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Fracture Property on CFRP Specimen with Adhesive Interface according to Laminate Angle at Opening Mode

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In this paper, CFRP specimens were processed with the configuration of opening mode to which various fiber laminate angles have been applied. It is possible to observe that the displacements of detachment at the adhesive interface differ from each other in both the experiment and analysis results. In case of the lamination at the angle of 30°, the detachment of adhesive interface occurred at the reaction force of 224 N with the progression of 5.24 m. In case of laminations at the angles of 45° and 60°, the detachment of bonded interface occurred with the reaction forces of 1134 N and 1100 N with the progressions of 4 mm and 4.7 mm, respectively. On the basis of these results, it was possible to discern that the differences in the detachment displacement of adhesive interface and reaction force occur according to the laminate angle in the CFRP with same material properties. Through this study result, it is thought that, unlike the existing woven type CFRP to which the laminate angle was not applied, securing of the basic fiber design data for manufacturing CFRP customized to the user's environment will be able to make contributions towards the improvement of the strength and stability of the bonded CFRP structures.

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1. Introduction

It is now possible to secure the material characteristics for a diverse range of user environments by enabling a single material to exhibit various characteristics through the application of improved composite materials.[1-10] Among these materials, carbon fiber reinforced plastic (CFRP) hardened along with epoxy with carbon fiber as the base has been widely used with the light metals in the modern industry on the foundation of its outstanding strength, rigidity, light weight, low thermal deformation rate, fatigue characteristics and chemical stability. Although there are the existing CFRPs composed of woven carbon fiber known as carbon fiber reinforced plastic, it is possible to manufacture products specialized to the environments of use by using the characteristics depending on the laminate angle by applying a diverse range of lamination methods through the use of the unidirectional carbon fiber. Moreover, it has the characteristic of being able to manufacture products with rigidity that are greater although they are thinner than the products composed of woven carbon fiber. However, CFRP equipped with light weight and high strength along with various other characteristics has various problems in manufacturing in comparison to the existing manufacturing method of metals. Unlike the metals that can be forged into highly complex configurations through casting, CFRP has the weakness in which it is molded for each of the component parts and bonded together. Moreover, in using the mechanical mounting method that accompanies physical contacts and pressure by bolts and rivets, etc., the structure fractures may occur due to the mountain pressure. Accordingly, the bonding methods by using thermal fusion or chemical adhesives are emerging as the means for solving such problems. The chemical bonding method by using adhesives is currently used even for the metallic materials by means of enhancing light weight. In this paper, the tensile characteristics of fiber reinforced plastic with characteristics that are different by depending on the laminate angle of the fiber and the effect of the tensile characteristics generated at the time on the detachment of an adhesive interface are investigated when the adhesives of epoxy series are applied to CFRP. For this purpose, the bonded interface is composed by using two specimens for opening mode with adhesives and the reaction force value at the displacement which happens at the detachment of bonded interface due to the forced displacement under the tensile test is calculated. It is thought that the assessment of the effect of fiber laminate angle at the bonded structure through this

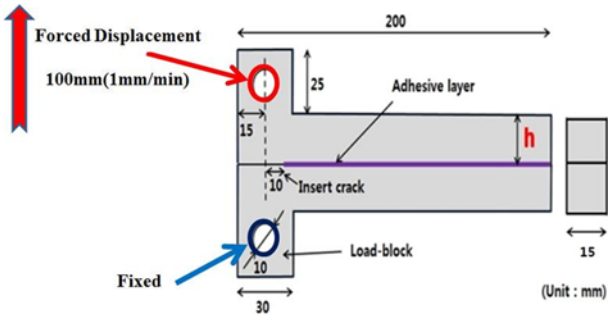

Fig. 1 Dimension of specimen

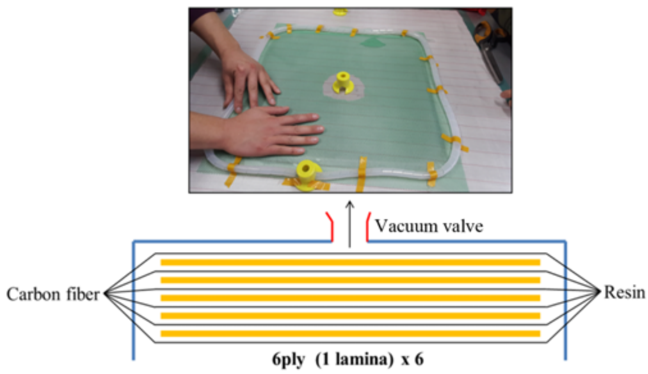

Fig. 2 Manufacturing of specimen by using vacuum molding method

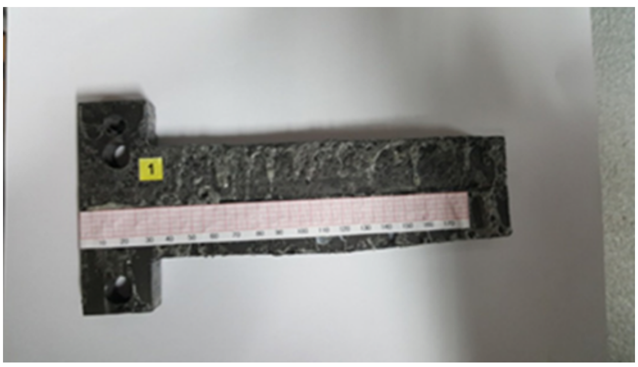

Fig. 3 Configuration of specimen

study can be utilized as the basic data for safety design.[11-17]

2. Static Experiment

2.1 Specimen and experimental condition

2.1.1 Manufacturing of specimen

Fig. 1 shows the dimension specimen and Fig. 2 shows manufacturing of specimen by using vacuum molding method. The vacuum molding method was used for manufacturing to minimize the generation of air bubbles within the material. The minimization of this bubble increases the strength of resin supporting the fiber. The specimen manufactured in this method is illustrated in Fig. 3. The thickness of the adhesive interface of double cantilever beam (DCB) specimen is coated with

Table 1 Material property of specimen

Material	Unidirectional carbon
Density (kg/m^3)	1.57
Young's Modulus XY (MPa)	1.32×10^5
Young's Modulus XZ (MPa)	8980
Young's Modulus ZY (MPa)	8980
Poisson's Ratio XY	0.3
Poisson's Ratio XZ	0.74
Poisson's Ratio ZY	0.3
Shear Modulus XY (MPa)	50769
Shear Modulus XZ (MPa)	2580.5
Shear Modulus ZY (MPa)	50769

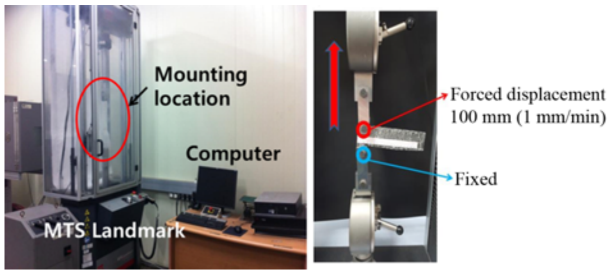

Fig. 4 Static experimental setup

consistent thickness in order to obtain the value of fracture toughness at the bonded joint of the adhesive interface and the tensile characteristics of specimen is assessed according to the laminate angle with the thickness of 15 mm. The material property of carbon fiber used for lamination in this study is illustrated at Table 1.

2.1.2 Test method

Test conditions applied to the specimen for the static experiment are illustrated in Fig. 4 and the pin hole located at the loading block of the specimen is fixed onto the jig connected to the load cell. The bottom load cell of the testing device is fixed, while the top load cell undergoes the forced displacement of 100 mm at the rate of 1 mm/min in the y-axis direction. Values of the reaction force generated while the forced displacement is in progress are obtained.

2.1.3 Analytic method

The data obtained through analysis was outputted to secure preliminary data ahead of the experiment. For the conditions of analysis, the boundary condition that is same as the testing conditions was simulated as shown by Fig. 1. The simulation analysis model for each of the specimens was composed by the layers with a thickness of 0.3 mm laminating six times in the unit of six layers. The fiber specimen was designed with the symmetry of laminate angle in order to minimize the occurrence of bending in the manufacturing process. The bonding conditions between the analytic models laminated in this method are set through the TB value by applying the cohesive zone material model illustrated in Fig. 5. It is possible to compute the reaction force on the adhesive force in proportion to the distance of movement of the nodes shared with each other by the external force. The accuracy of result values can be improved by carrying out the analysis of bonded areas by sharing the nodes between the finite element models precisely at the

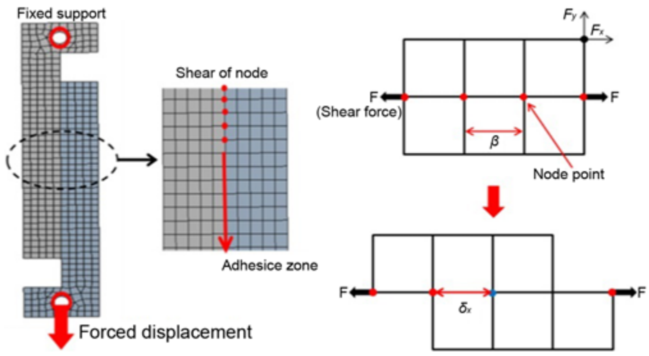

Fig. 5 Boundary condition applying cohesive zone material model

formation of the bonded interface. For the analysis model composed through the bonded interface applied with this method, the bottom pin hole is fixed while the top pin hole is moved to the y-axis direction under the same experimental condition. Material property values for the analysis are illustrated in Table 1, which are the same as the experimental condition.

3. Comparison of the Experimental and Analysis Results

3.1 Experimental results

Prior to the review of the experimental result, as the characteristic of the unidirectional fiber among the fiber reinforced plastic (FRP) with long fibers, each of the fibers has the reaction force against the external force by acting as axes and it can be anticipated that this force differs by depending on the fiber laminate angle. In addition, the stress that occurs in the structure acts from various directions simultaneously rather than acting only in a single direction. Accordingly, it is possible to secure the basic data for fiber design on the basis of the data obtained on the reaction forces from a diverse range of angles, rather than just in an axial direction.

As experimental result, Fig. 6 shows the force according to displacement in the specimen composed of the laminate angle of 30° and the maximum reaction force of 230 N was observed. In addition, the detachment of bonded interface, which is most important in the bonded structure, happened when displacement of approximately 3.6 mm occurred. After the occurrence of maximum reaction force in the bonded interface, the complete detachment happened at the displacement of 11 mm, a further displacement by 7.4 mm.

As experimental result, Fig. 7 shows the force according to displacement in the specimen composed of the laminate angle of 45° with the observation of the reaction force of approximately 1130 N and the displacement of 3.9 mm at the time of the occurrence of the detachment of bonded interface. In comparison to the aforementioned laminate angle of 30°, the displacement until the occurrence of the complete detachment of bonded interface is 11.2 mm, which is an increase by 51% when compared to that of the laminate angle of 30°. Moreover, it was observed that the reaction force value increased by about 80%.

As experimental result, Fig. 8 shows the force according to displacement in the specimen composed of the laminate angle of 60° with the observation of appearances that are different from the previous two experimental results. Although the reaction force until the occurrence of the initial detachment of bonded interface is similar to the results in cases of the laminate angles of 45° and 60°, this phenomenon can be seen that the consistent value of reaction force is shown from 1 mm to 2.5 mm. This area is the sector in which the impregnated fibers are offsetting the stress arising from the displacement with consistent value to certain extent in this displacement. The reaction force at the time was observed to be approximately 550 N. Moreover, it is possible to observe the occurrence of the sector in which the detachment of bonded interface occurs is later than the existing experimental values and this state can be considered to be the effect that the stress arising from tensile force is dispersed by the fibers effectively. Although there was no significant difference with the laminate angle of 45° in terms of the reaction force, and it is deemed that the laminate angle of 60° will be able to produce much more stable results under the condition of mode 1 by applying to the structure with the time of the detachment of bonded interface and the sector in which the reaction force is attenuated.

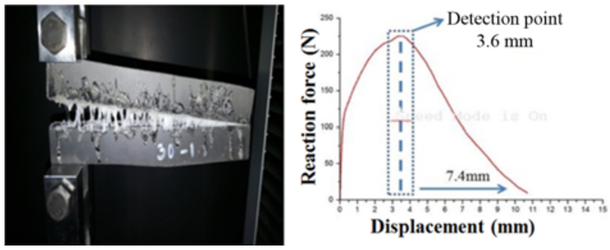

Fig. 6 Experimental result in the specimen at the laminate angle of 30°

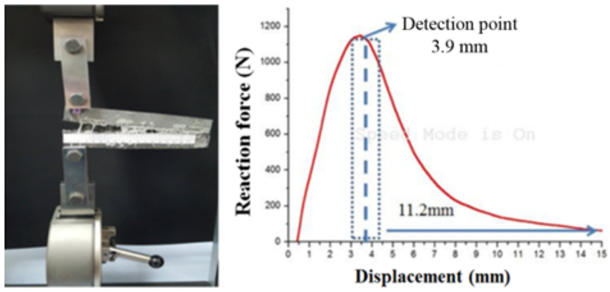

Fig. 7 Experimental result in the specimen at the laminate angle of 45°

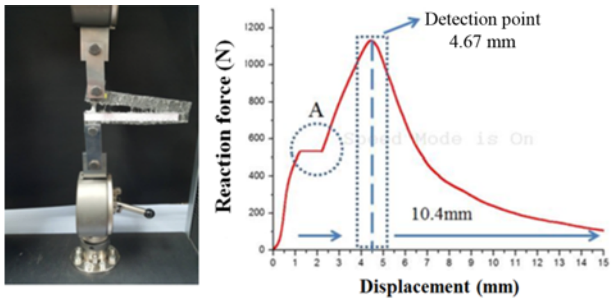

Fig. 8 Experimental results at the laminate angle of 60°

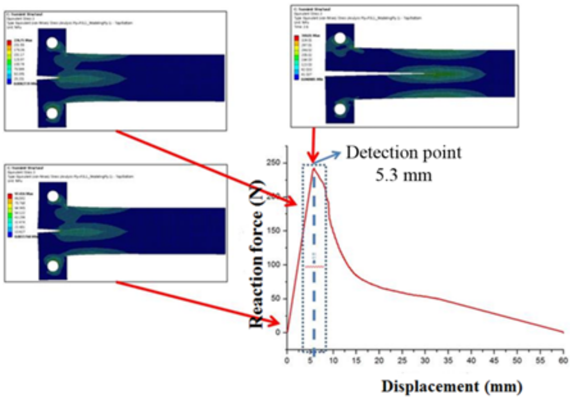

Fig. 9 Analysis results at the laminate angle of 30°

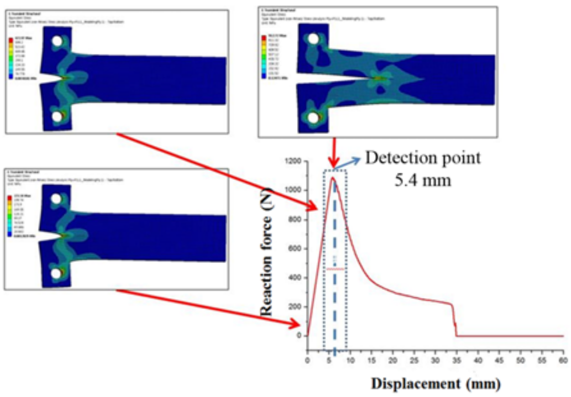

Fig. 10 Analysis results at the laminate angle of 45°

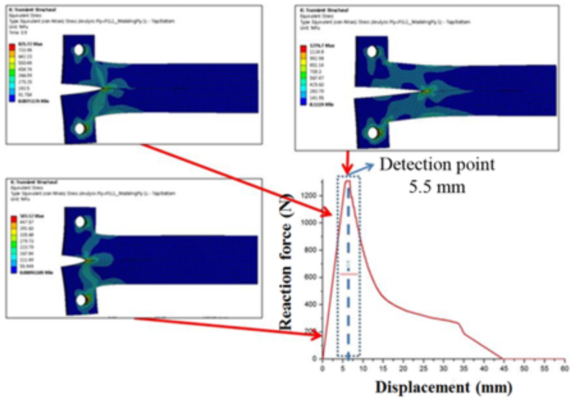

Fig. 11 Analysis results at the laminate angle of 60°

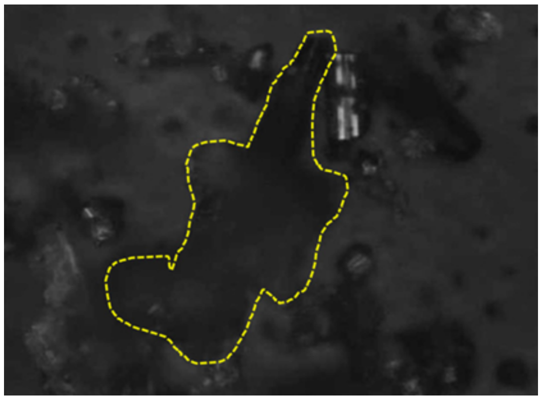

Fig. 12 Adhesive interface surface at the laminate angle of 30°

3.2 Analysis results

The analysis results in this study are slightly different from the experimental results. This is due to the connection of the nodes through the 'cohesive material zone model' used to reproduce the bonded interface. The bonded interface that was used in the actual experiment continues to have viscosity even when hardening. Accordingly, it shows the result of further delaying of the detachment of bonded interface due to this viscosity at the time of the occurrence of displacement. However, it is not possible to realize the viscosity that is the same as the actual viscosity in analysis. The connection between the nodes is severed when the external force applied exceeds the adhesive force, thereby resulting in a shorter sector in which the adhesive interface is maintained in comparison to the experimental values. It is thought that the error between experiment and analysis at the time of the occurrence of displacement occurs due to the deformation of slight sagging of the analysis model.

As analysis result, Fig. 10 shows the force according to displacement in the specimen composed of the laminate angle of 30° and, when compared to the experimental result of Fig. 6, the displacement occurs at about 5.3 mm with the maximum reaction force of 245 N. At this time, the errors compared with the experimental values were 32% and 8% for the displacement and reaction force, respectively. The equivalent stress that occurs in the specimen at the location at which the initial displacement begins is 97 MPa and the stress of 358 MPa happens at the point of the maxi-mum reaction force. It was possible to observe that these result values occurred below the yielding stress, thereby avoiding the fracture of the specimens.

As analysis result, Fig. 10 shows the force according to displacement in the specimen composed of the laminate angle of 45° and, when compared to the experimental result of the Fig. 7 the reaction force of 1130 N with an error of approximately 2% is shown with the displacement occurring at 5.5 mm with the error of 36% at the point of the maximum reaction force. The equivalent stress that occurs in the specimen at the location at which initial displacement begins is 223 MPa and the very high stress of 912 MPa is shown at the point of the maximum reaction force.

As analysis result, Fig. 12 shows the force according to displacement in the specimen composed of the laminate angle of 60° and, when compared to the results of Fig. 9, they display the reaction force of 1300 N with an error of approximately 11% with the displacement occurring at 6.0 mm with an error of 25% at the point of the maximum reaction force. When compared to the other two analyses, it is possible to observe that the displacement that occurs until the complete detachment of the adhesive interface becomes relatively shorter. On the other hand, the equivalent stress that occurs in the specimen at the location at which the initial displacement begins is 503 MPa and increases to the very high stress of 1276 MPa at the point of the maximum reaction force. Through this result, it can be seen that the structural stability against external force is illustrated at the laminate angle of 60° when applied to the structure.

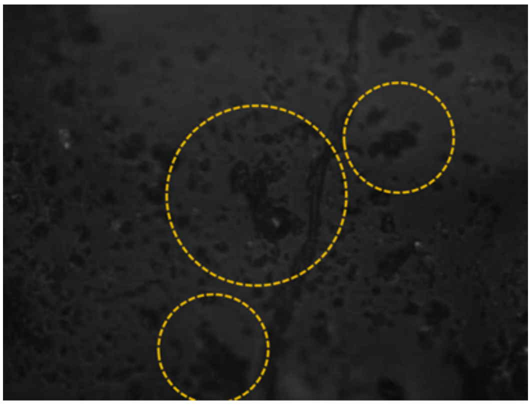

Fig. 13 Adhesive interface surface at the laminate angle of 45°

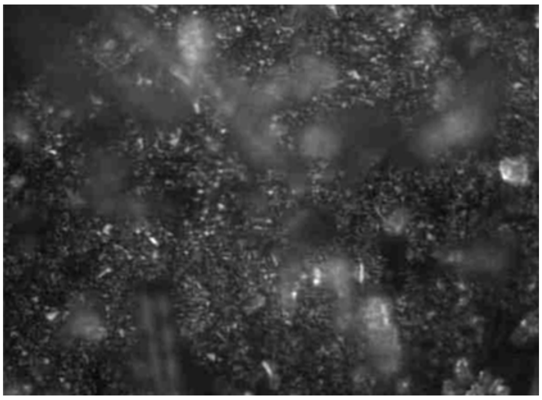

Fig. 14 Adhesive interface surface at the laminate angle of 60°

3.3 Configuration of adhesive interface

Regarding the specimen that formed the adhesive interface of chapter 3.1, the surface was filmed by using microscope in order to examine the presence of the fracture in the adhesive interface upon the completion of the experiment. Prior to filming, the adhesive remaining on the surface was removed by using a solvent without any surface processing. The specimen after the removal of the adhesives was observed at the same position and was able to investigate the effect of the laminate angle of the specimen bonded with adhesives on the bonded interface. Fig. 12 shows the configuration of interface for the laminate angle of 30°.

At the laminate angle of 30°, it was able to observe the trace of the detachment of the whole CFRP due to the effect of the short forced displacement of the adhesive interface. As the adhesive interface was detached at the short displacement as well as the low reaction force, it appears that the surface ended up quite rough. It is possible to see the clear differences when compared with Fig. 13 that shows the adhesive interface surface of the laminate angle of 45° and Fig. 14 in case of the laminate angle of 60°. In Fig. 14, it can be seen that the state of the surface of the adhesive interface of the laminate angle of 45° is better in comparison to that of the laminate angle of 30°. Unlike the laminate angle of 30° in which detachment of the adhesive interface occurred in large lump, it can be observed that the detachment occurs in small lump at the laminate angle of 45°. Due to this reason, unlike the laminate angle of 30° in which detachment of the bonded interface occurred rapidly at low stress, the laminate angle of 45° shows the latest time of detachment by displaying the relatively gradual stress curve.

The appearance that is substantially different from the adhesive interface surfaces of other previous laminate angles can be shown at Fig. 15 in case of the laminate angle of 60°. While the previous laminate angles showed the phenomenon of the detachment in lumps, the laminate angle of 60° illustrated the state in which only the resin on the surface was detached with the internal carbon fiber maintaining the intact configuration. At this time, the reaction force until the occurrence of detachment of the bonded interface is very high at 1130 N with the latest location of the detachment at 4.6 mm, thereby illustrating that the stress is being effectively dispersed at the corresponding laminate angle. Through these observations, it was possible to discern that the configuration of the adhesive interface can differ in accordance with the changes in the laminate angle and that such configuration can also differ, thereby obtaining the basic data for the fiber design.

4. Conclusion

In this paper, the tensile characteristics of CFRP specimen for mode 1 bonded with adhesive were confirmed through experiment and analysis. As the highest reaction force and displacement, the values are observed at the laminate angle of 60° in both analysis and experiment, in which this angle was evaluated to be most safe when applied to structures. In addition, on the basis of the result values of the experiment and analysis, the detachment of the bonded interface increasingly accelerates with the decrease in laminate angle, and it can be conjectured that the value of displacement at such time would be approximately 4 mm. In addition, the average error on the displacement at which the detachment of the bonded interface that occurs through experiment and analysis results is found to be 31%. Therefore, it is thought that the accuracy will be improved through the application of the adhesion curvature on the formation of the bonded interface by means of adhesion exfoliation at experiment instead of the existing reliance on the TB data at analysis. In addition, it was possible to confirm the reliability of reaction forces of the experiment and analysis as these values approach with an average error within approximately 7%.

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