ANALYSIS FOR MECHANICAL BEHAVIOR IN HYBRID BRAIDED COMPOSITE MATERIALS

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Keywords: *Hybrid composite materials, Resin hybrid, fiber bundle impregnated with flexible resin, Finite element analysis, Micro fracture, Prediction of stress-strain curve, Fracture mechanism*

1 Introduction

Hybrid composite materials are the material consists of more than two kinds of components. In hybrid composite materials, fiber hybrid, resin hybrid and interphase hybrid are included. Resin hybrid composite materials mean that some types of matrix resin are used in one composite material.

In this study, resin hybrid composite materials were analysis object and resin hybrid composite materials were applied to braiding composites. This resin hybrid braiding composite materials have infinite combination. Then, weaving structure and material constants are different, as the results, mechanical behavior of micro fracture and mechanical properties are different and it is very difficult to design resin hybrid braiding composite materials. Therefore, it is necessary to establish the design guide of these materials and it is effective to investigate by using numerical analysis method.

In this study, to investigate the effects of position and the number of fiber bundle impregnated with flexible resin on the fracture mechanism, by using finite element model considering micro fracture such as fiber fracture, matrix crack inside the fiber bundle and delamination between two fiber bundles, stress-strain curve and mechanical behavior of fracture progress in resin hybrid braiding composite materials were predicted.

2 Materials

The schematic drawing of braiding structure with middle-end fiber (MEF) was shown in Fig.1. Analysis object was flat braided composites, resin hybrid composite materials.

The braided fabrics were fabricated by two types of prepreg yarns with same carbon fiber and different matrix; one is resin with general versatility (T700-12-RC38-SX3: Nippon oil corporation) called Type N and the other is resin with flexibility (T700-12-RC35-25HS-B: Nippon oil corporation) called Type S. Here, the flexibility means lower modulus and high ultimate strain. These two resins had same-based polymer.

The seven kinds of specimens were fabricated with two types of prepreg yarns. The specimen ID and flexible fiber rate were shown in Table 1. 25 yarns for the braiding yarn and 10 yarns for the MEF were braided with a braiding angle of about 25 degrees. N25/N10 specimen was fabricated by using only Type N. N25/N6S4 and N25/S10 were fabricated by using Type N and S alternately as MEF. N15S10/N10, N10S15/N10, N5S20/N10 and S25/N10 were fabricated by using Type N and S alternately as braiding fiber. N25/N6S4 and N25/S10 were "MEF resin hybrid". N15S10/N10, N10S15/N10, N5S20/N10, S25/N10 were "braiding fiber resin hybrid".

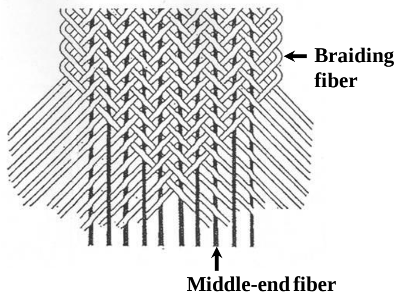

Fig.1 Schematic of braided fabric with MEF.

Table 1 Specimen ID and ratio of flexibility.

Specimens name (Braiding/Middle-end fiber)	Braiding fiber	Middle-end fiber	Flexible fiber rate
N25/N10	N×25	N×10	0%
N25/N6S4		N×6/S×4	10.9%
N25/S10		S×10	27.3%
N15S10/N10	N×15/S×10	N×10	29.1%
N10S15/N10	N×10/S×15		43.6%
N5S20/N10	N×5/S×20		58.1%
S25/N10	S×25		72.7%

3 Analysis method of resin hybrid composite materials

3.1 Analysis object

In this paper, the analysis results of N25/N10, N25/S10, N5S20/N10 and S25/N10 were introduced and analysis method of mechanical behavior in resin hybrid composite materials was stated.

3-2. Analysis procedure

First, by observation of internal structure in specimen, analysis model and cross sectional shape of each element were decided. Then, by combining tensile test results of N25/N10 and weaving structural model with normal resin, material constants of N were identified. Next, by combining tensile test results of S25/N10 and weaving structural model with flexible resin, material constants of S were identified. Finally, by using these detected material constants, stress-strain curves of N5S20/N10 and S25/N10 were predicted.

3.3 Analysis model

Fig.2 shows the weaving structural model represented flat braided composites. This model consists of 3-dimensional beam elements. The elements with thick line and dotted line represent middle-end fiber and braiding fiber bundle elements, and the elements with thin line represent resin elements. The resin elements consist of surface resin element at the surface of composite and cross resin element at the crossing point between two fiber bundles. In previous study [1], fracture mode of braided composite was investigated and it was clarified that crack inside of the fiber bundle was not generated in less than 45 degree of braiding angle. Therefore, interphase element inside of fiber bundle was not constructed in this analysis model.

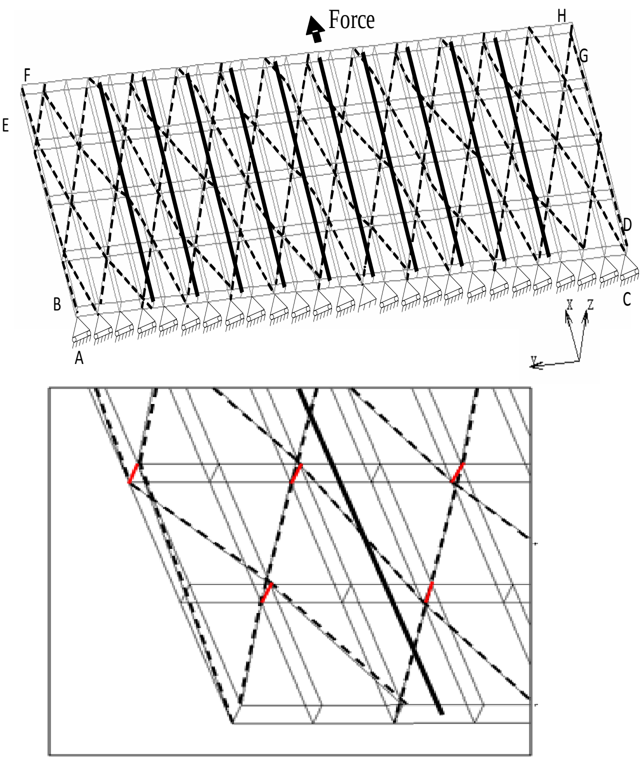

Fig.2 Analysis model of weaving structure.

3.4 Cross sectional shape

Cross sectional shape of each element for weaving structural model was shown in Table 2. These shapes in all elements were approximated to circle from cross sectional observation along braiding fiber. The cross sectional shapes of each fiber bundle element were calculated by using rectangular approximation with keeping the aspect ratio. In fiber bundle element, cross sectional area of N and S were different, Vf of N was 57% and Vf of S was 56%. In this case, the shape of each fiber bundle element was approximated rectangular shape with same cross section and aspect ratio.

Table 2 Geometry of textile.

Braiding angle (degree)	Distance between bundles(mm)	Cross-sectional Area (mm^2)		Fiber volume fraction (%)	
		N	S	N	S
25	3.126	0.787	0.800	57.0	56.1

3.5 Boundary condition

As the loading condition, incremental tensile displacement was adopted on the EFGH plane in Fig.2. One point of braiding fiber element on the plane of ABCD was selected to restrain the displacement and the rotation of all axes, and the other points on ABCD were selected to restrain the displacement in X axial direction and the rotation around Z axis. From analysis results, stress-strain curve was calculated.

3.6 Fracture theory

As the fracture theory, maximum principal stress theory was used. When the maximum principal stress in one element of braiding fiber or middle-end fiber elements reached the ultimate tensile strength of these elements, it was defined that entire of composite material was fractured.

3.7 Analysis condition

The braiding fiber element and middle-end fiber element in weaving structural model were considered to be a unidirectional fiber reinforced composite material. Then, material constants of these fiber elements as stress-strain curve were calculated as follows; Stress at each strain was calculated from the following equation (1).

$$\sigma = E_f \cdot \varepsilon \cdot V_f \left\{ 1 - \frac{1}{2} \left(\frac{E_f \cdot \varepsilon}{\sigma_c} \right)^{m+1} \right\} \qquad \sigma_C = \left(\frac{\sigma_0^m \tau L_0}{R_f} \right)^{1/m+1} \qquad (1)$$

R_f is diameter of filament, τ is interfacial shear strength, σ_0 is strength of filament, L_0 is gauge length, m is weibull modulus and V_f is fiber volume fraction. The catalog value was used for R_f,

σ_0 and modulus of fiber. V_f was calculated from the catalog value and cross sectional observation. However, m and τ were the unknown quantity. Therefore, analysis was performed with many patterns and material constants of fiber bundle were identified.

Material constants of each element were shown in Table 3. In the case of fiber bundle element, relationship between stress and strain calculated from the equation (1) was given as nonlinear elastic curve. The details of inputdata of fiber bundle element were shown in 4.1 and 4.2. The modulus of S was 90% of that of N, therefore, the effects of fiber bundle impregnated with flexible resin was considered. For surface resin element, material constants of unsaturated polyester resin were given as bilinear curve. Elastic modulus after the yield stress was tenth before the yield stress. In the case of cross resin element, it was assumed that elastic modulus was isotropic and elastic modulus of resin was given. This element represents interphase characteristics around fiber bundle. Therefore, strength is dependent on the stress component. Here, it was assumed that fracture was not generated at cross resin under compression stress.

Table 3 Material constants of each element for weaving structural model.

	Elastic modulus (GPa)	Yielding stress (MPa)
Fiber bundle element	Fiber bundle model	
Cross resin element	4.0	-
Surface resin element	4.0	60.5

4 Identification of material constants

4.1 In case of N

In braiding fiber bundle element and MEF bundle element, relationship between stress and strain from fiber bundle model was given as nonlinear elastic curve. Inputdata in this analysis was shown in Table 4. To identify material constants of N, many patterns in weibull modulus and interfacial shear strength were used for analysis. In this analysis, weibull modulus was assumed as 2.0, 4.0 and 8.0 and interfacial shear strength was assumed as 10MPa, 20MPa, 25MPa and 30MPa. These material constants of 12 patterns were used and the analysis object was N25/N10.

In this analysis, compression stress was generated at all cross resin element and therefore fractures were not generated at cross resin element. First, surface resin element reached the yield stress. The multiple fiber fracture has been generated and progressed as the stress generated in fiber bundle was increased. Then, the elastic modulus of the fiber bundle gradually was decreased, and the final fracture was generated.

From analysis results, stress-strain curve was calculated. Fig.3 shows stress-strain curves in case weibull modulus was 4.0 and interfacial shear strength was 10MPa. This stress-strain curve and ultimate strength in analysis were almost corresponded with experimental result. Therefore, material constants of normal resin could be identified.

Table 4 Input data for fiber bundle model with N.

Weibull modulus	***m* = 2.0 , 4.0 , 8.0**
Scale parameter	$\sigma_0 = 5000$ (*MPa*)
Gauge length	$L_0 = 10$(*mm*)
Fiber volume fraction	Vf = 0.57
Diameter of filament	$R_f = 7.5(\mu m)$
Interfacial shear strength	**τ = 10 , 20, 25, 30 (MPa)**
Modulus of filaments	$E_f = 235$(*GPa*)

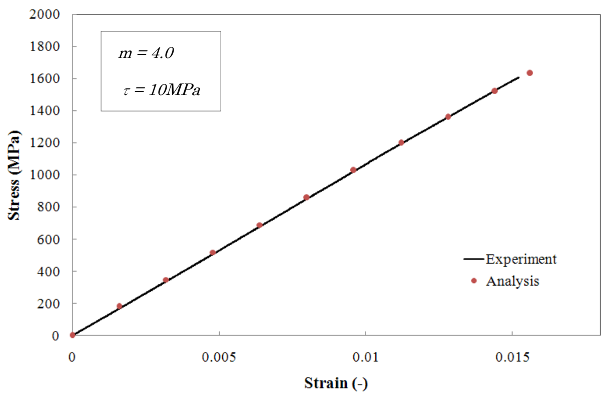

Fig.3 Stress-strain curves for N25/N10.

4.2 In case of S

Material constants of cross resin element and surface resin element were same with those in case of N. In material constants of fiber bundle, inputdata was shown in Table 5. In this analysis, weibull modulus was assumed as 2.0 and 4.0 and interfacial shear strength was assumed as 10MPa, 20MPa and 30MPa. These material constants of 6 patterns were used and the analysis object was S25/N10.

In this analysis, fracture mechanism was same with that in case of N. From results, stress-strain curve was calculated.

In all cases that interfacial shear strength was 10MPa, 20MPa and 30MPa, elastic region was the almost same curve. However, nonlinear region had a little difference. In case of 10MPa and 30MPa, strength of analysis results was smaller than that of experimental results. In addition, in case of 20MPa and 30MPa, the final fracture occurred at MEF of N. In case of 10MPa, the final fracture occurred at braiding fiber of S. Fig.4 shows stress-strain curves in case weibull modulus was 2.0 and interfacial shear strength was 20MPa. This stress-strain curve and ultimate strength in analysis were almost corresponded with experimental result. Therefore, material constants of flexible resin could be identified.

Table 5 Input data for fiber bundle model with S.

Weibull modulus	***m = 2.0 , 4.0***
Scale parameter	$\sigma_0 = 5000\ (MPa)$
Gauge length	$L_0 = 10(mm)$
Fiber volume fraction	Vf = 0.561
Diameter of filament	$R_f = 7.5(\mu m)$
Interfacial shear strength	$\boldsymbol{\tau = 10\ , 20\ , 30\ (MPa)}$
Modulus of filaments	$E_f = 235(GPa)$

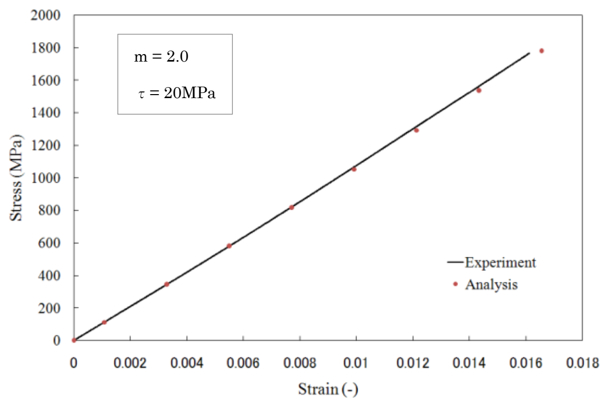

Fig.4 Stress-strain curves for S25/N10.

4.3 Analysis of mechanical behavior in resin hybrid composite materials

Table 6 shows the detected input data for fiber bundle model. When flexible resin was applied to composites, it was clarified that weibull modulus decreased and interfacial shear strength increased. By using these material constants, stress-strain curve of N25/S10 and N5S20/N10 were calculated. Fig.6 and Fig.7 show these stress-strain curves of N25/S10 and N5S20/N10. These stress-strain curves and ultimate strength in analysis were almost corresponded with experimental result.

Table 6 Input data for fiber bundle model.

	N	S
Weibull modulus	***m = 4.0***	***m = 2.0***
Interfacial shear strength	$\boldsymbol{\tau = 10\ (MPa)}$	$\boldsymbol{\tau = 20\ (MPa)}$
Modulus of fiber bundle	$\boldsymbol{E_f = 134\ (GPa)}$	$\boldsymbol{E_f = 118\ (GPa)}$

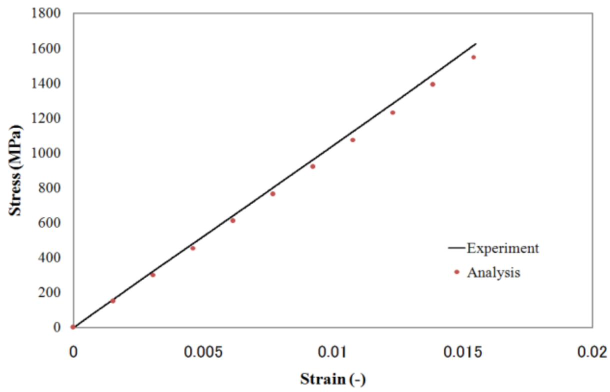

Fig.6 Stress-strain curves for N25/S10.

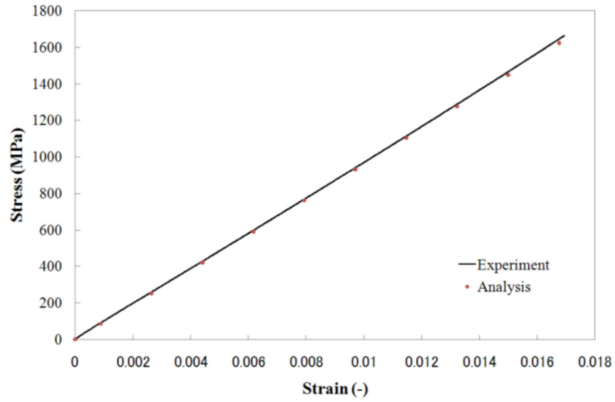

Fig.7 Stress-strain curves for N5S20/N10.

6. Conclusion

In this study, resin hybrid braiding composite materials were analysis object and the effects of position and the number of fiber bundle impregnated with flexible resin on the fracture mechanism were investigated. Finite element analysis considering geometry of textile and micro fracture was performed. By comparing between this analysis result and experimental results, the material constants of fiber bundle impregnated with normal and flexible resin was identified. That is, it was possible that interfacial properties such as weibull modulus and interfacial shear strength were quantified. Then, the prediction of stress-strain curve of resin hybrid composite and progress of fracture behavior became realized. In this analysis method, mechanical behavior in many kinds of resin hybrid composite materials can be analyzed. It was considered that these techniques are useful for control of the fracture and the optimization of the material design of resin hybrid composite materials in which the progress of micro fractures became more complex.

References

[1] K. Sakoda, “Design for mechanical behavior of hybrid textile composites considering micro fractures”, Master thesis, Kyoto Institute of Technology (2010).