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Experiment and Analysis Verification of Shearing Fracture Characteristic of Tapered Double Cantilever Beam with Aluminum Foam

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In this study, mode II(sliding) adhesive strengths of tapered double-cantilever beam (TDCB) specimens of aluminum foams bonded with adhesives were evaluated by finite element analysis. Models were fabricated for testing, and their length and thickness were 200 mm and 25 mm, respectively, while the angles between the adhesive layers and the horizontal direction for models (a), (b), and (c) were 8º, 10º, and 12º, respectively. The joint adhesive method was applied to the models that were made of Al-SAF40, aluminum foam. To generate the crack in shear direction, one end of the loaded block was restrained with a frictionless support while the other end of the loaded block was set to be displaced at the rate of 10 mm/min in the adhesive layer. The analysis and comparison result between the 3 different models revealed that the larger the tilt angle θ of sliding mode was, the larger the maximum load became, while the time to reach the maximum load and the time taken until the load disappeared were shorter as the value increased in the displacement-force reaction curve. This study can be applied to real structures with tapered contact surfaces by analyzing fracture behaviors and characteristics of composite materials such as aluminum foams bonded with adhesives.

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1. Introduction

Composite materials are materials made from two or more different materials by combining them to create properties that cannot be realized by single material. That is, it is a material made by combining two or more materials of different composition or ingredient macroscopically. Their application areas can be divided into structural applications and functional material applications by taking advantage of their excellent mechanical properties. Structural composite materials ensure toughness, strength, and temperature resistance so that they can be applied to many areas including power generation and turbine engine materials (parts that require high temperature and wear resistance), aerospace materials (parts that require high strength and toughness such as propellants), and industrial process equipment (heat exchangers, burners, furnace fans, and high-temperature fixtures).[1,2] Functional composite materials can be applied to various electronic parts and sensors using their electronic and magnetic properties, medical-purposed materials using their anti-bacterial properties, and environmental materials such as high-temperature gas filters and catalytic filters using their heat- and chemical-resistant properties. The emphasis on basic research of these composite materials has increased in order to provide data required for the systematic identification of their mechanical properties. In addition, the development of new high-quality materials and accurate analysis methods for fracture strength as well as safe design has attracted much attention by many researchers.[3,4]

When the joint method by punching with welding or drilling followed by fastening with bolts or nuts is applied to structures made with composite materials, processing time increases along with the weight of the assembly. In addition, fracture and deformation can occur in composite materials such as aluminum foams during assembly due to pressure from mechanical fasteners. Because of the above problems, the use of bonded structures, in which composite materials are attached using special adhesives such as epoxy, has increased in recent years. However, despite designs with sufficient strength and stiffness, fractures occur often in the mechanical or adhesive structures due to impact. Interfacial fracture behavior is generally found in adhesive joints due to interfacial cracks where an initial crack progresses from a bonded interface. Accordingly, manufacturers have considered the advantages of new adhesives compared to conventional joint technologies in terms of engineering composition and structural joints. Nonetheless, adhesive strength in a joint is considerably reduced under impact load conditions.[5]

Data for fracture toughness in adhesive joints are critical to determine the bond method in adhesively bonded structures. Therefore, the importance of basic research to provide accurate analysis of fracture strength, safe design, and development of new high-quality composite materials has increased. Evaluation methods based on nominal stress have been used for the strength evaluation of adhesive joints, but this is difficult under complex loading conditions or for adhesive joints in complex structures. Thus, evaluation methods using fracture mechanics have been most widely used for adhesive joint strength evaluation in recent years. The approach to fracture mechanics is to evaluate fracture toughness for the analysis of crack occurrence and growth, which is classified into crack opening mode (mode I) or crack sliding mode(mode II), depending on crack progress.[6-8]

In this study, tapered double-cantilever beam (TDCB) specimens of aluminum foam composite material were modeled followed by finite element analysis in accordance with the British Standard (BS 7991)[9] and the International Standard Organization (ISO 11343)[10] by examining and evaluating the adhesive strength with regard to mode II of TDCB adhesive structures made with aluminum foams.

2. Design of Analysis Model

Fig. 1 shows the change from the crack opening mode(mode I) of the TDCB specimen in the experiment[11] to the sliding mode (mode II) specimen used in this study. According to the redesigned TDCB model, Fig. 2 shows the 2D modeling design of the TDCB specimens with different tilt angles θ. The meshes of 3D model are divided with the hexagonal elements. But the meshes of 2D model are divided with the tetragonal elements. As the thickness is applied into 2D model in analysis, the configuration can be embodied like 3D model. As the analysis time can be reduced. 2D model is more useful than 3D model in this study.

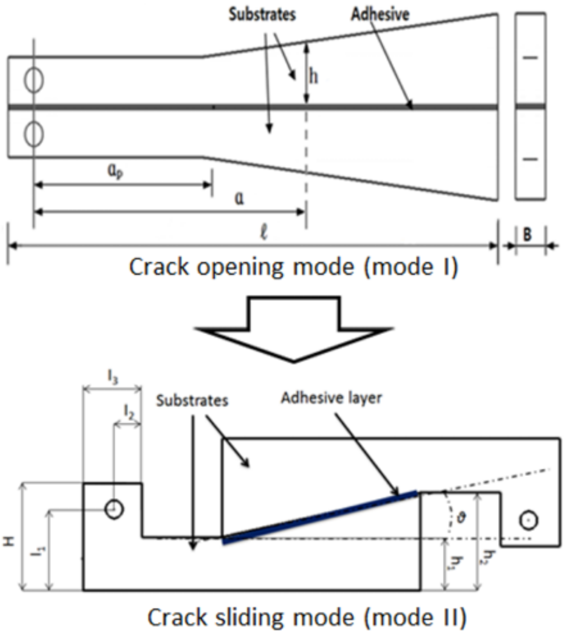
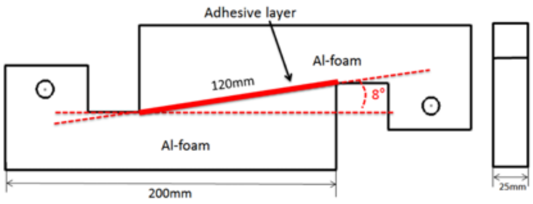


Fig. 1 Design of TDCB specimen

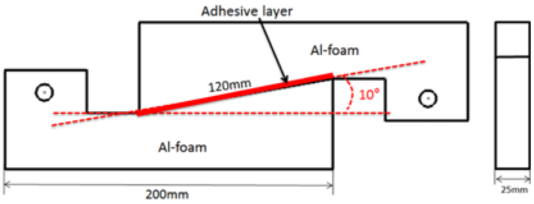
Models were designed with length and thickness of 200 mm and 25 mm, respectively. There are various kinds of the joints bonded with adhesive at the automobile at the real manufacturing process. This study investigates the specimen through experiment and analysis according to the tilt angle as the fundamental model of TDCB used frequently at the field of mechanics. If the specimen is made with the tilt angle below 5°, the error becomes higher as it is difficult to produce. If the specimen has the tile angle of more than 12°, the damage is happened at link part at experiment. And so, three models with tilt angles of 6°, 8° and 10° are designed representatively.

The reason for setting the angle of adhesive surface as parameter is that the angle of adhesive area in real structures using adhesives can vary as shown in Fig. 3. Thus, the shear strength evaluation of adhesive area was conducted by varying the angle at adhesive area as parameter in this study to simulate real structures as much as possible.[12,13]

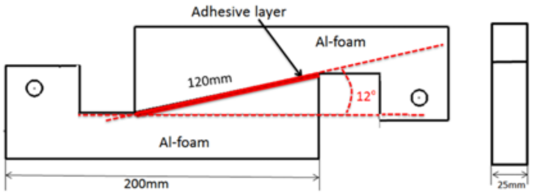
In addition, this study examined the shear characteristics of the



(a) Contact surface of 8°



(b) Contact surface of 10°



(c) Contact surface of 12°

Fig. 2 Designs of models

Fig. 3 Application of adhesive structure

specimens according to a tilted adhesive surface angle of the TDCB specimens. As shown in Fig. 5, in the case of using excessively strong adhesives, shear did not occur in the adhesive interface, but fracture occurred in the aluminum foam specimens instead. In that case, shear fracture could be observed in the adhered interface. Therefore, in the present study the specimens were bonded using industrial spray adhesive with appropriate adhesive strength that cannot generate fracture in the specimen. Aluminum foam specimens made by FOAMTECH located in Republic of Korea were used in this experiment. Specimen surfaces were not flat or smooth in general but had rough surfaces with irregular pores of 3 to 5 mm in diameter. When adhesives are sprayed onto such a rough surface, most of the adhesive penetrates into the pores. Because the applied amount of adhesive can influence the experimental result significantly, spray was applied for 2 seconds to the surfaces of all specimens in this study. In addition, all the specimens were dried for 15 min, and the specimens were bonded to each other by applying the load of 2 kg perpendicular to the adhered surface for 4 hours.[14,15]

3. Experimental Setup and Results

The apparatus used in this experiment was a Landmark tester from MTS Company as shown in Fig. 6. The maximum force that can be applied to the specimen is 10 kN. By using the load cells of this experiment equipment, the resistance force and the displacement at the loading point, which are generated when the specimens are separated, can be measured. Data were outputted to computer, and all the processes before and after the experiment were recorded by a video camera. Crack locations were measured in the video images. The pins were installed in holes in the load blocks of the specimens and mounted to jigs connected to the load cell as shown in the above figure. The upper load cell was fixed while the displacement was applied in the downward direction by the lower load cell. The displacement speed was set to 10 mm/min.

Three types of the specimens showed similar behavior, so the specimen with the tilt angle of $\theta = 12^{\circ}$ was selected as being representative. Fig. 7 shows the static experiment performed with regard to the shear mode of the specimens. The forced displacement increased continuously from 0 to 10 mm, and complete separation occurred in the area where more than 10 mm displacement occurred.

Fig. 8 shows the graph of the displacement-force reaction of the 3

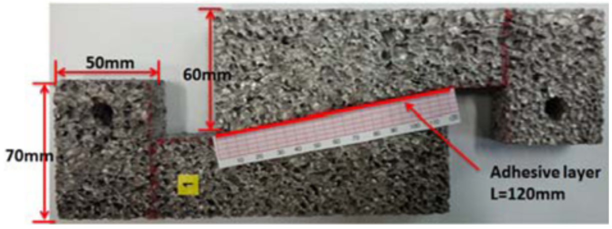


Fig. 4 Experimental specimen

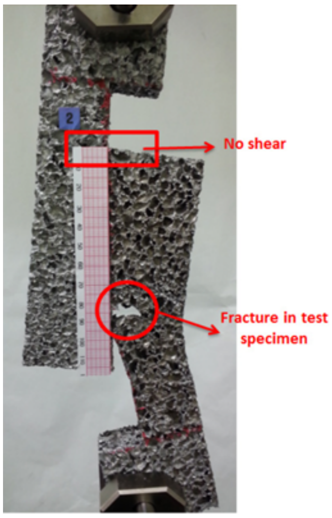


Fig. 5 Failure of test specimen

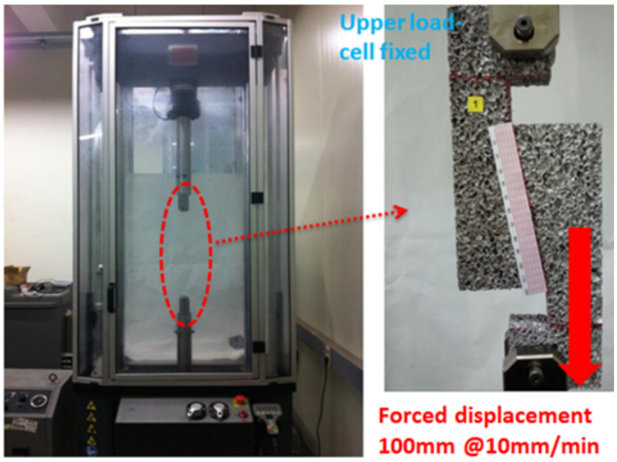


Fig. 6 Experimental setup

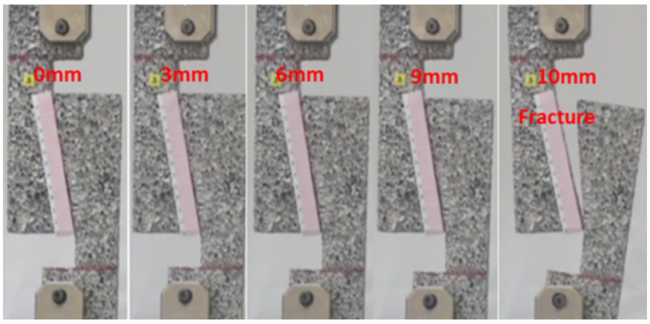


Fig. 7 Specimen configurations during process of forced displacement ($\theta = 12^{\circ}$)

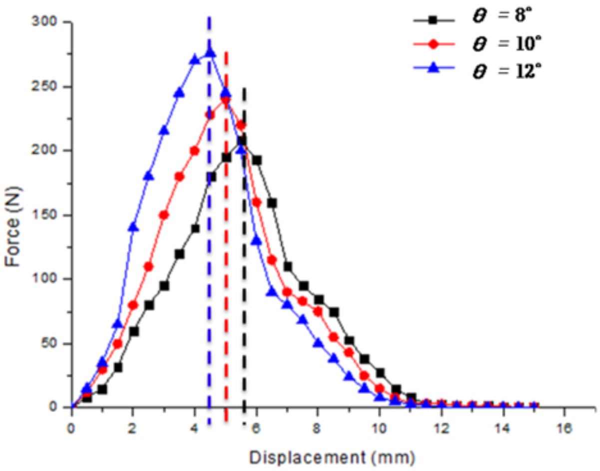


Fig. 8 Experimental graphs of displacement–force reactions

specimens. Among them, the specimen with the tilt angle of 8° had the maximum force reaction value at 208 N according to the forced displacement. Each 2° increase of angle increased the force reaction linearly according to the forced displacement. The maximum force reactions at 10° and 12° were 240 N and 280 N, respectively. As the angle increased by 2°, the force also increased by linearly by 35 N. When forced displacement of about 4 to 6 mm was applied to the 3 types of the TDCB specimens, the maximum force occurred and then adhesive strength was shown to reduce rapidly after the maximum force zone was passed. Once the forced displacement progressed 10 to 11 mm, the adhesive strength almost disappeared. The larger the angle of the tilted surface was, the shorter the time to reach the maximum force and the subsequent complete disappearance of the force.

4. Numerical Analysis Setup and Results

In order to compare and verify the data obtained through the experiment, finite element analysis was conducted with constraint condition same as experiment. In this study, 3 types of TDCB specimens were modeled and divided with meshes through the finite element model method, thereby determining the force reaction. To generate crack in the shear direction, one side of the loaded block was restrained with the frictionless support while the other side of the loaded block was set to be displaced at the rate of 10 mm/min in the adhesive layer. The coefficient of friction is near 0 and the free sliding is allowed. A boundary condition was set as shown in Fig. 9 with regard to the model of the tile surface angle $\theta = 12°$. Table 1 shows the property of the aluminum foam TDCB model.[16] The numbers of nodes in the modeling with tilt angles $\theta = 8°$, $\theta = 10°$, and $\theta = 12°$ were 1,506, 1,458, and 1,644 while the number of elements were 1,338, 1,288, and 1,464 respectively.

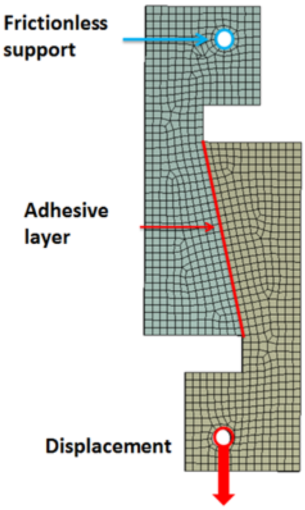


Fig. 9 FE model and constraint condition

Table 1 Property of aluminum foam

Property	Value
Density(kg/m^3)	400
Young's modulus(MPa)	2,374
Poisson's ratio	0.29
Yield strength(MPa)	1.8
Shear strength(MPa)	0.92

Fig. 10 shows the equivalent stress on the specimens in the TDCB specimen model with a tilt angle $\theta = 12°$ according to the forced displacement(D). As shown in the figure, as the forced displacement increased from 0 to 6 mm, the equivalent stress of the specimen also increased. Then, the equivalent stress decreased until 10 mm of the displacement, after which it almost disappeared.

Fig. 11 shows the simulation graph of displacement-force reactions at 3 types of specimens. The data obtained through experiment was somewhat different due to various errors (machine vibration, friction, and other variables), while the data obtained through the simulations did not contain these errors by obtaining constant result values. Fig. 11 below shows that the maximum force occurred in the area when the forced displacement reached 4 to 6 mm, and then the force almost disappeared once the forced displacement reached 10 to 11 mm. As in the experiment, the simulation result showed that the larger the tilt angle was, the shorter the time to reach the maximum force and subsequent complete disappearance of the force.

5. Comparison between Experimental and Simulation Data

Fig. 12 shows a graph of comparison between experimental and

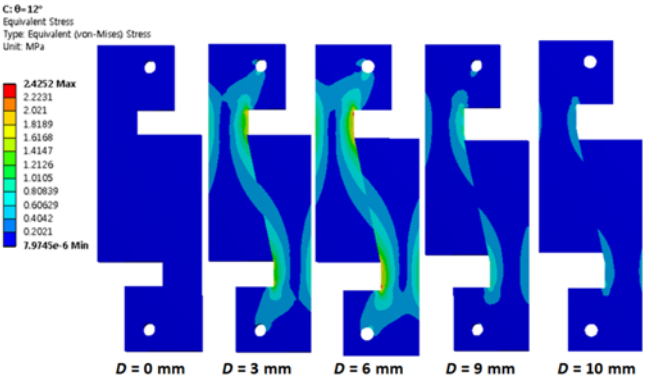


Fig. 10 Specimen configuration at analysis process on model ($\theta = 12°$)

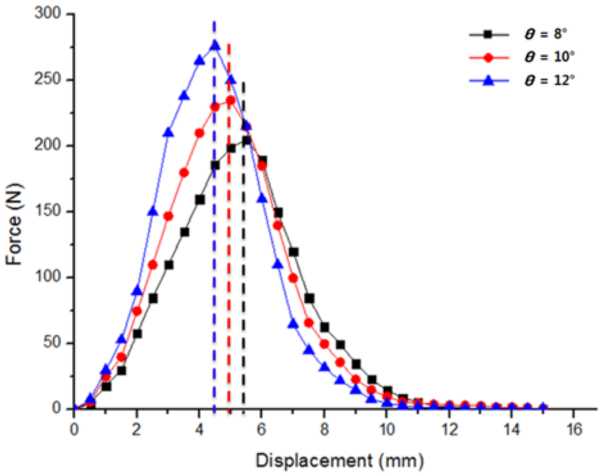


Fig. 11 Simulation graphs of displacement-force reaction at 3 types of the specimens

simulation data. In order to show the graph distinctively, two specimens of tilted angles of $\theta = 8^{\circ}$ and $\theta = 12^{\circ}$, which had the minimum and maximum values, respectively, among the 3 specimens, were compared. As shown in the graph, the force reaction value in the simulation had nearly same force reaction value as in the experiment. In the area where the maximum force occurred, the force-displacement curve in the simulation and experiment had the similar shape as well. However, the relatively large difference was shown in the area where the force reaction decreased after the maximum force reaction occurred. This reason was that the adhesive did not disappear but remained on the surface during the experiment by providing the friction force. However, in the analysis, adhesive inertia cannot be represented by causing some differences between the results.

6. Conclusions

The experiment and analysis regarding the shear force of adhesive structures made with aluminum foams with different angles were performed, and the following results were derived;

1.When forced displacement of 4 to 6 mm was reached on 3 TDCB specimens, the maximum force occurred, and then the rapid reduction of adhesive strength was shown in the experiment after the maximum force zone was passed. Once the forced displacement of 10 to 11 mm was reached, the adhesive strength almost disappeared. The larger the angle of tilted surface was, the shorter the time to reach the maximum force and the time taken until the force disappeared completely.

2.The comparison and verification of the results of finite element analysis and the experiment data were nearly the same. However, there was the slight difference between the experiment and analysis graphs because in the experiment the adhesive did not disappear but remained on the surface where force reaction decreased after the maximum force reaction occurred during the experiment providing friction force.

3.Based on the analysis result obtained in this study, the behavior of composite materials was similar to that observed in experiments can be obtained with finite element analysis. In addition, this method can be applied to real structures composed of aluminum foam composite materials bonded with adhesives by analyzing fracture behaviors and identifying mechanical characteristics. Hereafter, it is expected that the durability can be confirmed by measuring the fatigue life and failure through fatigue test of TDCB specimen.

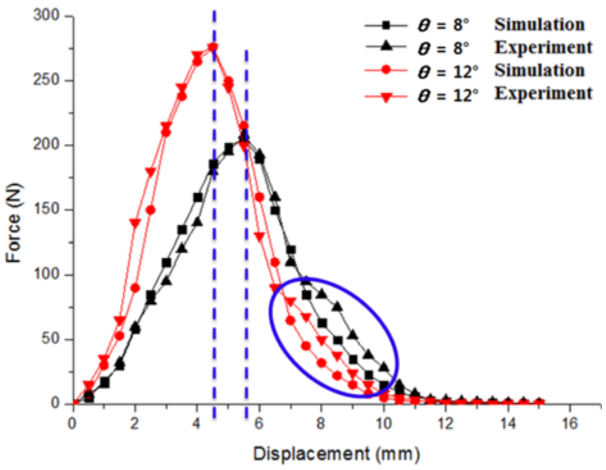


Fig. 12 Comparison between experimental and simulated displacement -force reactions

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