

A STUDY ON SEPARATING FORCE BETWEEN LAMINATE COMPOSITE PART AND TOOL

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1 Introduction

Composites are widely used material in aerospace, automotive and military industries due to their unique mechanical properties. In composite fabrication, the polymer matrix composite part is usually laid on the tool in sticky prepreg form and is solidified by curing process in an autoclave. The tool is generally made of metal like steel or aluminum alloy. Before the prepregs are laid up, a release agent is spread on the tool surface, which after curing helps in easy extraction of the finished composite part from the tool. It is normally believed that there is no significant interaction in terms of physical bonding between tool and part once the release agent is applied. The authors found that though the role of CTE mismatch between part and tool is important to reduce the separating force. The mismatch can help in easy removal of part from tool. The CTE mismatch results in shear interaction between the tool and the curing part along their interface, inducing residual stresses in the part leading to warpage [1]. Twigg et al [2,3] conducted experiment with uni-directional CFRP samples fabricated on flat tools to investigate the warpage.

The large CTE gap between part and tool is helpful in separating easily thick composites. However, if the CTE difference is low, larger separating force will be required. For example, in some large composite structures such as aircraft fuselage that require high precision, it is found that high force is needed for separating part from tool if the CTE gap is low. Therefore, low CTEs though improve the dimensional accuracy of the finished part, they also increase the separating force.

This paper studies the effect of CTE mismatch on separation force required to extract the part from tool composite. It uses double cantilever beam composite specimens of CFRP laid up on same material plate. The fracture energy is determined by experiments. The numerical analyses are conducted by using fracture energy data obtained from the experiments. Finally, the load-axial displacement results from numerical analysis are compared with that of the experiment.

2 Double cantilever beam(DCB) theory

In this work, we use DCB to determine the separating force required to pull apart the CFRP part from the CFRP tool those are cured together in an autoclave. The separating force is calculated by measuring the fracture energy released due to crack propagation along part and tool interface, the separation force can be calculated. For applying DCB model, it is assumed that there is an adhesive layer between tool and part.

The energy release rate G_{1c} due to propagation of an initial crack of length a subjected to an axial load P can be calculated as

$$G_{1c} = \frac{P^2}{2B} \cdot \frac{dC}{da} \quad (1)$$

where C is compliance and B is width of the specimen.

If the adhesive layer is thin, dC/da can be expressed as

$$\frac{dC}{da} = \frac{8}{E_s B} \left(\frac{3a^2}{h^3} + \frac{1}{h} \right) \quad (2)$$

where E_s is the flexural or tensile modulus of substrate and h is thickness of one substrate beam.

By combining Eqs. (1) and (2), we obtain a simple relation between release energy and applied load as

$$G_{Ic} = \frac{4P^2}{E_s B} \left(\frac{3a^2}{h^3} + \frac{1}{h} \right) \quad (3)$$

The value of G_{Ic} calculated from Eq. (3) is used in the numerical analysis as the fracture energy input.

3 Experiment and numerical analysis

3.1 Specimen

Fig. 1 shows the schematic of CFRP composite specimen fabricated for DCB tests. Both the part and tool are made of same CFRP material and have equal thickness. The interface is shown in red. One cantilever acts as part and the other as tool. The samples are fabricated using 20 plain woven CFRP plies. After the plies as tool cured, the release agent was spread on the tool. The sample was cured at 250 °F for 90 min. at 41 psi in an autoclave. Masking film was used to introduce a 2-inch long initial crack. And the other 20 plies as part laid up and cured on composite tool. Finally, grip hooks are bonded on both composites plate for applying axial load. Fig. 2 shows the DCB test specimen after the experiment is done.

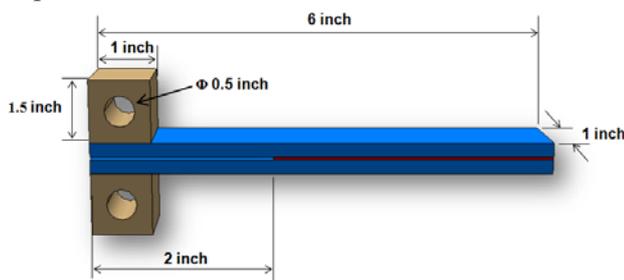


Fig.1 Schematic of DCB specimen



Fig.2 DCB specimen of CFRP

3.2 Experimental setup

DCB tests are performed by hydraulic universal test machine with fracture mechanics grip (Landmark 100 ton, MTS Co.) as shown in Fig. 3. An axial displacement of 1 mm per one second is applied. The crack length was measured at regular intervals by high speed digital camera, because the crack propagation speed was very fast. To this end, an inch-scale was fixed to the stationary cantilever for precise measurement of crack length.

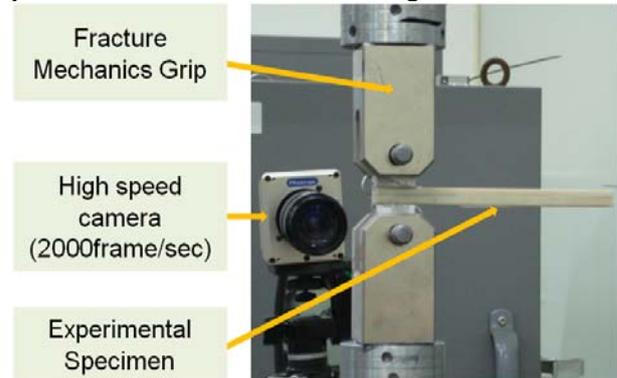


Fig.3 Experimental arrangement

3.3 Numerical analysis

A commercial finite element analysis (FEA) software ABAQUS/Explicit 6.7 is used to perform the numerical analysis of the fracture phenomena observed in the DCB tests. Fig. 4 shows the finite element models and boundary conditions for the numerical analysis. The interface is modeled as cohesive element which is defined by fracture energy except initial crack region. The constant velocity 1 mm/s is applied at the center of upper hook grip block (Fig. 4). As boundary condition, all degrees of freedoms without out of plane rotation is given on lower grip hook block are fully constrained. Therefore, the reaction force corresponding to the experimental value measured at load cell can be used as the output at the fixed point in numerical analysis. Both hook grip blocks are perfectly bonded at the double cantilever beams. The elastic modulus and Poisson's ratio of hook material is 230 GPa and 0.23, respectively.

Table 1 lists the material properties of the CFRP composite specimens used in DCB tests. The

properties were provided by the manufacturer Korean Air.

Table 1 Material properties of CFRP composites specimen

Parameter	CFRP
Elastic modulus, E_1 (GPa)	53.78
Elastic modulus, E_2 (GPa)	53.78
Shear modulus, G_{12} (GPa)	3.50
Shear modulus, G_{13} (GPa)	3.50
Shear modulus, G_{23} (GPa)	3.50
Poissons' ratio, ν_{12}	0.06
CTE, α_1 ($1/^\circ\text{C}$)	0.89×10^{-6}
CTE, α_2 ($1/^\circ\text{C}$)	0.89×10^{-6}

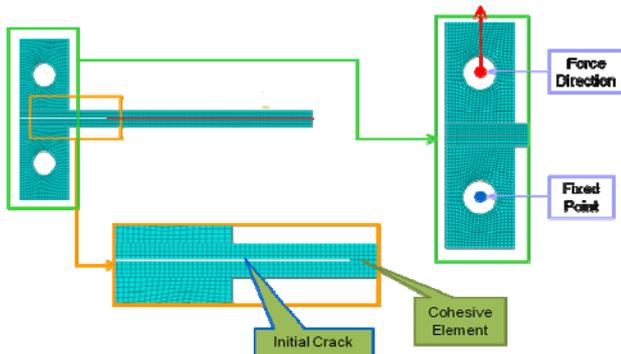


Fig.4 Finite element model of the DCB specimen

4 Result and Discussion

4.1 Critical Energy release rate

Fig. 5 shows the load versus time history of CFRP tool and part specimen with a 0.5 inch initial crack. The actual loading start at 0.5 sec and the peak load is observed at around 0.6 sec. The peak load can regard to general problems during manufacturing process of specimens. Therefore, in standard DCB tests the peak load is ignored until initial crack is observed. Once the crack initiates, load values are measures. The release process requires no load. But in this experiment, initial load and release process is omitted because separating load observed is too low. Since the constant axial velocity is applied, time domain is in accord with the axial displacement domain. Fig. 6 shows typical compliance reduction to increasing crack length.

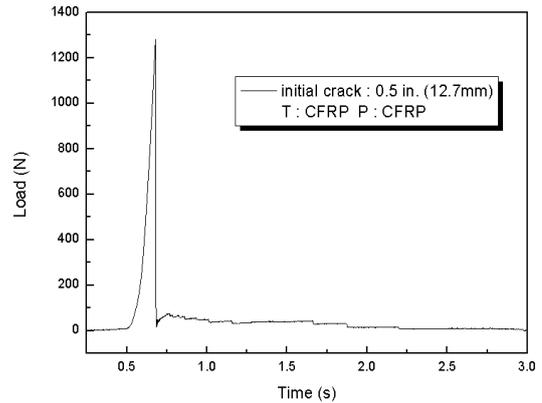


Fig.5 Load-time history of CFRP tool and part specimen subjected to DCB test.

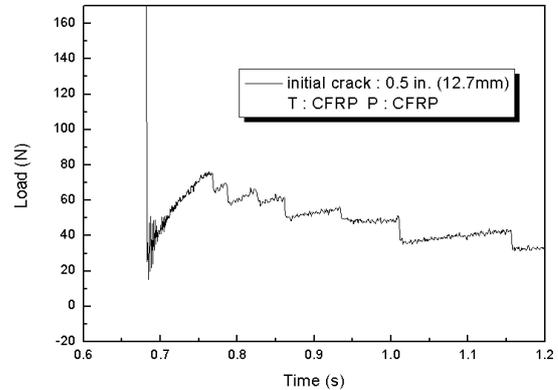


Fig.6 Load-time history of specimen both CFRP of tool and part. The initial load conditions are not shown.

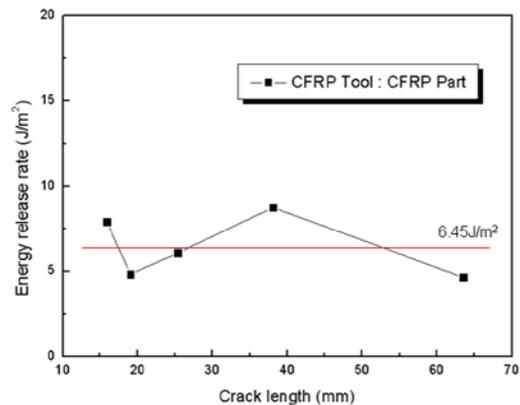


Fig.7 Energy release rate along crack length of CFRP part and tool DCB specimen

The critical fracture energy (G_{1c}) is calculated from Eq. 3. And crack length, a , and load, P are measured from the images captured by the high speed camera

and the corresponding instantaneous load-time curve, respectively.

Fig. 7 presents calculated energy release rate along crack length. For fracture energy for numerical analysis 6.45 J/m^2 is chosen as average value.

4.2 Comparison of Load-axial displacement between experimental and numerical results

The load-axial displacement graphs obtained by experiment and numerical results are shown in Fig. 8. The initial peak load is not shown in experimental result. The load difference around 0.8 mm axial displacement indicates that average energy release rate is used in the numerical analysis. Except that, overall load values from numerical result fit well along the axial displacement with experimental result.

As a result, even though release agent is coated on the tool, some combining force between part and tool still exist. In other words, unless there is CTE gap between tool and part, relatively higher force will be required to separate composite part from the tool.

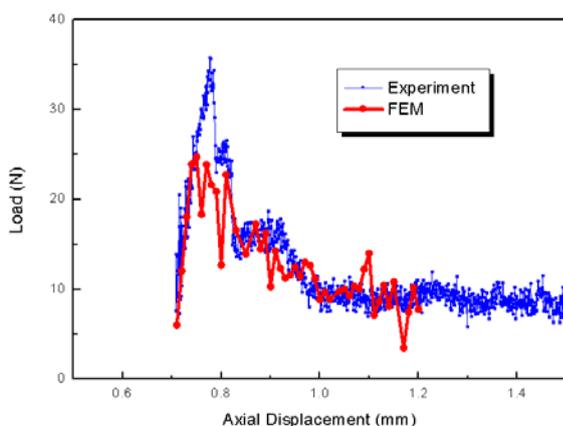


Fig.8 Load-axial displacement comparison of CFRP part and tool with 1.5 in. initial crack.

The reason why in case of high CTE gap less separation force is required is that if the gap is high there will be high thermal deformations in the part and tool. The deformations at the interface will break the interfacial bonds generated between the part and tool during the curing process. If the CTE mismatch is large, considerable thermal movements will occur at the interface, breaking significant number of bonds. Once the bonds are broken, less energy will be required to separate the part from tool.

However, in case of low CTE mismatch, there will be less thermal effects and therefore less number of interfacial bonds will be broken. It will result in requirement of significantly higher amount of separation energy.

5 Conclusions

This study starts to seek the reason why high separating force is needed in a large composite structure which is cured on low CTE tool. Critical fracture energy is calculated by DCB tests. And numerical analyses are performed with the fracture energy data obtained by experimental result. Finally, the load-axial displacement results from numerical results are compared with experimental result.

We found that interfacial bonding energy exists between release agent-coated tool and part of the CFRP specimen. We also showed that the necessary separation force required to overcome the interfacial bonding energy can be calculated using critical energy release data obtained from experiments. The results can help understand the interfacial interactions as well as calculate the separating force in huge composite structures that require precise dimension.

Acknowledgement

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