EFFECT OF INTERNAL STRUCTURE ON MECHANICAL PROPERTIES OF BRAIDED COMPOSITE TUBES

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Abstract

The purpose of this study is to clarify the relationship between the internal structure and mechanical properties for carbon fiber braided composite tube. Carbon fiber reinforced braided composite tubes, with fiber bundle orientation angle (called "Braiding angle") of 30, 45, 60 degree, were fabricated. The cross-section along the braided fiber bundle of the composite was observed and the parameters for the internal structure, that is braiding angle, distance between fiber bundles, and shape of the fiber bundle cross-section (aspect ratio and area of the fiber bundle), were quantified. And 4-point bending test was performed for each specimen, the relationship between the internal structure and the bending properties was clarified. Furthermore, Finite Element Model considering the internal stricture was proposed and bending modulus was estimated.

1 Introduction

The fiber reinforced plastic material is widely used as industrial materials instead of steel materials because of its superior specific strength. Especially tubular composite material has been used as structural material such as sporting goods, platform of vehicle, construction products and so on. As often as not, composite tubular members is manufactured with sheet laminating with unidirectional prepreg sheet and filament winding methods. Using textile material as reinforcements for fabricating composite tube, plane woven fabric or tubular braided fabric are often used. Woven fabric and tubular braided fabric have similar structure in microscopic view, but braided fabric has good features as fiber assembly.

The schematic drawing of braided fabric is shown in Fig. 1. One of the important features is continuity of the fiber bundle in the braided fabric. The all fiber bundles are continuously oriented, so that the seamless composite tube can be fabricated with tubular braiding technique. Moreover, the excellent mechanical properties were expected because of the continuity of fiber bundle. Other characteristic is capability of changing the braiding angle. Using woven fabric or unidirectional prepreg sheet for fabricating the composite tube, the fiber orientation angle is fixed uniformly. On the other hand, in braided fabric, all fiber bundles are diagonally oriented in longitudinal direction, and the angle of the fiber bundle to the longitudinal direction can be adjusted freely. Therefore, the mechanical properties can be variously designed according to the requirement.

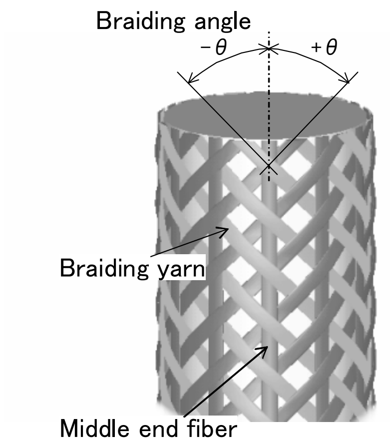

Fig.1. Schematic drawing of braided fabric.

The braiding angle, the distance between braiding yarns, and the cross-sectional shape of braiding yarn are are fundamental parameters for the internal structure of the braided fabric. These parameters are not independent value and have the interrelationship with each other. For example, by changing the braiding angle, the distance between braiding yarns, area and aspect ratio of the braiding yarn is automatically changed. In the result, the fiber density and the thickness of the layer are changed. Fiber density and the thickness increase with increase in the braiding angle. Since the interrelationship of these parameters have not been clarified, the designing the structural member of braided composite is difficult in considering the mechanical properties and the dimension such as thickness of layers.

In this study, the relationship between the internal structure of the braided composite and the mechanical properties was investigated on carbon fiber reinforced braided composite tube. Effects of the braiding angle on the internal structure and the mechanical properties of the composite tube were investigated by 4-point bending test. Furthermore, Finite Element Method (FEM) was performed to estimate the braiding structural model constructed by using beam element.

2 Experiment

2.1 Fabrication

Three braiding angle of 30, 45, 60 degree were chosen and each sample was called N30, N45, N60, respectively. The composite tubes were fabricated by tubular braiding machine (Murata Machinery, Ltd.) using 48 carbon prepreg yarns (Nippon oil corporation, in which fiber is the carbon yarn (TORAYCA T700-6k) and the resin is modified epoxy (Nippon oil corporation; resin impregnated ratio is 35wt%)).

For the fabricating process, prepreg yarns were braided around the mandrel with 20mm diameter. Then PP tape was wrapped around the preforms stacked with a few layer up to the predefined thickness of the braided tube and it was cured in an oven at 80oC for half an hour and at 130oC for 1.5 hours. The photograph and specification of the fabricated tubes are shown in Fig. 2 and Table 1, respectively. The number of stacking layers is decreased with increase in the braiding angle to keep the same thickness of composite tube with different braiding angle since the thickness of one layer increases with increase in the braiding angle.

2.2 Cross sectional observation

Observation of cross-section along the braiding yarn was performed for clarifying the parameters corresponding to the internal structure which decide the mechanical properties. Fig. 3 shows schematic drawings of the cross-section along the braiding yarn. From the picture of the cross-section, distance between fiber bundles, aspect ratio and

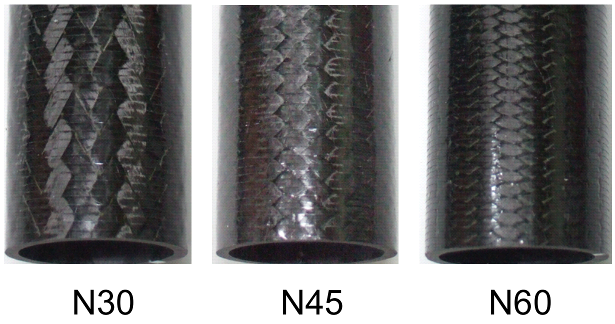

Figure 2. Photograph of the specimens.

Table 1 Specification of the specimens.

	Braiding angle (°)	Number of layers	Inner and Outer diameter (mm)	Vf (%)
N30	30	5	20.0×23.3	54.9
N45	45	4	20.0×23.3	53.8
N60	60	3	20.0×23.6	55.2

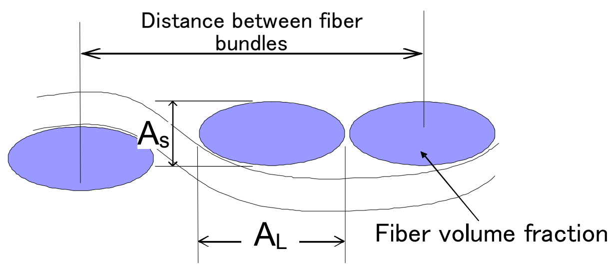

Fig 3. Schematic drawing of the cross-section along the braiding yarn.

area of the fiber bundle cross-section were quantified. Aspect ratio was calculated by dividing long axis by short axis of elliptical shape of the fiber bundle cross-section.

2.3 Bending test

The four-point bending test was performed by using the pulley unit and the metal solid-core bar as shown in Fig. 4. The pulley unit and the round bar are capable of decreasing the stress concentration generated at the point of support and loading nose. The rosette gage was stuck on the surface of the center and bottom part of the specimen to measure

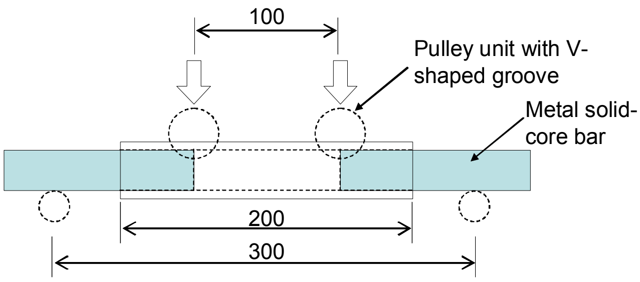

Fig 4. Schematic drawing of 4-point bending test.

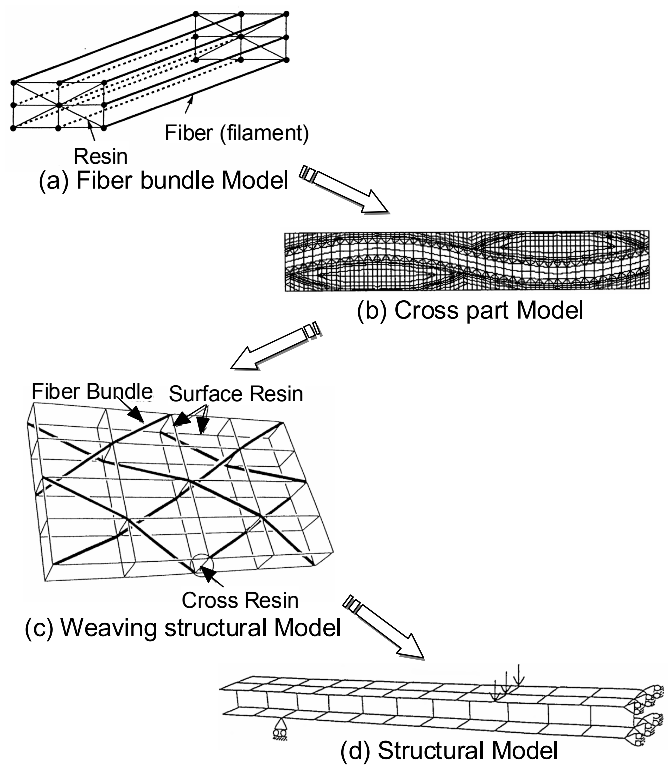

Fig.5 Procedure of braided composite analysis

the local tensile strain of the tube and to calculate the principal strain. The bending test was performed by using an INSTRON universal testing machine with a span length of 300mm and cross-head speed of 5mm/min.

2.4 Finite element method analysis

The procedure of the FEM analysis for braided composite was shown in Fig. 5. These analysis models were composed of 4 steps of model from micro model to macro model. These models are combined and used according to the requirement. In this study, both weaving structural model representing the braiding structure and the structural model representing the pipe structure were used.

The weaving structural model of the braided composite was shown in Fig 6. This model consists of 3-dimensional beam element to represent structure of the unite cell for the braided composite. The elements with thick line represent the fiber bundle element, and the other elements represent the resin element. The resin element consists of Surface Resin Element at the surface of composite and Cross Resin Element at the cross section of fiber bundle as shown in Fig.6. The shape of each element was rectangular cross-sectional shape and the shape was obtained by experimental observation in this study. The material constants were calculated with Rule of Mixture from the material constants of each fiber and matrix and Vf (Fiber volume fraction) in fiber bundles.

The structural model of braided composite pipe is shown in Fig.7. This model was divided by shell element. The material constants of each element were obtained by the results of weaving structural model. Namely, the elastic modulus and Poison's ratio obtained by weaving structural model were

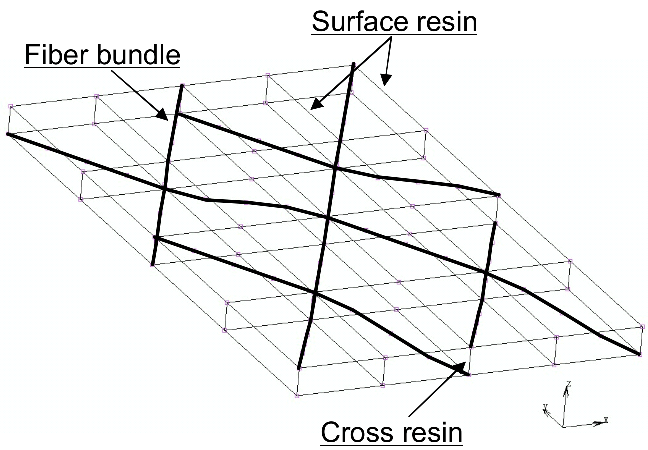

Fig.6 Weaving structural model

employed. The boundary condition was applied as actual 4-point bending test. From the deflection and the reaction force, the modulus of the pipe could be calculated.

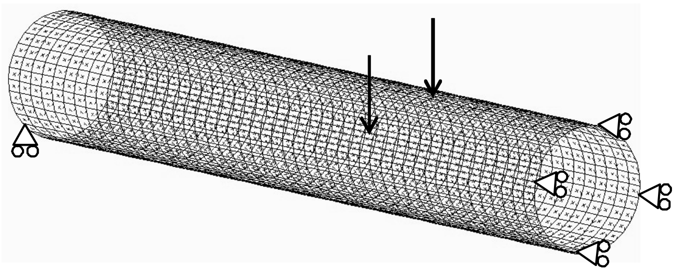

Fig.7 Structural model

3 RESULT AND DISCUSSION

3.1 Macroscopic Observation

Cross-sectional view of the each braided composite tube along the braiding yarn was shown in Fig.8. The ellipse cross-section of the fiber bundle can be seen in this figure. From these pictures, the parameters of the aspect ratio and area of the fiber bundle cross-section were obtained as shown in table 2. It is clarified that aspect ratio of the N30 and N45 is the same value and that of N60 is higher. The area of the fiber bundle cross-section decreases and the fiber volume fraction inside fiber bundle increases with increasing in braiding angle.

The distance between fiber bundles was examined as shown in Table 3. Here, two kinds of calculation procedure were introduced. One is the theoretical distance calculated from the circumference of the mandrel and the number of fiber bundle (distance A). The other is the least distance calculated from the geometric shape of the fiber bundle cross-section obtained from the observation results (distance B). In the case of N30, distance A is higher than distance B. Then, both distance is same vale at N45 and distance B is higher than distance A at N60.

From these results, the relative position of braided fiber bundle at the cross-section can be classified into 3 cases as shown Fig. 9. In "Case I" and "Case II", only the distance between fiber bundles is different and fiber bundles are limit to come close in "Case II". At the N30, distance A is larger than distance B. This means that the distance between fiber bundles is large enough and the structure is represented by Case I. In the case of N45, distance A and B is the same value. This means that the adjacent fiber bundles come close to limit as represented by "Case II" of Fig. 9. In the case of N60, distance A is smaller than distance B. This means that the distance between fiber bundles is too small to set the all fiber bundles around the circumference of mandrel. Therefore, in order to set the all fiber bundle around the mandrel, movement of the fiber bundle should be generated to the thickness direction.

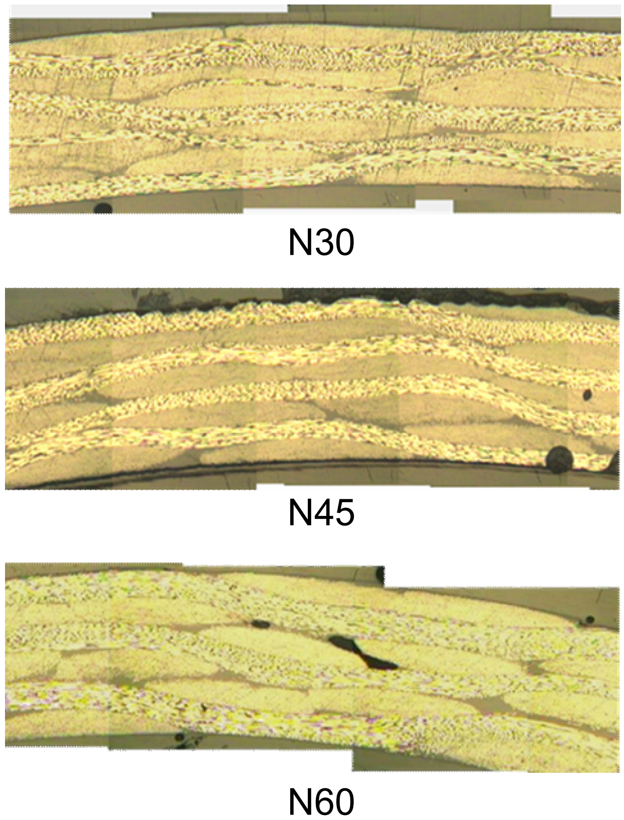

Fig.8 Cross sectional view along the braiding yarn.

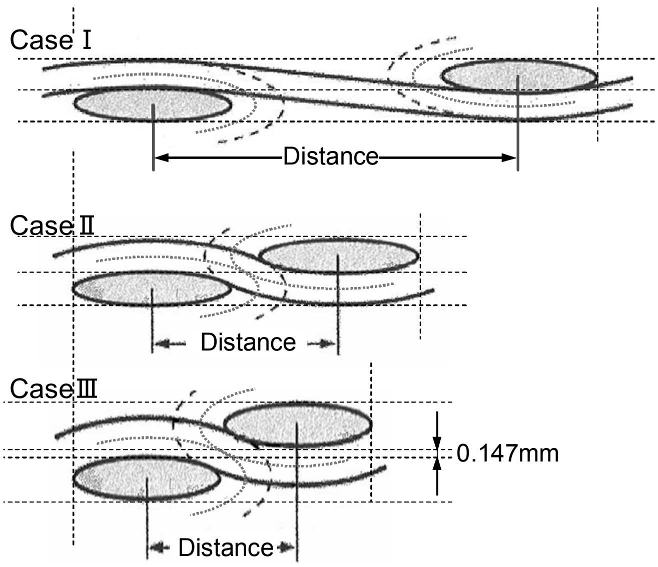

Fig.9 Schematic drawing of braiding structure.

The shift amount of fiber bundle to the thickness direction was investigated. Fig. 10 shows the relationship between the distance B and the shift amount of the fiber bundle in the thickness direction.

From this figure, shift amount in the thickness direction can be obtained by the theoretical distance calculated by the mandrel circumference and number of fiber bundle. In the case of N60, the distance was 3.3, namely the shift amount in the thickness direction resulted in more than 0.147 mm. The schematic illustration of internal structure was shown in "Case Ⅲ" of Fig. 9. The distance at "Case Ⅲ" became smaller than that at "Case Ⅱ" because of the shift of the fiber bundle in thickness direction.

From the quantifications of the internal structure, it is clarified that the mechanism of movement of fiber bundles. And the thickness, crimp ratio and Vf in fiber bundle have been obtained as shown in table 4. From this table, it is clarified that the crimp ratio and Vf in fiber bundle increase with increase in the braiding angle and the thickness is almost same value from 30 to 45 degree in braiding angle and increase from 45 to 60 degree. The results of this section is essential not only for estimating the mechanical properties investigated in next section, but also for the designing the dimension of the tube, that is, the prediction of the thickness.

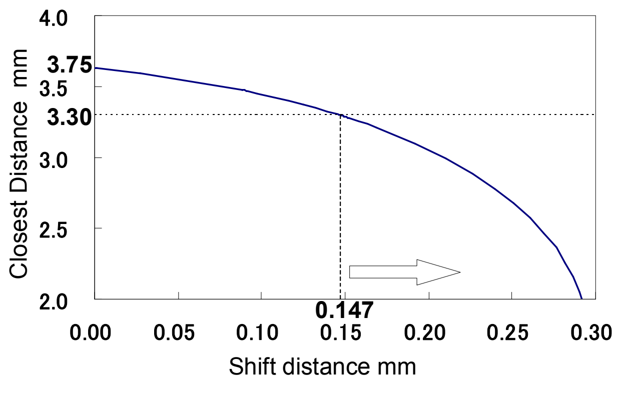

Fig.10 Relation between closest distance-shift distance

3.2 The results of bending test and FEM analysis

Table 2 shows bending modulus E_{ex} obtained by 4-point bending test. Also analytical modulus (E_{FEM}) and the achievement ratio were shown in this table. The achievement ratio A_{FEM} was obtained by dividing the bending modulus by the analytical one ($=E_{ex}/E_{FEM}$).

The bending modulus E_{exp} and the theoretical modulus E_{FEM} decreased with increase in the braiding angle. A_{FEM} of N60 was more than 80%, on the other hand, A_{FEM} of N30 and N45 was much lower than that of N60. It is considered that one of the reasons is the nesting of fiber bundles. In the case of N30 and N45, there is the enough distance between fiber bundles for the nesting between laminates to occur. However, in the case of N60, the distance of the fiber bundles is quite small and the nesting can not occur. In the present model, internal structure was considered as single layer. Further consideration of multi layer structure is needed. Moreover, in actual experiments, the pulley unit and the round bar are capable of decreasing the stress concentration generated at the point of support and loading nose. In the case of smaller braiding angle, local deformation occurred at the loading point because of lower modulus in circumferential direction, in which only loading point was deformed and deformation of tensile side became smaller to the deflection. This should be considered at the structural model

Table 2 Bending modulus and Achievement ratio.

	Modulus E_{ex}	Modulus E_{FEM}	Achievement ratio A_{FEM}
30-48	40.6	72.5	56.0
45-48	15.4	43.3	35.6
60-48	10.8	12.8	84.3

4 Conclusion

In this study, investigation of internal structure and mechanical properties of braided composite tube with different braiding angle was performed. The relationship between braiding angle and other parameters decided the braiding structure (the distance between fiber bundles, the aspect ratio and area of fiber bundle cross-section) was investigated. Furthermore, 4-point bending test was performed for each specimen, and the relationship between the internal structure and the bending performance was discussed. Finally, Finite Element Model considering the internal stricture was proposed.