1 Introduction

The braided fabrics are one of the typical textiles and have been expected to be excellent preforms as reinforcements for composite materials. Fig. 1 shows the schematic drawing of braided fabrics. One of the important features is the continuity of fiber bundles which oriented diagonally called braiding yarns (BY), and braided fabrics have capability to change orientation angles of braiding yarns called braiding angles. Another feature is that fiber bundles called middle end yarns (MEY) can be inserted into BYs along the longitudinal direction, so that excellent mechanical properties are expected. In addition, braided fabrics can be fabricated by using various kinds of BY and MEY with different properties simultaneously. Therefore, mechanical properties of braided composites can be variously designed according to requirements. In previous study, it was clarified that internal structures of braided fabrics were determined by four structural parameters; braiding angle, distance between braiding yarns, area and cross-sectional shape of braiding yarns, and these parameters have interrelationship with each other. For example, by changing braiding angle, a distance between braiding yarns, area and cross-sectional shape of fiber bundles are automatically changed. Therefore it proves a challenge to design mechanical properties and dimension of braided composites because to predict the internal structures of braided fabrics is very difficult. In recent study, the internal structural parameters and these interrelationships of braided composites with thermo-setting resin has been clarified. While in the case of braided composites with thermoplastic resin, the impregnation mechanism of thermoplastic resin is completely different from that of thermosetting resin because thermoplastic resin changes from a solid to a liquid state during impregnation process. In addition, thermoplastic resins with liquid state in high temperature usually have much higher viscosity than thermo-setting resin with liquid state. Because of these differences, in order to predict internal structures of braided composites with thermoplastic resin, it is necessary to investigate the impregnation process or mechanism of thermoplastic resin into fiber bundles and the change in internal structural parameters.

The purpose of this study is to establish the prediction method for internal structural parameters of braided composites with thermoplastic resin. In order to investigate the impregnation process and internal structural parameters, braided fabrics were fabricated with changing a distance between braiding yarns, and braided composites were fabricated with changing molding time. Cross-sectional observation was performed to investigate effects of the molding time and distance between braiding yarns on impregnate state and cross-sectional area and shape of braiding yarns. In addition, interrelationship between these parameters was estimated experimentally and numerically by reference to the prediction method for internal structure of braided composites with thermosetting resin.
2 Materials and Specimen Fabrication

Two intermediate materials; commingled yarn and advanced micro braided yarn (A-MBY); were employed for braided composites with thermosetting resin. Commingled yarn was a material in which reinforcing fibers and resin fibers were commingled. A-MBY was a material in which a reinforcing fiber bundle was covered with resin fiber bundles by using braiding technique. The structure of commingled yarns and A-MBY was shown in Fig.2 and Fig.3 respectively.

Carbon fibers (T700-12000-60E, 800tex, Toray Industries) were used as reinforcement and PA66 resin fibers (235dtex, Asahi-kasei chemical Industries) were used as matrix resin. One layer of braided fabrics was fabricated on a straight mandrel with two types of intermediate materials. Specification of braided fabrics was shown in Table 1. 16 of BY and 8 of MEY were used for the fabrication. 5 types of specimens were prepared with different distance between braiding yarns. The distance between braiding yarns were controlled by changing a diameter of mandrel and braiding angles.

Specimens were removed from the mandrel after fabrications. The tubular braided fabrics were flatten and put into metal mold and molded under heat and pressure. Finally, plates of strip specimens with 20 or 50mm in width were formed as shown in Fig.4. In order to investigate the internal structure for one-layer of braided composites, aluminum plate (1mm thickness) was inserted into braided composites to separate both layers before molding, because the plate of specimen had double layers which come from tubular structure of braided fabrics. The molding condition was shown in Table 2. Molding pressure was 3MPa, molding temperature was 290 degrees C, and molding time was changed as 30s, 1min, 3min, 5min, 10min, 30min.

![Fig.1. Structure of braided composites.](image1)

![Fig.2. Structure of commingled yarn.](image2)

![Fig.3. Structure of advanced-micro braided Yarn.](image3)

![Fig.4. Image of compression molding.](image4)
3 Experimental procedures
After cutting the specimen along the BYs and embedding it into epoxy resin, the cross-sections were polished and observed using an optical microscope. Schematic image of cross-sections along a BY was shown in Fig. 5. Cross-sections of fibers bundles were represented by an elliptical shape in this figure. Gray ellipses show cross-sections of BYs and white one shows MEY. A distance between yarns \((L)\), major axis \((A_L)\) and minor axis \((A_S)\) of BYs were measured in each cross-section. Aspect ratio of fiber bundle cross-section \(( = A_S/A_L)\) was calculated by \(A_S\) divided by \(A_L\), and corresponding to cross-sectional shape of the fiber bundle which is one of the structural parameters. Gap between braiding yarns \((\text{Gap})\) was calculated by subtracting the \(A_L\) from \(L\). And volume fraction of fibers in fiber bundles \((V_f)\) was calculated by dividing cross-sectional area of fiber bundles \((\text{tex/density})\) by area of reinforcing fiber bundle \((A)\). The relationship between quantified values of aspect ratio, major axis \(A_L\), volume fraction of fiber \(V_f\), gap between braiding yarns and molding time was investigated.

![Fig. 5 Schematic image of cross-sections along the braiding yarn.](image)

4 Results and Discussion
Change in cross-sectional shape of fiber bundles
The cross-sectional photographs for 3 types of specimens with commingled yarns with molding time of 1, 5, and 10 min were shown in Fig. 6 (a)-(c) respectively. White parts in these photos were resin rich region in fiber bundles. It was found that braiding yarns and middle end yarns were flattened (aspect ratio was decreased) with increase in molding time from these photos. In Fig. 6(a), resin rich region, impregnated and unimpregnated region were observed. And resin rich region unevenly existed in fiber bundles.

However, resin rich region in fiber bundles decreased with increasing molding time from 1 min (Fig. 6(a)) to 10 min (Fig. 6(c)). Fibers were distributed more uniformly with increasing molding time because of the flow of melted resin in fiber bundles.

The relationship between thickness of one layer and molding time in both specimens with two types of intermediate materials was shown in Fig. 7. The thickness decreased with increasing molding time and the thickness of commingled yarns was thicker than that of A-MBY. The relationship between major axis of braiding yarns and molding time was shown in Fig. 8. Major axis was increased with increasing molding time and major axis of commingled yarns was thicker than that of A-MBY. The relationship between aspect ratio of braiding yarns and molding time was shown in Fig. 9. Aspect ratio was decreased with increasing molding time and aspect ratio of A-MBY was larger than that of commingled-yarns. The relationship between \(V_f\) in braiding yarns and molding time was shown in Fig. 10. \(V_f\) in braiding yarn was increased with increasing molding time. \(V_f\) of commingled-yarns was as much as that of A-MBY. However, \(V_f\) of commingled-yarns tended to be smaller than that of A-MBY at short molding time 30 s and 1 min.

From these results, it was clarified that resin in fiber bundles were impregnated into fiber bundles with increasing molding time and the cross-sectional shape of fiber bundles was flattened (aspect ratio was decreased), and differences between commingled-yarns and A-MBY was found in cross-sectional shape of fiber bundles.

![Fig. 6 Cross-sectional photos for 3 types of specimens with commingled yarns at 1 min, 3 min, 10 min.](image)
Prediction of internal structures for braided composite with commingled yarns.

In the case of the specimen with commingled yarns, aspect ratio as a function of a distance between braiding yarns are shown in Fig.11. Unfilled squares, triangles and circles were experimental values for molding time 1, 3, 10 min. These results were obtained from the cross-sectional observation of braided composites. In previous study, it was suggested that aspect ratio for braiding yarns of braided composites with thermo-setting resin and distance between braiding yarns had the minimum values and aspect ratio could be approximated as a function of distance between braiding yarns by fractional function $F(x)$ as shown in Eq. (1). $F(x)$ is aspect ratio, $x$ is distance between braiding yarns, $a$ is proportional constant, $b$ is minimum distance between braiding yarns and $c$ is minimum aspect ratio. This expression shows that $x$ converges on $b$, and $F(x)$ converges on $c$. In other words, this expression shows minimum value of the distance between braiding yarns is $b$ and minimum value of aspect ratio is $c$. The minimum distance $b$ could be geometrically calculated when neighboring braiding yarns were contacted with each other assuming maximum aspect ratio of fiber bundle cross-section was 1. After that, $a$ and $c$ were decided to make approximate expression $F(x)$ as close as possible to measured values.
First, it was investigated whether this method for the internal structures of thermo-setting braided composites could be applied on braided composites with thermoplastic resin with commingled yarns. After deciding b, a and c were decided in the same way as mentioned above in each molding time. The obtained values of parameters a, b, and c are shown in Table 3 and approximated curves are shown in Fig. 11 as dashed lines. It was clarified that a was decreased with increasing molding time while c showed constant value regardless of molding time. From these results, it was suggested that aspect ratio of braided composites with thermoplastic resin could be predicted as a function of a distance between braiding yarns by changing parameter a according to molding time.

Then, prediction of other parameters (Major axis of fiber bundle cross-section, Gap) was conducted. Major axis was calculated by following expression (2) with area of an ellipse corresponding to cross-sectional shape of the braiding yarns. The predicted values of major axis are shown in Fig. 12 as dashed lines. Additionally, gap between braiding yarns was predicted by following expression (3). The predicted values of gap between braiding yarns are shown in Fig. 13 as dashed lines. From these results, predicted values of major axis and gap were in good agreement with measured values.

As these results, it was suggested that the internal structures with thermoplastic composites could be predicted even if in commingled yarns for intermediate material.

\[
F(x) = \frac{a}{(x-b)} + c \tag{1}
\]

\[
A_L(x) = 2 \cdot \sqrt{\frac{\text{Area of fiber bundle}}{\pi \cdot F(x)}} \tag{2}
\]

\[
\text{Gap}(x) = x - A_L(x) \tag{3}
\]
Prediction of internal structures for braided composite with A-MBY

Secondly, it was investigated whether the prediction of the internal structures with thermo-setting composites was applied on A-MBY.

Aspect ratio of A-MBY as a function of a distance between braiding yarns is shown in Fig.14. Experimental values for molding time 1min, 10min, 30min are shown as unfilled squares, triangles and circles which were obtained from the cross-sectional observation. As in the case with commingled yarns, a and c were decided with constant number b by changing a and c to make approximate expression $F(x)$ as close as possible to measured value. The values of each parameter are shown in Table 4 and predicted values were shown in Fig.14 as dashed lines. It was clarified that c was a constant value and a was decreased with increasing molding time as same as commingled yarns.

Then, prediction of other parameters (Major axis of fiber bundle cross-section, Gap) was also conducted. Major axis was calculated by expression (2) or (3). These results are shown in Fig.15 and Fig.16. Each predicted values of major axis and gap between braiding yarns were in good agreement with each measured value. From these results, it was suggested that the internal structures of braided composites with A-MBY also could be predicted.

Comparison between braided fabric reinforced thermo-setting and thermoplastic composite.

Next, approximate expression $F(x)$ of braided composites with thermo-setting and thermoplastic resin was compared. Each parameter was shown in Table 5 and approximated values of aspect ratio for thermo-setting resin or thermoplastic resin are shown in Fig.17 as a solid line or a dashed line.
Experimental data of braided composites with commingled yarns (molding time was 10min) and A-MBY (molding time was 30min) were used. It was found that the amount of change in aspect ratio was difference between thermo-setting resin and thermoplastic resin.

In the case of the specimen with commingled-yarns, the amount of change in aspect ratio for commingled-yarns was larger than that of thermo-setting braided composites. During molding, the resin fibers inside of commingled yarns melted and impregnated into the space between reinforcing fibers under pressure in thickness direction. Then fiber bundles of commingled-yarn specimen was flatten more than those of thermo-setting specimen. Therefore $a$ of commingled-yarn specimen was larger than that of thermo-setting resin specimen and the amount of change in aspect ratio for commingled-yarns was larger than that of thermo-setting resin.

In the case of the specimen with A-MBY, the amount of change in aspect ratio for A-MBY was almost as much as that of thermo-setting braided composites. However, in short distance between braiding yarns 2.0-5.0 mm, aspect ratio for A-MBY was larger than that for thermo-setting composites. And then $a$ of A-MBY was also larger than that of thermo-setting specimen.

In order to clarify the reason of the results, the relationship between unimpregnated ratio and a distance between braiding yarns was investigated for A-MBY. Unimpregnated ratio was calculated from unimpregnated area of fiber bundles divided by area of fiber bundles as shown in Eq. (4). The relationship between unimpregnated ratio and distance between braiding yarns for A-MBY was shown in Fig.18. Unimpregnated ratio was decreased with increasing distance between braiding yarns. Therefore, in order to clarify the reason, cross-sectional photos of A-MBY with a distance between braiding yarns of 2.6mm and 8.3mm were investigated. Those photos were shown in Fig.19. When a distance between braiding yarns was short in Fig.19 (b), impregnation was completed enough. Therefore it was found that impregnation state was changed depending on a distance between braiding yarns. As the result, aspect ratio for A-MBY was larger than that for thermo-setting composites and $a$ of A-MBY was larger than that of thermo-setting specimen because there was unimpregnated area in small range of distance between braiding yarns.

Additionally, major axis of fiber bundles of braiding yarns and Gap for each specimen was also compared. Those calculation results were based on Eq. (2) and Eq. (3). Fig. 20 shows the relationship between major axis of fiber bundles of braiding yarns and a distance between braiding yarns and Fig. 21 shows the relationship between gap between braiding yarns and a distance between braiding yarns. Each calculated values had good agreement with measured values respectively.

As the results, it was suggested that the internal structures of thermoplastics composites could be predicted in the same way as thermo-setting composites.

\[
\text{Unimpregnated ratio} = \frac{\text{unimpregnated area of fiber bundle}}{\text{area of fiber bundle}} \tag{4}
\]

<table>
<thead>
<tr>
<th>Material</th>
<th>$a$</th>
<th>$b$</th>
<th>$c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-12k-12k</td>
<td>0.190</td>
<td>0.925</td>
<td>0.030</td>
</tr>
<tr>
<td>Commingled yarn-10min</td>
<td>0.227</td>
<td>0.924</td>
<td>0.005</td>
</tr>
<tr>
<td>A-MBY-30min</td>
<td>0.290</td>
<td>0.846</td>
<td>0.010</td>
</tr>
</tbody>
</table>

![Fig.17 Aspect ratio as a function of a distance between braiding yarns](image)
Fig. 18 Relationship between unimpregnated ratio and a distance between braiding yarns.

(a) 2.6mm

(b) 8.3mm

Fig. 19 Cross-sectional photos of A-MBY at 2.6mm, 8.3mm distance between braiding yarns

Fig. 20 Major axis as materials of a distance between braiding yarns

Fig. 21 Gap as materials of a distance between braiding yarns.

5 Conclusion

The purpose of this study is to predict the internal structural parameters for braided fabric reinforced thermoplastic composite. The braided fabric was fabricated with two kinds of intermediate materials. During molding with heat and pressure, effects of molding time on the mechanism of impregnation and internal structural parameters were investigated. As a result, followings were the conclusion obtained in this study.

- It was suggested that the relationship between dimensional and internal structural parameters of thermoplastic resin with commingled yarn and A-MBY could be predicted by numerator function $F(x)$ of braided fabric reinforced composites.
- In thermoplastic resin, it was suggested that internal structural parameters of thermoplastic resin were changed by intermediate materials and resin content.
- In thermoplastic composites with commingled yarns, it was observable that resin rich region in fiber bundles decreased with increasing molding time because of the flow of melted resin in molding products and fibers in fiber bundles were distributed more uniformly. Furthermore, it was clarified that cross-sectional shape of fiber bundles were flattened (aspect ratio was decrease) and resin within fiber bundles impregnate in fiber bundles.
• In thermoplastic composites with A-MBY, although there was unimpregnated domain with a distance between braiding yarns was short, it was observable that the amount of change became larger than thermo-setting resin with a distance between braiding yarns became long and with increase of impregnation.

Reference
1) R. Morinaga, M. Imamura, A. Ohtani, A. Nakai
Dimensional and Internal Structural Design for Braided Fabric Reinforced Thermo-setting Plastic Composite. JCCM2012