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Adhesive interface-peeling properties of tapered double cantilever beam bonded with dissimilar material under in-plane and out-of-plane shear conditions

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Abstract In this study, the lightweight composite materials of carbon fiber-reinforced plastic, aluminum and aluminum foam were applied as three different bonding materials of CFRP-Al6061, Al6061-Al-form and CFRP-Al foam. Then, they were manufactured in a form of tapered double cantilever beam with adhesive interface. The adhesion-peeling properties and fracture behavior under the opening and tearing modes on the adhesive interfaces of double cantilever beams were examined through the static experiment. The results indicated that CFRP-Al6061 was most advantageous under both in-plane and out-of-plane shear conditions in terms of durability applicable to the actual design. In contrast, the Al6061-Al form specimen was most disadvantageous. Through these experiments, this study aimed to investigate the adhesion-peeling properties and fracture behavior of the bonded dissimilar materials having the adhesive interface. The results can be effectively used at developing lightweight composite materials and the bonding technologies for other materials.

1. Introduction

Nowadays, the environmental pollution and increase in fuel economy have emerged as critical issues in machinery and automotive industries. Since a machine is mostly powered by fossil fuels, such an operation generates exhaust fumes. In addition, as a machine becomes heavier, more fuels are needed, generating more emissions and eventually resulting in environmental pollution. So, it is essential to reduce the weight to avoid the environmental pollution and enhance the fuel economy. In other words, the weight reduction can improve the fuel economy and at the same time decrease the emission, reducing the environmental pollution to a certain level. Many studies on lightweight design have been conducted within the automotive industry. These weight reduction methods include the material change and changes at material bonding methods. While the durable and strong metallic materials were mostly used in the past, there have been studies on the development and application of light-weight composite material. In terms of material bonding instead of conventional bonding which uses nuts and bolts, rivet connection or welding, the simple but strong adhesive bonding method has been applied. This adhesive bonding method has been commonly used at making the lightweight composite materials. And such lightweight composite materials include FRP, aluminum and aluminum foam. They have the lightweight properties, but bonding them by using conventional connection methods is extremely difficult. So far, there have been many studies on various materials concerning their stiffness and strength. However, because there have been few studies on the interface of adhesively bonded structures, it's been difficult to find related data [1-8]. Furthermore, the lightweight composite materials have also been used as bonded dissimilar materials made of other materials. Therefore, the adhesion-peeling data have become more important. In accordance with British Standards of BS 7991 and ISO 11343, the lightweight composite materials of carbon fiber-reinforced plastic (CFRP), aluminum and aluminum foam were applied as three different bonding materials (CFRP-Al6061, Al6061-Al-foam, CFRP-Al foam). Then, they were manufactured in a form of tapered double cantilever beam (TDCB) with adhesive interface. The adhesion-peeling properties and fracture behavior under the opening (mode 1) and tearing (mode 3) modes as the adhesive interface of double cantilever beams (DCBs) were examined through a static experiment. Through these experiments, this study aimed to investigate the adhesion-peeling properties and fracture behavior of the bonded dissimilar materials having the adhesive interface. The study results can be effectively used in developing lightweight composite materials and the bonding technologies for other materials [9-15].

2. Specimen and experimental set-up

2.1 Specimen

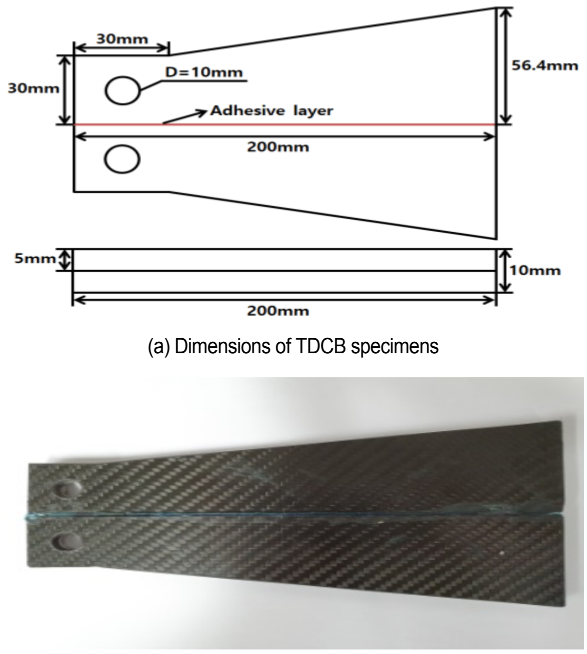
To investigate the adhesion-peeling and fracture properties on the adhesive interface of TDCB specimens composed of the dissimilar material bonded with adhesive, three specimens of CFRP-aluminum, CFRP-Al foam and aluminum-Al foam were manufactured. And the static experiments were carried out under mode 1 (in-plane shear) and mode 3 (out-of-plane shear) conditions. As pointed out, the bonded structure with the adhesive interface us exposed to an environment under the axial load (mode 1) and the torsional load (mode 3). So, modes 1 and 3 were set as the experimental conditions in this study. The TDCB specimens designed in accordance with BS 7991 and ISO 11343 were adopted as the study models as shown by Fig. 1 [16, 17]. The configuration of tapered double cantilever beam can be applied to the study specimens at investigating the durability. So, in order to examine the tendency of the shear characteristics at adhesive interface at the tapered double cantilever beam, the tapered shape was applied to all the specimens. All specimens were the same in terms of an adhesive interface area and the slant angle with 12°, as the experimental results, the strength property at the specimen with a slope angle of 12° was confirmed to be the best. Therefore, this study was conducted by setting all the specimens as the slope angle to 12°. Also, they were all 10 mm-thick specimens with the unidirectional (UD) CFRP laminated structure of [±60/0] s. The stacking angle of CFRP used was set by using quasi-isotropic laminate. The laminated structure of CFRP with [±60/0] s was acknowledged to have the good strength. So, the stacking angle was set to [±60/0] s in this study. This manufacturing condition is applied to the design of all the specimens. For the specimen bonding, PARTITE 7420 methacrylate structural adhesive was applied [18-22]. Table 1 shows the material properties for CFRP, Al6061, Al-foam used in the experiment. Also, Table 2 shows the properties for PARTITE 7420 metacrylate structural adhesive at bonding the specimens.

Table 1. Material properties of CFRP, Al6061, Al-foam.

Material	CFRP	Al6061	Al-foam
Density	1760 kg/m^3	2700 kg/m^3	400 kg/m^3
Young's modulus	135000 MPa	68900 MPa	4000 MPa
Poisson's ratio	0.1	0.33	0.35
Bulk modulus	56250 MPa	67549 MPa	4444.4 MPa
Tensile yield strength	-	187 MPa	1.6 MPa
Tensile ultimate strength	1860 MPa	328 MPa	1.9 MPa

Table 2. Material properties of PARTITE 7420 methacrylate structural adhesive.

PARTITE 7420 methacrylate structural adhesive	
Breaking strength	13 ~ 16.5 MPa
Elongation rate	110 ~ 130 %



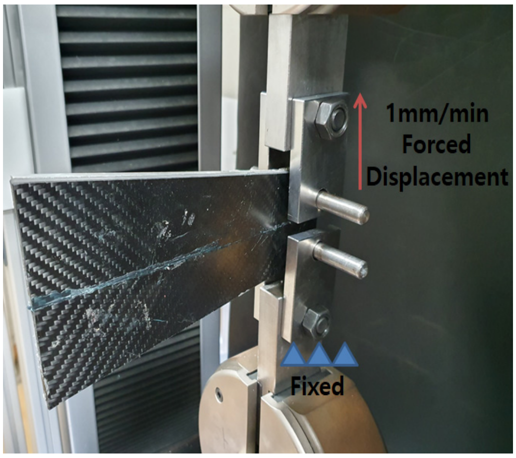
(a) Dimensions of TDCB specimens

(b) Configuration of TDCB specimens

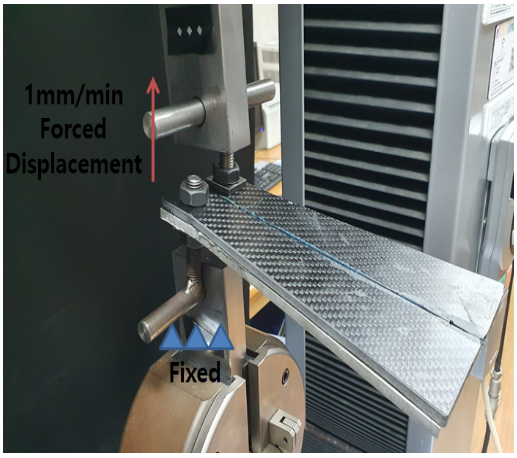
Fig. 1. Experimental TDCB specimen for modes 1 and 3.

2.2 Experimental set-up

Fig. 2 shows the experimental set-ups with TDCB specimen for modes 1 and 3. For this experiment, SHIMAZU's AG-X universal testing machine (UTM) was adopted. The specimens were applied to the forced displacement of 1 mm/min. Also, the specimens were mounted at the upper and lower load cells through pins and pin holes on the specimens, and the lower load cell was fixed for the restraint condition. Then, the static



(a) Mode 1 type



(b) Mode 3 type

Fig. 2. Experimental set-ups.

fracture on the adhesive interface begins by transferring the load from the upper load cell. The experimental conditions applied to each specimen were all the same. For the specimens in out-of-plane shear (mode 3) conditions, a jig was additionally applied between the UTM and specimens [23-30].

3. Static experiment under in-plane shear condition for mode 1

3.1 Experimental results of CFRP-Al6061 TDCB specimens for mode 1

Fig. 3 shows the graph results of forced displacement to reaction force obtained after carrying out a static experiment with the CFRP-Al6061 TDCB specimen under in-plane shear conditions. As the forced displacement progressed, the adhesion-peeling reaction force which occurred at the adhesive interface gradually increased. Specifically, when the forced displacement of 3.8 mm progressed approximately, the maximum adhesion-peeling reaction force of about 3900 N occurred. Then, the specimen was fractured, and the adhesion-peeling reaction force on the adhesive interface decreased.

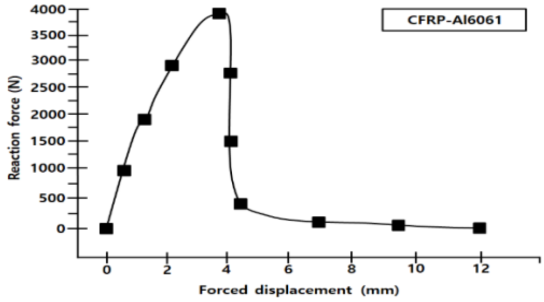


Fig. 3. Graph of forced displacement to reaction force at the CFRP-Al6061 TDCB specimen for mode 1.

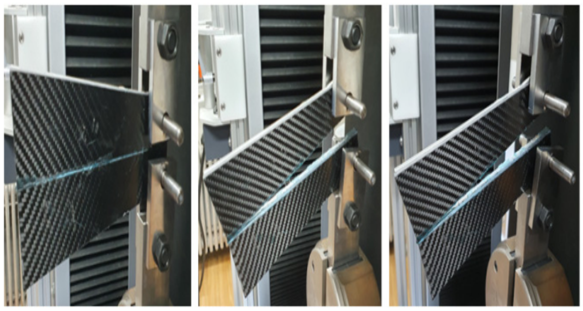


Fig. 4. Experiment process of CFRP-Al6061 TDCB specimen for mode 1.

3.2 Experimental results of CFRP-Al foam TDCB specimens for mode 1

Fig. 4 shows an actual experimental process. This figure was illustrated as the whole process that the specimen's adhesive interface was being peeled and eventually fractured. Fig. 5 shows the graph results of forced displacement to reaction force obtained after carrying out a static experiment with the CFRP-Al foam TDCB specimen. As the forced displacement progressed, the adhesion-peeling reaction force which occurred at the adhesive interface gradually increased. When the forced displacement of 2.6 mm progressed approximately, the maximum adhesion-peeling reaction force of about 2800 N occurred. Then, the specimen was fractured, and the adhesion-peeling reaction force on the adhesive interface decreased. Fig. 6 shows an actual experimental process. This figure was illustrated as the whole process that the specimen's adhesive interface was being peeled and eventually fractured.

3.3 Experimental results of Al6061-Al foam TDCB specimens for mode 1

Just like the two cases of CFRP-Al6061 and CFRP-Al foam TDCB specimens, Fig. 7 shows the graph results of forced displacement to reaction force obtained after carrying out a static experiment with the Al6061-Al foam TDCB specimen. As the forced displacement progressed, the adhesion-peeling reaction force which occurred at the adhesive interface gradually increased.

When the forced displacement of 2.3 mm progressed approximately, the maximum adhesion-peeling reaction force of

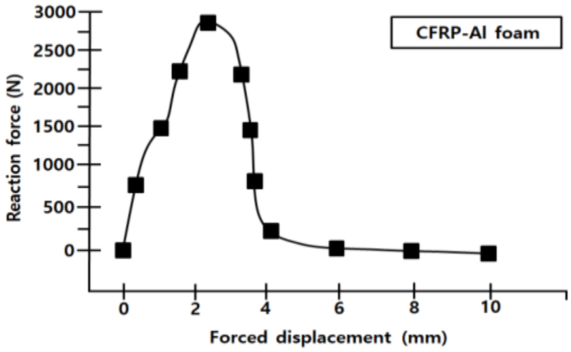


Fig. 5. Graph of forced displacement to reaction force at the CFRP-Al foam TDCB specimen for mode 1.

Fig. 6. Experiment process of CFRP-Al foam TDCB specimen for mode 1.

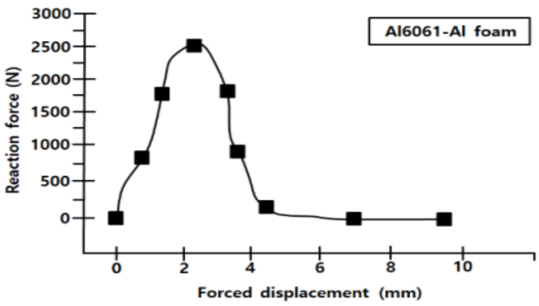


Fig. 7. Graph of forced displacement to reaction force at the Al6061-Al foam TDCB specimen for mode 1.

Fig. 8. Experiment process of Al6061-Al foam TDCB specimen for mode 1.

about 2100 N occurred. Then, the specimen was fractured, and the adhesion-peeling reaction force on the adhesive interface decreased. Fig. 8 shows an actual experimental process.

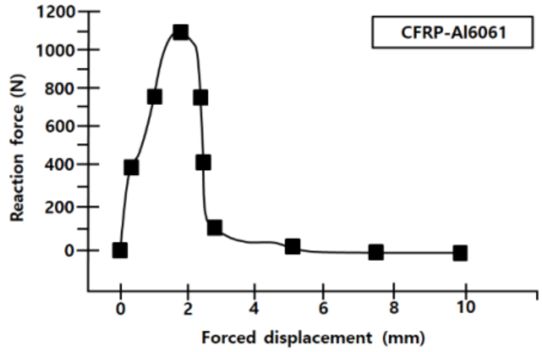


Fig. 9. Graph of forced displacement to reaction force at the CFRP-Al6061 TDCB specimen for mode 3.

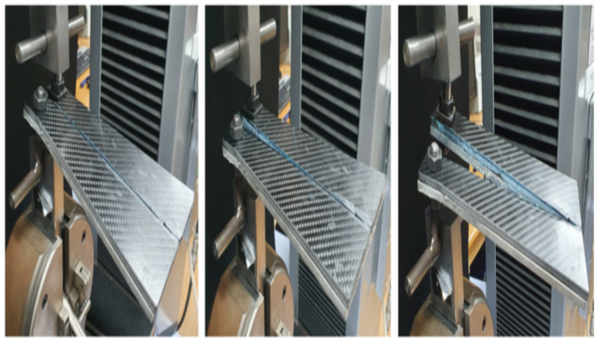


Fig. 10. Experiment process of CFRP-Al6061 TDCB specimen for mode 3.

This figure was illustrated as the whole process that the specimen's adhesive interface was being peeled and eventually fractured.

4. Static experiment under out-of-plane shear condition for mode 3

4.1 Experimental results of CFRP-Al6061 TDCB specimens for mode 3

Fig. 9 shows the graph results of forced displacement to reaction force obtained after carrying out a static experiment with the CFRP-Al6061 TDCB specimen under out-of-plane shear conditions. As the forced displacement progressed, the adhesion-peeling reaction force which occurred at the adhesive interface gradually increased. When the forced displacement of 6 mm progressed approximately, the maximum adhesion-peeling reaction force of about 1100 N occurred. Then, the specimen was fractured, and the adhesion-peeling reaction force on the adhesive interface decreased. Fig. 10 shows an actual experimental process. This figure was illustrated as the whole process that the specimen's adhesive interface was being peeled and eventually fractured.

4.2 Experimental results of CFRP-Al foam TDCB specimens for mode 3

Fig. 11 shows the graph results of forced displacement to re-

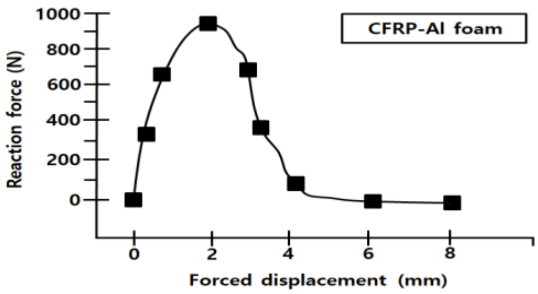


Fig. 11. Graph of forced displacement to reaction force at the CFRP-Al foam TDCB specimen for mode 3.

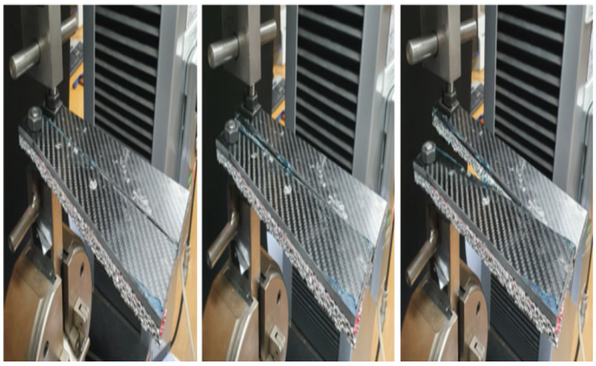


Fig. 12. Experiment process of CFRP-Al foam TDCB specimen for mode 3.

action force obtained after carrying out a static experiment with the CFRP-Al foam TDCB specimen. As the forced displacement progressed, the adhesion-peeling reaction force which occurred at the adhesive interface gradually increased. When the forced displacement of 2 mm progressed approximately, the maximum adhesion-peeling reaction force of about 950 N occurred. Then, the specimen was fractured, and the adhesion-peeling reaction force on the adhesive interface decreased.

Fig. 12 shows an actual experimental process. This figure was illustrated as the whole process that the specimen's adhesive interface was being peeled and eventually fractured.

4.3 Experimental results of Al6061-Al foam TDCB specimens for mode 3

Fig. 13 shows the graph results of forced displacement to reaction force obtained after carrying out a static experiment with the Al6061-Al foam TDCB specimen. As the forced displacement progressed, the adhesion-peeling reaction force which occurred at the adhesive interface gradually increased. When the forced displacement of 1.9 mm progressed approximately, the maximum adhesion-peeling reaction force of about 480 N occurred. Then, the specimen was fractured, and the adhesion-peeling reaction force on the adhesive interface decreased. Fig. 14 shows an actual experimental process. This figure was illustrated as the whole process that the specimen's adhesive interface was being peeled and eventually fractured.

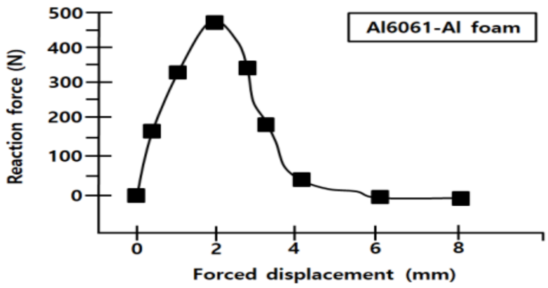


Fig. 13. Graph of forced displacement to reaction force at the Al6061-Al foam TDCB specimen for mode 3.

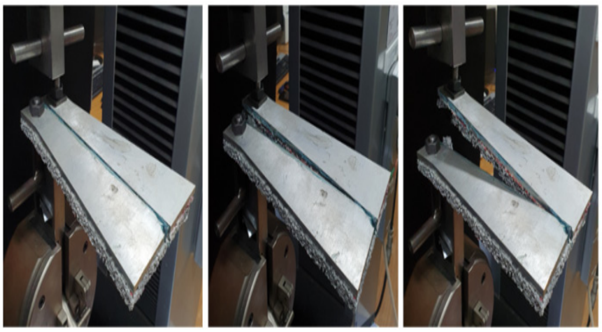


Fig. 14. Experiment process of Al6061-Al foam TDCB specimen for mode 3.

5. Study results

5.1 Experiment results under in-plane shear conditions for mode 1

Table 3 shows the maximum adhesion-peeling load and the forced displacement of TDCB specimens by carrying out the static experiment under in-plane shear conditions. In terms of both maximum adhesion-peeling load and forced displacement at the corresponding load occurrence, the CFRP-Al6061 specimen was shown to have the highest. In other words, the CFRP-Al6061 specimen was stronger than the other two specimens. Actually, this specimen was fractured to the last. Therefore, it is thought that CFRP-Al6061 is most advantageous in actual design. By contrast, the Al6061-Al foam specimen was shown to have the lowest in terms of maximum adhesion-peeling load and forced displacement at the corresponding load occurrence. Hence, it is most disadvantageous in to actual design. In particular, even though the same shape and same adhesive were applied to specimens, the Al6061-Al foam specimen was shown to have just about a half strength of CFRP-Al6061 specimen in terms of maximum adhesion-peeling load.

5.2 Experimental results under out-of-plane shear conditions for mode 3

Table 4 shows the maximum adhesion-peeling load and the forced displacement of TDCB specimens by carrying out the static experiment under out-of-plane shear conditions. Just like the experiment performed under in-plane shear conditions, the

Table 3. Comparison of maximum adhesion peeling loads for TDCB specimens (mode 1).

Specimen	Forced displacement (mm)	Maximum adhesion-peeling load (N)
CFRP-Al6061	3.8	3900
CFRP-Al foam	2.6	2800
Al6061-Al foam	2.3	2100

Table 4. Comparison of maximum adhesion peeling loads for TDCB specimens (mode 3).

Specimen	Forced displacement (mm)	Maximum adhesion-peeling load (N)
CFRP-Al6061	1.8	1100
CFRP-Al foam	2	950
Al6061-Al foam	1.9	480

CFRP-Al6061 specimen was shown to have the highest strength in terms of both maximum adhesion-peeling load and forced displacement at the corresponding load occurrence, confirming its advantage in design. In addition, the Al6061-Al foam specimen was shown to have the lowest strength in terms of maximum adhesion-peeling load and forced displacement at the corresponding load occurrence, confirming its disadvantage in design. Even though the same shape and same adhesive were applied to specimens, the Al6061-Al foam specimen was seen to have the strength far inferior to CFRP-Al6061 specimen.

When compared with in-plane shear conditions, the maximum adhesion-peeling load and forced displacement at the corresponding load occurrence were shown to have the lower strength at all specimens under out-of-plane shear conditions. Unlike in-plane shear conditions in which the axial load existed, the torsional load was found in out-of-plane shear conditions. Therefore, the adhesive interfaces at the specimens under out-of-plane shear conditions become relatively narrower than in-plane shear conditions at enduring such a load. This study aims at investigating the characteristics of the delamination due to debonding and the fracture behaviour on the inhomogeneous materials bonded with adhesive interfaces. So, it can be utilized as the basic data in developing the FRP composite materials.

6. Conclusions

To investigate the adhesion-peeling and fracture properties on the adhesive interface of TDCB specimens composed of the dissimilar material bonded with adhesive, three specimens of CFRP-aluminum, CFRP-Al foam and aluminum-Al foam were manufactured. Also, the static experiment were carried out with these specimens under mode 1 (in-plane shear) and mode 3 (out-of-plane shear) conditions. The study results are as follows:

(1) According to the static experiment under in-plane shear conditions, CFRP-Al6061 specimen was shown to have the strength better than CFRP-Al foam or Al6061-Al foam specimen in terms of the maximum adhesion-peeling load and forced displacement at the corresponding load occurrence. Therefore, it is thought that CFRP-Al6061 specimen is strongest and most advantageous among all three specimens in actual design.

(2) According to the static experiment under out-of-plane shear conditions as well, CFRP-Al6061 specimen was shown to have the strength better than the other two specimens in terms of maximum adhesion-peeling load and forced displacement at the corresponding load occurrence. Therefore, it is confirmed that CFRP-Al6061 specimen is strongest and most advantageous among all three specimens in actual design.

(3) Under both in-plane and out-of-plane shear conditions, the Al6061-Al form specimen was most disadvantageous in strength and design. To use this material through bonding with adhesive, it needs to be improved. When compared to in-plane shear conditions, maximum adhesion-peel load and forced displacement were lower in all specimens under out-of-plane shear conditions. Unlike in-plane shear conditions in which the axial load existed, the torsional load was found in out-of-plane shear conditions. Therefore, the adhesive interface at the specimens under out-of-plane shear conditions becomes relatively narrower than in-plane shear conditions at enduring such a load.

(4) This study aimed to investigate the adhesion-peeling properties and fracture behaviors of the specimen bonded dissimilar materials having the adhesive interface. It is thought that the result of this study can be used at developing the composite materials with lightweight and the advanced technologies for bonding with other materials, based on the FRP materials.

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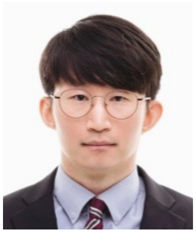

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