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A study on fracture behaviors of aluminum and CFRP jointed with pin†

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Abstract

Weight reduction has been acknowledged in the automotive industry. Particularly, the weight reduction of automotive body is an eco-friendly technology development, as the corresponding fuel consumption or amount of gas polluting the atmosphere is greatly reduced. As a substitute light-weight material, Aluminum is frequently employed while there is CFRP (carbon fiber reinforced plastic) as the most highlighted material in the future. However, one of the problems is concerned with the coupling of light-weight materials. Particularly, in the case of CFRP having a certain fiber structure orientation, the direction perpendicular to fibers exhibits the disadvantage although each direction of fiber has great advantages in the durability and mechanical properties. Therefore CFRP materials will lose advantages of the material when holes or cracks have occurred in the material. Thus, in this study, mechanical characteristics occurring in stationary parts and cracked parts were investigated by producing holes and cracks in the center of the specimen fixed by a pin by using aluminum-6061, CFRP for woven type, and CFRP for unidirectional type. Also, experimental result data were confirmed by using the finite element analysis method and the verification was made by comparing the data corresponding with experimental data. The structural analyses were performed with the design of fiber structure and the lamination process was used for a more accurate design of CFRP. As experiments were performed by conducting with a universal tester by SHIMADZU Company of AG-X 50 kN, the reliabilities of analyses were verified.

Keywords: Aluminum; Carbon fiber reinforced plastic; Woven type CFRP; Unidirectional type CFRP; Mechanical property

1. Introduction

In this study, AL-6061 and CFRP (carbon fiber reinforced plastic) were used as light-weight materials currently in the experiments and the analyses were conducted as the basic data to identify the effects of the loads applied by the coupled mechanical structure with bolts or rivets [1-4]. Weight reduction is important in the automotive industry to maintain eco-friendliness [5-7]. The weight reduction of car body is a method capable of reducing fossil fuel consumption and smog gas generation [8-10]. The currently widely used material for weight reduction is aluminum, while the material under the spotlight as the light-weight material in the next generation. CFRP is divided into the carbon fibers for the woven type and the laminates stacking for the unidirectional type in a given direction. Such a CFRP where material characteristics are varied with fiber directions has the low durability when the separation has occurred from fastening of bolts or rivets, etc. and the fiber direction is broken due to the generation of cracks. To avoid such phenomenon, therefore, then positions of holes in the material should be designed appropriately. And the study on the property of CFRP shown at crack part has been going not much. As the analysis of stress intensity and concentration, the fracture trend due to crack can be guessed at the fatigue fracture. Likewise, the basic data exemplified as the fatigue fracture can be utilized when the material of machine is used by analyzing the fracture trend due to the crack at the aluminum and CFRP. In order to identify such characteristics in this study, the experiments and analyses were conducted by applying the load where three holes of 10 mm in diameter, that were pierced in the aluminum, the woven type CFRP, and the unidirectional type CFRP having a thickness of 2 mm, a width of 30 mm, a length of 100 mm, along with pins connected to holes at the tip of the upper and lower parts and a crack produced in the center hole [11-13]. This is an experiment suitable to checking for mechanical properties at pin holes for both tips and at the center crack. Also, to compare and analyze such experiments, the finite element analysis method was used. The finite element analysis method allows for the minimization of the number of experiments and the more visual analysis of resulting data [14-16]. In the present

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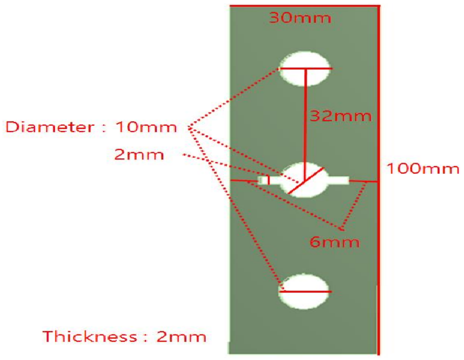

Fig. 1. Dimensions of analysis specimen.

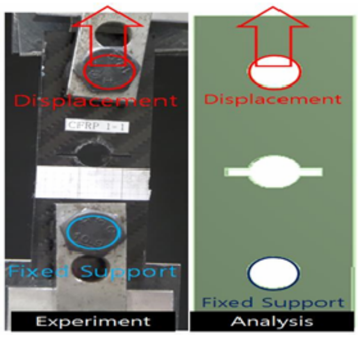

Fig. 2. Experiment and analysis conditions.

analysis, ANSYS was used as the finite element program, and fiber structures using ACP were designed to realize the CFRP structure. The occurrence of separation and interference at individual plies upon implementation of experiments in this study has been affirmed through this analysis.

2. Analysis conditions and results

2.1 Analysis model and conditions

As shown in Fig. 1, the analysis model had a circle of 10 mm in diameter drilled in the center part of specimen having a width of 30 mm, a length of 100 mm and a thickness of 2 mm. And both circles of 10 mm in diameter with the center at 32 mm apart from the center of the center circle were drilled in symmetry with the upper and lower parts. 2 mm-wide cracks in a straight line were generated by excluding the margin of 6 mm on both sides in the specimen. An analysis model was drawn by using the CATIA program.

As shown in Fig. 2, the analysis condition was set up by describing the experimental condition where displacement was given at a static speed by connecting with the jig supported by the pins to tensile tester after the installation of pins in holes at both ends with the center crack in order to make the analysis condition similar to the experimental condition. The lower pin was connected to the lower hole subjected to the fixed support and the upper pin subjected to the displacement. And the upper pin was made to move until the maximum of 6 mm at a static speed. Here, 6 mm is an excessive length in the specimen with a presence of a crack where a complete fracture of CFRP as a brittle material has occurred completely, and it can also be thought to exceed the yield stress in the case of aluminum. Also, in this study, three types of materials were used. Material properties for these materials are as shown in Table 1.

Table 1. Material properties for analysis model.

	Density (kg/m^3)	Young's modulus (MPa)	Poisson's ratio	Yield strength (MPa)
Aluminum-6061	2.7	68900	0.33	276
Woven type CFRP	1.52	70000	0.03	960
Unidirectional type CFRP	1.57	1.32×10^5(X) 8980(Y) 8980(Z)	0.3(XY) 0.74(YZ) 0.3(XZ)	1440(X) 51.72(Y) 51.72(Z)

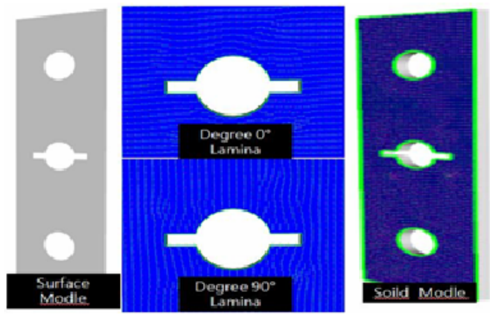

Fig. 3. CFRP modeling for unidirectional type.

2.2 Analysis modeling of CFRP for unidirectional type

CFRP for unidirectional type is the stacking of fibers having a given direction, and is a stacking of two sheets of laminate having lamination angles of [0/90/90/0]. To use such a special structure for finite element analysis, the fiber structures should be numerated and the numerated shape be made into a solid to conduct the mesh work. Thus, the characteristics as a function of fiber direction were numerated by using the APDL (ANSYS parametric design language), and the laminated fibers were conversed into the solid by using ACP (ANSYS composite prep-post). As shown in Fig. 3, the shapes of 0° and 90° in lamination angle for individual fibers were modeled by the numerical analysis technique.

2.3 Mathematical formulae used to the study of CFRP composite material

The formula expressing the shear modulus G value by use of elastic modulus and Poisson's ratio is as following Eq. (1). Also, the transformation matrix [T] is defined with ply coordinate and laminate coordinate and [T] is the matrix formula on the individual fiber angle. The Eqs. (2) and (3) on [T] are denoted with m and n as cosθ and sinθ, respectively. And plane-stress reduced stiffness matrix is defined as the Eq. (4)

and this formula transforms from stress into deformation. In this study, 3 dimension elements are eliminated by excluding the effect of 3 dimension because of having the load in a straight line. The subscript at all formulae shows the element with 3 dimensional direction at a piece of fiber string.

$$\mathbf{G} = \frac{E}{2(1+v)} \tag{1}$$

$$[T_1] = \begin{bmatrix} m^2 & n^2 & 2mn \\ n^2 & m^2 & -2mn \\ -mn & mn & m^2-n^2 \end{bmatrix} \tag{2}$$

$$[T_2] = \begin{bmatrix} m^2 & n^2 & mn \\ n^2 & m^2 & -mn \\ -2mn & 2mn & m^2-n^2 \end{bmatrix} \tag{3}$$

$$[\mathbf{Q}] = \begin{bmatrix} \frac{E_1}{1-v_{12}v_{21}} & \frac{v_{21}E_1}{1-v_{12}v_{21}} & 0 \\ \frac{v_{21}E_1}{1-v_{12}v_{21}} & \frac{v_{12}E_2}{1-v_{12}v_{21}} & 0 \\ 0 & 0 & G \end{bmatrix}. \tag{4}$$

By using the above obtained formulae, the in-plane stiffness matrix [A] is arranged as the following Eq. (5). Also, the matrix formula to verify in-plane force per unit length{N} is substituted and obtained by using this formula. Herein, k is the ply number of laminar layer and t is the thickness of each ply. [B] at the Eq. (6) is the bending-stretching coupling matrix. As [D] is the bending stiffness matrix, it can be ignored in this study in case of the plane load. [B] is the matrix formula shown with odd function. And k is the number of each ply at the Eq. (5). Also, k is the curvature shown at mid-plane at the Eq. (6) [17].

$$[\mathbf{A}] = \int_{-\left(\frac{h}{2}\right)}^{\left(\frac{h}{2}\right)} [\bar{Q}_{ij}]\,dz = \sum_{k=1}^{n} [\bar{Q}_{ij}]^{[k]} t_{ply}^{[k]} \tag{5}$$

$$\begin{Bmatrix} N \\ M \end{Bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{Bmatrix} \epsilon^0 \\ k \end{Bmatrix}. \tag{6}$$

2.4 Analysis result of aluminum-6061

Fig. 4 shows the contour of equivalent stress for aluminum-6061. Maximum equivalent stress appears around the crack, and the part showing the maximum equivalent stress of 298.02 MPa may be considered to the occurrence of a fracture as the yield strength of aluminum-6061 is 276 MPa. Also, the influence of stress was affirmed to be exerted up to the center hole and the hole positioned at both tips of the specimen. It was considered to be the effect on the stress appearing around the crack and the deformation of the specimen rather than the effects due to the pin. Fig. 5 shows the graph of a reaction force due to the displacement of the analysis model, and the maximum value of 6604 N was affirmed at the displacement of 3.1 mm. The values after the maximum value exhibit the tendency for inversely proportional reduction, and overall tendency is seen to be the same although the value did not become 0 N even at the maximum displacement of 6 mm.

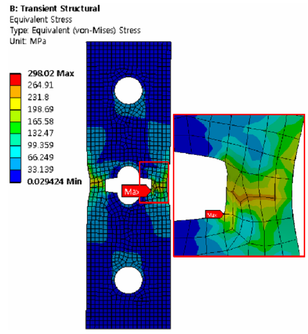

Fig. 4. Contour of equivalent stress at aluminum-6061 specimen.

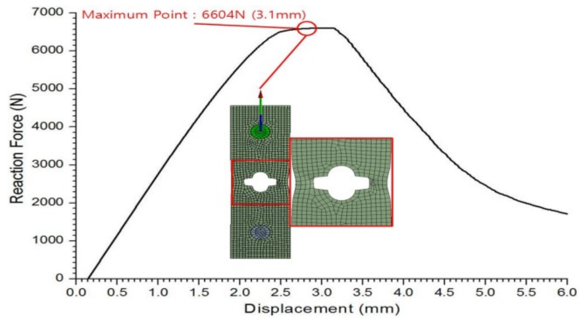

Fig. 5. Reaction force due to displacement in aluminum-6061 specimen.

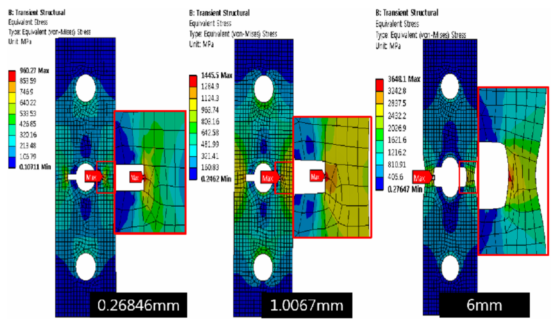

Fig. 6. Contour of equivalent stress at CFRP for woven type.

2.5 Analysis result of CFRP for woven type

Fig. 6 is the contour of equivalent stress in CFRP for woven type, where a fracture can be seen to have occurred at a displacement of 0.26846 mm, as the yield strength of the material of 960 MPa was exceeded, and the occurrence of a fracture can be seen to have occurred in the whole area at the tip of crack part at a displacement of 1.0067 mm. The continuous extension without exhibiting a fractured shape of material is seen at the maximum displacement of 6 mm. The fractured point can be seen by using the yield strength of the material.

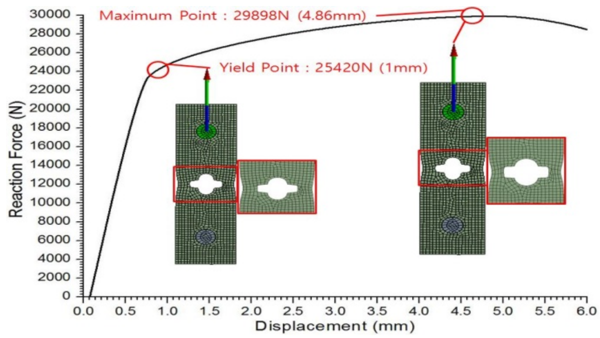

Fig. 7. Reaction force due to displacement in CFRP for woven type.

Also, in view that stress is applied to only the bottom of the hole part of the pin applied with loads, the fracture of the material due to the pin can be seen to be slower than the material fracture due to cracked part as a similar state to aluminum - 6061.

Fig. 7 shows the graph of reaction force due to the displacement for the woven type CFRP. The yield point occurred at a displacement of about 1 mm in Fig. 6. Although a value of 29898N was observed at the displacement of 4.86 mm as it progressed up to the maximum displacement of 6 mm designated in the analysis, the maximum reaction force can be considered to be 25420 N in the range until actual fracture occurs.

2.6 Analysis result of CFRP for unidirectional type

Fig. 8 shows the contours of equivalent stresses per ply of CFRP for unidirectional type. Unlike the woven type, the unidirectional type can be considered to have fiber directions along a straight line per ply. Particularly, eight plies exhibit the different propensities since two sheets of laminates having lamination angles of [0/90/90/0] were used in this study. Fig. 8 schematically shows four representative types excluding plies having overlapped features, where ply 1 has a fiber angle of 0°, being perpendicular to the load direction. Thus, since the load is acted in an outward direction of the pin coupled part with the occurrence of the load, the damage to the material can be considered to have occurred due to the pin. Maximum equivalent stress is 14881 MPa, and seen in the crack part. Also, since the yield strength of 1440 MPa is exceeded, the fracture can be considered to have occurred. Ply 2 has the fiber angle of 90°, being parallel to load direction. Since equivalent stress is occurred toward the inside of the part coupled with the pin with the application of load, i.e. toward the center of the specimen, the damage to the specimen due to the pin is small. Maximum equivalent stress is 54935 MPa, seen at the cracked part. Ply 5 is the first ply of the second laminate with the fiber angle of 0°. Since equivalent stress is occurred outward of the pin coupling part as with ply 1, the damage to the specimen due to the pin occurs. Maximum equivalent stress is 6261.9 MPa, and applied to the upper part of the center hole, based on which it can be seen that the deformation of specimen occurs in a direction other than the load direction, and

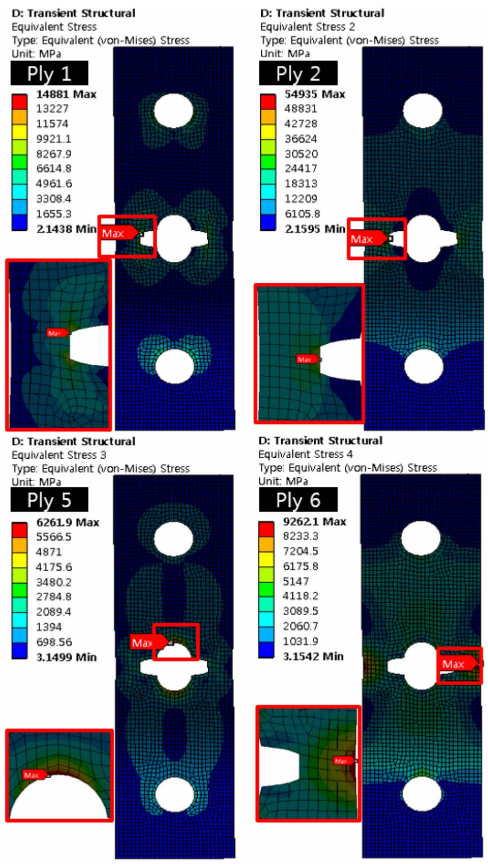

Fig. 8. Contour of equivalent stress distribution in CFRP for unidirectional type.

thus, the occurred deformation causes the separation from and interference with other plies. Ply 6 has the fiber angle of 90°. Since much of the equivalent stress produced in the pin coupling part is distributed in the direction of the center part of the specimen in a similar way to ply 2, there is no material damage due to the pin. However, maximum equivalent stress is 9262.1 MPa, being happened in the opposite direction to the crack progression direction. This state demonstrates the occurrence of separation and interference between plies due to damage and deformation of individual plies in a similar way to ply 5.

3. Verification with experimental results

In order to verify the analysis results, the experimental specimens have the same dimension as the analysis model, and a universal tester by SHIMADZU Company of AG-X 50kN was employed as an experimental instrument. Experimental condition had the rate of 0.5 mm/min with the lower part being fixed and displacement imposed as shown in Fig. 9.

3.1 Experimental result of aluminum-6061

Fig. 10 shows a test graph for aluminum-6061. Maximum reaction force was 7326 N, seen at the displacement of

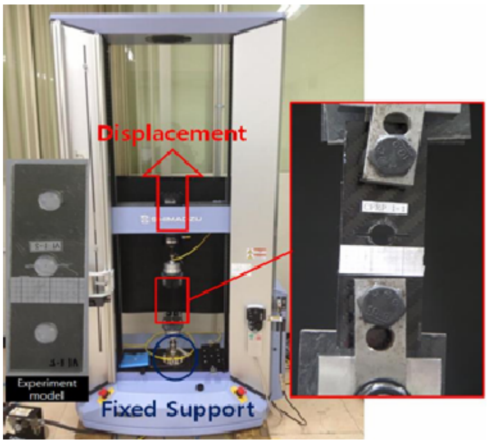

Fig. 9. Experimental setup.

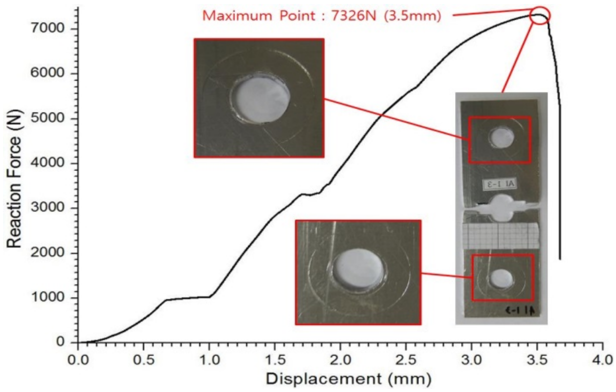

Fig. 10. Aluminum-6061 experimental result (reaction force due to displacement).

3.5 mm. Experimental values were observed to be higher than analysis values by about 10 %, and maximum reaction force was also shown at a displacement higher by about 10 %. This is attributed to the occurrence of deformation in the part coupled with the pin. Considering the shape of the part coupled with pin in Fig. 10, a light distortion can be affirmed. Thus, while there was no effect on the pin coupling part as the analysis considered to be an ideal situation in which it is considered that there is an effect with a difference from the analysis as much as 10 % occurring in the experiment. However, such difference of 10 % from the analytical value can be considered to justify reliability of the analysis. Also, there is a nonlinear part in the part where reaction force is increased, which suggests the occurrence of slipping of the pin as complete adherence for coupling between the pin and the specimen is difficult in experiments. In the analysis, it appears to be linear as a gap between the pin and the specimen is set up to be nonexistent.

3.2 Experimental result of CFRP for woven type

Fig. 11 shows the graph of reaction force due to displacement in CFRP for woven type. The graph shows the characteristics of CFRP as a brittle material where the values are drastically lowered after the maximum point, showing the slight vibration by which some values are observed lastly as an error in the experimental instrument. Maximum reaction force is 29986N, and is shown at a displacement of 1.2 mm. Although the value of maximum reaction force is almost similar to the analysis value, the experimental value is shown to be lower by about 75 % in the displacement acted upon. This may be explained as a phenomenon observed as the analysis recognizes the ductility due to inability to destroy the element in the analysis. The first fracture point observed in the experiment was shown to be similar to the yield point in the analysis, with the value of the first fracture point being 23702 N seen at the displacement of 0.8 mm. This is a value differing from the analysis value by 7 %, while the displacement also has the difference of 0.2 mm by showing the difference of 20 %. This can be suggested to be a reliable value. The first fracture in the experiment starts from inside of the specimen so that its visual confirmation is difficult. Also, considering the test piece in Fig. 11, each fiber can be seen to be broken. This is a characteristic of FRP (fiber reinforced plastic) having a fiber structure, which can be visually affirmed in the case of the woven type although it is shown to be smaller than the unidirectional type. In the case of CFRP for woven type, The deformation of the part coupled with pin is considered not to be much because of the strong rigidity.

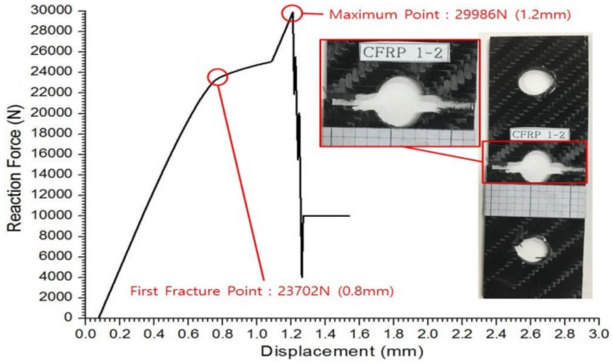

Fig. 11. Experimental results for woven type CFRP (reaction force due to displacement).

4. Conclusion

This study was investigated on mechanical characteristics of the part of specimen coupled to pin or bolt and the effects of cracks seen in the specimen with aluminum and CFRP. The following conclusions have been derived.

(1) In case of aluminum-6061, the maximum reaction force of 6604 N occurs at the displacement of 3.1 mm in analysis, while the maximum reaction force of 7326 N occurs at the displacement of 3.5 mm in the experiment. Both maximum reaction force and displacement show the difference of 10 %, which is due to the deformation of the part coupled to pin.

(2) In case of CFRP for woven type, maximum reaction

force of 29898 N occurs at the displacement of 4.86 mm at analysis, while the maximum reaction force of 29986 N occurs at a displacement of 1.2 mm at experiment. This is the phenomenon where the occurrence of a fracture cannot be realized by the element structure in the analysis so as to recognize the brittle material of CFRP as a ductile material. However, the values of maximum reaction force are almost similar. The yield point in analysis is 25420 N, seen at a displacement of 1 mm, while the first fracture point of 23702 N occurs at the displacement of 0.8 mm so that it may be considered to be similar.

(3) At the study of middle tension with crack, CFRP has the property of strength more compared with Aluminum-6061. By investigating the experimental data, the steep ascending curve is shown at CFRP. That is, the side design of intensity becomes superior because the material of CFRP is not shown to have much deformation. And CFRP is shown to have the lower stress concentration by examining the result analytically. Therefore, CFRP is thought to become favorable at the structure in which more intensive design is demanded at frequent fatigue load. At the existing structural fiber material, it is difficult to apply the mathematical formulae to analysis. But the possibility of finite element application at the composite material of fiber structure can be confirmed through this study result.

(4) In both aluminum-6061 and woven type CFRP, the fractures occur rapidly at the cracked part. Since fractures cannot be realized in the analysis, they can be seen by the identification as the yield strength of material property. Due to the characteristics of CFRP for unidirectional type, the occurrence of separation and interference at individual plies upon implementation of experiments with the same methods as those of this study has been affirmed through this analysis, which is considered attributable for the occurrence of reaction force in other directions than load direction as the load transmitted to each ply is acted in fiber direction.

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