EFFECT OF NAPS WITH ANISOTROPIC ORIENTATION BETWEEN LAYERS ON MECHANICAL PROPERTIES OF WOVEN COMPOSITES

J. Hirai¹*, A. Ohtani², A. Nakai², H. Hamada³

¹Composite Machinery Department, Tsudakoma Corp., Kanazawa, Japan
²Gifu University, Gifu, Japan ³Kyoto Institute of Technology, Kyoto, Japan

* j-hirai@tsudakoma.co.jp

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1 INTRODUCTION

The laminated fiber-reinforced composite materials have much influence on the mechanical properties; especially compression characteristics and flexural properties because interlaminar strength in out-of-plane direction is much lower compared with that in in-plane direction. In previous study, effects of naps on the carbon woven fabrics on interlaminar strength were investigated. In order to improve the interlaminar strength, various secondary processes have been applied to laminated fabrics, for example, stitching[1] and Z-Anchor[2] and so on, but these processes have propensity to decrease in-plane properties by giving damage to fibers. Moreover, without giving damage to fibers, some processes also applied to improve interlaminar strength, for example, Z-Pin[3] and thermoplastic powder, but these processes are adapted only to special applications because of some problems in the productivity and cost. In previous studies, the amount of naps were changed by cutting a part of warp or weft fiber bundles, and the relationship between interlaminar shear strength of laminate and the amount of naps were studied [4]. As a result, interlaminar strength has improved, but the in-plane properties decreased with increase in naps. In this study, in order to improve in-plane properties of composite laminates with naps, weft fiber bundles were partially cut to make naps with “Anisotropic” orientation. This method can make possible to generate naps equally without decreasing the productivity in fabric production on weaving machine. The effect of naps with “Anisotropic” orientation on interlaminar strength and in-plane mechanical properties were investigated.

2 EXPERIMENTS

2.1 Kinds of Nap Clothes

The naps were generated on both faces by “Naps Generating Machine” with cutter to cut only the surface of weft fibers of carbon fiber woven fabrics for making anisotropic naps. Three kinds of nap clothes (NAP A, NAP B and NAP C) with different quantities of naps were prepared by adjusting the position and contact pressure of the cutter. Fig.1 shows the magnified photograph of each clothes. Photographs of naps on cloth surface of three kinds of nap clothes (NAP A, NAP B and NAP C) are shown. Table 1 shows average nap density and length, and total nap length. The number of naps in the range of clothes was counted by watching with the microscope, and the nap density was defined as average value of that per 1cm². The nap length was defined as average of all nap length. The total nap length, a nap density and an average of nap length on all laminated cloth were multiplied, calculated as the total length of naps in test pieces of per 1cm².

Fig.1 Photographs of naps on cloth surface
2.2 Specimens and Test Methods

In this study, three kinds of woven fabrics with naps and non-nap cloth were prepared. 12 layers of each clothes were stacked and molded with the vinyl ester resin (R-806B, Showa Denko K.K.) by hand lay-up method. Fig.2 shows cross-sectional photos of specimens (NAP A, NAP B and NAP C) from longitudinal and transverse directions. Fig.3 shows the model of naps in interlayer. From these photos and model, some filaments were observed in the interlaminar resin rich region only in the photo from transverse direction. For these specimens, tensile test (JIS-K-7073), test for flexural properties (JIS-K-7074), short span bending test (JIS-K-7078), DCB test (JIS-K-7086), open-hole tensile test (JIS-K-7094), and 3-point bending impact test (JIS-K-7084) were carried out.

3 RESULTS AND DISCUSSION

First, tensile test (JIS-K-7073) was carried out. The size of coupon specimens was 200mm×25mm×3mm, and the size of gauge length was 100mm, and five coupon specimens of each sample were tested.

Fig.4 shows the relationship between tensile stress and deflection in longitudinal direction corresponding to warp direction of woven fabrics. It was clarified that NAP B and NAP C have the high tensile stress in longitudinal direction, and they have the high fracture deflection. It was clarified that fabrics with much nap have the high tensile stress and the high fracture deflection in longitudinal direction.

Fig.5 shows the relationship between tensile strength in longitudinal direction and total nap length. The tensile strength was increased almost linearly to the total length of nap. From this graph, the tensile strength increased up to 5%.

Fig.6 shows the photographs of cross sections in longitudinal and transverse direction of each specimen (NAP A, NAP B and NAP C). From these
cross-sectional pictures, the length of carbon fiber bundle of each specimen was measured. Table 2 shows the average value of heights of warp and weft yarn of each specimen. With increasing total nap length, the height of weft yarn was decreased. Therefore, it was considered that, by decreasing the crimp of warp yarn, the tensile strength in warp direction was increased.

<table>
<thead>
<tr>
<th></th>
<th>NON NAP</th>
<th>NAP A</th>
<th>NAP B</th>
<th>NAP C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warp Yarn</td>
<td>0.180</td>
<td>0.180</td>
<td>0.167</td>
<td>0.167</td>
</tr>
<tr>
<td>Weft Yarn</td>
<td>0.180</td>
<td>0.167</td>
<td>0.153</td>
<td>0.153</td>
</tr>
</tbody>
</table>

Next, test for flexural properties (JIS-K-7074) was carried out. The size of coupon specimens was 80mm×10mm×3mm, and the distance of between fulcrums was 60mm, and five coupon specimens of each sample were tested.

Fig. 7 shows flexural stress in longitudinal direction for each specimen as a function of deflection. Fig.8 shows flexural stress in transverse direction for each specimen as a function of deflection. From these results, relationship between flexural strength and total nap length was investigated. Fig.9 shows flexural strength in each direction for each specimen as a function of total nap length. As is the case with results of tensile test, flexural strength in longitudinal direction increased with increase in amount of naps. Meanwhile, the strength in transverse direction decreased with increase in amount of naps.
Fig. 8 Relationship between flexural stress in transverse direction and deflection

Fig. 9 Relationship between flexural strength and total nap length

Fig. 10 Photographs of the fracture surface after bending test. In all specimens, fracture occurred at compression side. In the case of non-nap specimen, fracture was delamination and continuously propagated straight along the surface of layers. While in the case of NAP A, B, C, the delamination was restrained.

Longitudinal direction Tranverse direction

(a) NON NAP
(b) NAP A
(c) NAP B
(d) NAP C

Next, short span bending test (JIS-K-7078) was carried out. The size of coupon specimens was 21mm×10mm×3mm, and the distance of between fulcrums was 15mm, and five coupon specimens of each sample were tested.

Fig. 11 shows relationship between interlaminar shear stress and deflection in longitudinal direction for each specimen obtained from short span bending test as a function of deflection. It was clarified that NAP B has the highest interlaminar shear stress in longitudinal direction, and all specimens have almost same fracture deflection.

Fig. 12 shows relationship between interlaminar shear stress and deflection in transverse direction for each specimen obtained from short span bending test as a function of deflection. It was clarified that NON NAP has the highest interlaminar shear stress in transverse direction, and all specimens have almost same fracture deflection.

Fig. 13 shows relationship between interlaminar shear stress in each direction and total nap length for each specimens obtained from short span bending test as a function of total nap length. Shear strength in transverse direction slightly decreased, while that in longitudinal direction increased with increase in amount of naps.
Next, DCB test (JIS-K-7086) was carried out. The size of coupon specimens was 140mm×25mm×3mm, and the polyimide film was inserted between the sixth and seventh layers, and the film crack depth was 40mm, and the pre-crack was approximately 2mm, and five coupon specimens of each sample were tested.

Fig.14 shows relationship between interlaminar fracture stress and deflection obtained from DCB test. It was clarified that NAP C has the highest interlaminar fracture stress, and all specimens have almost same fracture deflection.

Fig.15,16 shows relationship between interlaminar fracture toughness and total nap length obtained from DCB test. Interlaminar fracture toughness value increased with increase in amount of naps. Especially that of Sample C was about 40% larger than that of non-nap specimen.
Next, the open-hole tensile test (JIS-K-7094) was carried out. The size of coupon specimens was 200mm×30mm×3mm, and the size of gauge length was 100mm, with φ 10 drilled hole in center position, and five coupon specimens of each sample were tested.

Fig.17 shows relationship between open-hole tensile strength in longitudinal direction and total nap length for each specimen obtained from open-hole tensile test as a function of total nap length. This open-hole tensile strength was increased in case the total nap length was less than about 15-20 cm/cm², and this open-hole tensile strength was decreased in case the total nap length was more than about 15-20 cm/cm². From this result, it was clarified that open-hole tensile strength was increased in more than 5% by making total nap with about 15-20 cm/cm². Fig.18 shows photographs of the fracture surface after open-hole tensile test.

Finally, 3-point bending impact test (JIS-K-7084) was carried out. The size of coupon specimens was 110mm×10mm×3mm, and the distance of between fulcrums was 90mm, and five coupon specimens of each sample were tested.

Fig.19 and 20 shows bending impact load in longitudinal and transverse direction for each specimen obtained from 3-point bending impact test as a function of deflection. It was clarified that NAP A and B have the higher bending impact load in longitudinal direction, and all NAP specimens have longer deflection than NON NAP specimen. Meanwhile, all specimens have nearly same deflection in transverse direction.
Fig. 19 Relationship between bending impact load and deflection in longitudinal direction

Fig. 20 Relationship between bending impact load and deflection in transverse direction

Fig. 21 shows relationship between total absorbed energy in longitudinal direction and total nap length for each specimen obtained from impact bending test as a function of total nap length. This total absorbed energy was increased in case the total nap length was less than about 10 cm/cm$^2$, and this total absorbed energy was decreased in case the total nap length was more than about 10 cm/cm$^2$. It was clarified that there was the appropriate total nap length to get the highest total absorbed energy.

Fig. 22 shows relationship between absorbed energy to max load and total nap length for each specimen. This absorbed energy to max load was increased in case the total nap length was less than about 10 cm/cm$^2$, and this absorbed energy to max load was decreased in case the total nap length was more than about 10 cm/cm$^2$. It was clarified that there was the appropriate total nap length to get the highest absorbed energy to max load.

Fig. 23 shows relationship between impact flexural strength and total nap length in longitudinal direction for each specimen. This impact flexural strength was increased in case the total nap length was less than about 10-15 cm/cm$^2$, and this impact flexural strength was decreased in case the total nap length was more than about 10-15 cm/cm$^2$. It was clarified that there was the appropriate total nap length in longitudinal direction to get the highest impact flexural strength.

Fig. 24 shows relationships between impact flexural strength and total nap length in transverse direction. This absorbed energy to max load was increased in case the total nap length was less than
about 10 cm/cm², and this absorbed energy to max load was decreased in case the total nap length was more than about 10 cm/cm². It was clarified that there was the appropriate total nap length in transverse direction to get the highest impact flexural strength.

From these results, it was clarified that total absorbed energy, absorbed energy to max load and impact flexural strength were increased in more than about 10% by making total nap with about 10cm/cm².

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The effects of appropriate naps were evaluated and clarified by examinations and revealed that it was possible to control mechanical properties of composites by choosing the appropriate density and length of naps.

4 CONCLUSIONS

In this study, interlaminar shear and tensile, interlaminar fracture toughness, drop weight impact test for CFRP made by the nap clothes were investigated experimentally. It has been confirmed that interlaminar shear strength was increased by higher density and length of naps. It was thought that fracture toughness improved by generation of appropriate naps. Also, it was confirmed that property of impact absorption was improved by naps. The trend was admitted that both tensile strength and tensile elastic modulus decreased, but it should be improved by the way to make appropriate naps.

The effects of appropriate naps were evaluated and clarified by examinations and revealed that it was possible to control mechanical properties of composites by choosing the appropriate density and length of naps.

References