) and \( c \) were determined by changing \( a \) and \( c \) to make approximate expression \( F(x) \) as close as possible to measured values and the values of the parameters were shown in Table 3. The approximated curve was shown as a solid line in Fig.10.
Table 3 Parameters in $F(x)$ for “T-12k-none”.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>a</th>
<th>b</th>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-12k-none</td>
<td>0.090</td>
<td>0.955</td>
<td>0.054</td>
</tr>
</tbody>
</table>

Based on the result, major axis of fiber bundles of braiding yarns and gap between braiding yarns were calculated. By using a formula for area of an ellipse corresponding to the cross-sectional shape of braiding yarns and $F(x)$, major axis $A_L(x)$ was calculated as follows:

$$S_{BY} = \pi \left( \frac{A_L}{2} \right) \left( \frac{A_S}{2} \right)$$  \hspace{1cm} (7)

$$A_S = A_L F(x)$$  \hspace{1cm} (8)

$$\therefore A_L(x) = \frac{4S_{BY}}{\pi F(x)}$$  \hspace{1cm} (9)

The relationship between major axis and distance between braiding yarns was shown in Fig.12. Each data point was measured values of major axis and a solid line was calculated values of that by equation (9). Major axis was increased with increasing distance between braiding yarns. Calculated values of major axis had good agreement with measured values of that.

In addition, based on the result, gap between braiding yarns $\text{Gap}(x)$ was calculated by subtracting calculated major axis from distance between braiding yarns as follows:

$$\text{Gap}(x) = x - A_L(x)$$  \hspace{1cm} (10)

The relationship between $\text{Gap}$ and distance between braiding yarns was shown in Fig.13. Each data point was measured values of $\text{Gap}$ and a solid line was calculated values of that by equation (10). $\text{Gap}$ was increased with increasing distance between braiding yarns. Calculated values of gap between braiding yarns had good agreement with measured values of that.

Consequently, it was suggested that internal structural parameters of braided composites (aspect ratio and major axis of fiber bundles of braiding yarns, gap between braiding yarns) could be calculated by the following procedure in Fig.14.

3.2 Effects of filament number of middle-end-yarns on internal structural parameters for braided structure with middle-end-yarns.

In the next place, in order to investigate effects of filament number of middle-end-yarns on internal structural parameters, three specimens: “T-12k-
none”, “T-12k-6k” and “T-12k-12k” were investigated. The relationships between aspect ratio and distance between braiding yarns were shown in Fig.15. Each data point was represented by a solid and open square for “T-12k-none”, triangle for “T-12k-6k” and circle for “T-12k-12k” with 65 and 45 degrees in braiding angle. Based on the preceding section 3.1, as with “T-12k-none”, each result for “T-12k-6k” and “T-12k-12k” was approximated respectively by determining parameters a, b and c in F(x). Because same type of braiding yarns “12k” was used to fabricate each specimen, the way to determine b was same for each specimen. Therefore the value of b for each specimen was also same. Then, a and c were determined by changing a and c to make each approximate expression F(x) as close as possible to each measured value. The values of parameters were shown in Table 4. The relationship between a and filament number of middle-end-yarns were shown in Fig.16. The relationship between c and filament number of middle-end-yarns were shown in Fig.17. Then, a was increased and c was decreased in proportion to filament number of middle-end-yarns and each parameters were represented as follows:

\[ a(n_{MEY}) = 0.0083n_{MEY} + 0.089 \]  
\[ c(n_{MEY}) = -0.0020n_{MEY} + 0.054 \]

where \( n_{MEY} \) is filament number of middle-end-yarns (ex. 12k: \( n_{MEY} = 12 \), 6k: \( n_{MEY} = 6 \)). It was found that a and c could be represented as a function of distance between braiding yarns. Each approximated curve was shown as a solid or a dashed line in Fig.15. Aspect ratio was increased with increasing filament numbers of middle-end-yarns in shorter distance between braiding yarns of 2.0-6.0mm, and decreased in longer that of 6.0-10.0mm.

In order to clarify the deformation mechanism of cross-sectional shape of braiding yarns, cross sectional photos were investigated in more detail.

First, the deformation mechanism in shorter distance between braiding yarns of 2.0-6.0mm was described below. Cross-sectional photos of “T-12k-12k” or “T-12k-none” at about 2.0mm in distance between braiding yarns were shown in Fig.18. These photos were typical ones in distance between braiding yarns from 2.0 to 6.0mm. As shown in Fig.18 (1) for “T-12k-12k”, braiding yarns were compressed and by middle-end-yarns. Therefore major axis were shortened more and minor axis were lengthened more than the condition without middle-end-yarns in Fig.18 (2) for “T-12k-none”. Thus
aspect ratio was increased, and $a$ tended to increase in proportion to filament number of middle-end-yarns.

Next, the deformation mechanism in longer distance between braiding yarns of 6.0-10.0mm was described below. Typical Cross-sectional photos of “T-12k-12k” or “T-12k-none” at about 10.0mm in distance between braiding yarns were shown in Fig.19. As shown in Fig.19 (2) for “T-12k-none”, fiber bundles of braiding yarns parallel to the cross-section were crimped along the intersectional fiber bundles of braiding yarns because middle-end-yarns were not between braiding yarns, and the intersectional fiber bundles were compressed because of the crimp. Therefore major axis of braiding yarns were shortened and minor axis of braiding yarns were lengthened by the pressure from braiding yarns parallel to the cross-section with larger crimp. Meanwhile, as shown in Fig.19 (1), the deformation of braiding yarns was restrained in the presence of middle-end-yarns because middle-end-yarns also sustained the pressure from braiding yarns parallel to the cross-section. Thus $c$ representing the minimum aspect ratio was decreased in proportion to filament number of middle-end-yarns. As the result, aspect ratio could be calculated by $F(x)$ even if filament number of middle-end-yarns were changed, and structural deformation mechanism was clarified.

In addition, along with “T-12k-none”, each major axis and Gap as a function of distance between braiding yarns was calculated respectively for “T-12k-6k” and “T-12k-12k”. The relationships between major axis and distance between braiding yarns were shown in Fig.20. Each data points was the measured value of major axis, and a solid or dashed line was the calculated value of that by equation (9) for “T-12k-none”, “T-12k-6k” and ”T-12k-12k”. Major axis was increased with increasing distance between braiding yarns. Each calculated value had good agreement with each measured value.

The relationships between Gap and distance between braiding yarns were shown in Fig.21. Each data point was the measured value of gap between braiding yarns, and a solid or dashed line was the calculated values of that by equation (10) for “T-12k-none”, “T-12k-6k” and ”T-12k-12k”. Gap between braiding yarns was increased with increasing distance between braiding yarns. Each calculated value also had good agreement with each measured value.

![Cross-sectional photos at about 2.0 mm in distance between braiding yarns.](image1)

(1) T-12k-12k

(2) T-12k-none

Fig.18 Cross-sectional photos at about 2.0 mm in distance between braiding yarns.

![Cross-sectional photos at about 10.0 mm in distance between braiding yarns.](image2)

(1) T-12k-12k

(2) T-12k-none

Fig.19 Cross-sectional photos at about 10.0 mm in distance between braiding yarns.
In the preceding section 3.1, the procedure to calculate internal structural parameters of braided composites without middle-end-yarns was proposed. Additionally, in this section, internal structural parameters with considering middle-end-yarns were investigated. As the result, effects of filament number of middle-end-yarns on internal structural parameters were found as follows: Aspect ratio of fiber bundles of braiding yarns corresponding to cross-sectional shape of fiber bundles could be calculated by $F(x)$ and calculating the parameters $a$ and $c$ in $F(x)$ according to filament number of middle-end-yarns. And the result suggested that internal structure of braided composites could be predicted if the relationship between internal structural parameters and conditions of fabrication, such as property of fiber, was clarified. Here, the procedure to predict internal structural parameters of braided composites was proposed as shown in Fig.22: First, conditions of fabrication for braided composites were determined. Then distance between braiding yarns and parameters ($a$, $b$, $c$) in $F(x)$ were also determined automatically. Next, aspect ratio could be predicted by $F(x)$ in equation (4). Based on the prediction result, automatically, major axis of fiber bundles of braiding yarns could be predicted by $A_L(x)$ in equation (9) and gap between braiding yarns could be predicted by $Gap(x)$ in equation (10).

![Fig.20 Relationship between major axis and distance between braiding yarns for “T-12k-none”, “T-12k-6k” and “T-12k-12k”.](image)

![Fig.21 Relationship between gap between braiding yarns and distance between braiding yarns for “T-12k-none”, “T-12k-6k” and “T-12k-12k”.](image)

![Fig.22 Procedure to predict internal structural parameters of braided composites.](image)

### 4 Conclusion

In this study, the prediction method of internal structure for designing braided composites was proposed. Following results were obtained:

- Aspect ratio, major axis of fiber bundles of braiding yarns and gap between braiding yarns were functions of distance between braiding yarns regardless of the difference in braiding angle.
- Aspect ratio for fiber bundle cross-sections of braiding yarns as a function of distance between braiding yarns could be approximated by a fractional function $F(x)$.
- Major axis of fiber bundles of braiding yarns and gap between braiding yarns as a function of distance between braiding yarns could be calculated based on the approximate expression $F(x)$.
- Parameters $a$ and $c$ in $F(x)$ could be represented as a function of filament number of middle-end-yarns.