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A Study on Mode I Interlaminar Fracture Toughness of Foam Core Sandwich Structures

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ABSTRACT

This paper investigates the characteristics of interlaminar fracture toughness of foam core sandwich structures under opening mode by using the double cantilever beam (DCB) specimens which are Carbon/Epoxy and foam core composites. Instead of using a DCB specimen of symmetric geometry, a non-symmetric DCB specimen was used to calculate the interlaminar fracture toughness.

Three approaches for calculating the energy release rate(G_{IC}) were used and fracture toughness of foam core sandwich structures made by autoclave, vacuum bagging and hotpress were compared. Experiment, analysis using nonlinear beam bending theory, and numerical work by FEM methods were performed. Bonding surface compensation and equivalent moment of inertia were used to calculate the energy release rate in nonlinear analytical work. Conclusions of experimental, nonlinear analytical and FEM methods were compared. It is, also, shown that the vacuum bagging forming can substitute the method of autoclave without serious loss of Mode I energy release rate(G_I).

Keywords: Fracture Toughness, Compliance Method, Bonding Surface Compensation

1. Introduction

A composite which consists of two or more separate materials combined in a macroscopic structural units is made from various combinations of different materials.

The advantage of advanced composite is higher modulus and lower density. In many applications such as aerospace and automotive structures, structural weight is very important. Depending on whether the structural design is strength-critical or stiffness-critical, the material used should therefore have a high strength-to-weight ratio(or specific weight) or a high stiffness-to-weight ratio(or specific stiffness).

Foam core sandwich structure which is one of composites, is widely used in aircraft, rapid electronic railway vehicle and light weight structure because of their superior specific stiffness, specific strength, heat protection and sound-absorption.

Delamination, or interlaminar fracture is a very important failure mode in composite materials, and research activity regarding the onset and growth of delaminations has continued at a high level for the past decade or so.

In order to understand delamination better and, consequently, the best ways to improve interlaminar fracture toughness, there is an obvious need for delamination experiments which make it possible to isolate a single mode of crack growth.

Mode I delamination has always been of interest because of the obvious weakness of the interlaminar region in through-thickness tension. Perhaps the most widely used mode I interlaminar fracture test method is the double cantilever beam(DCB) test, which was originally developed for studying fracture of adhesively bonded joints, then later adapted for interlaminar fracture of composite laminates.

This paper investigates the characteristics of interlaminar fracture toughness of foam core sandwich structures under opening mode by using a DCB specimen, a Carbon/Epoxy and foam core composite. Instead of using a DCB specimen of symmetric geometry, a non-symmetric DCB specimen was used to calculate the interlaminar fracture toughness.

Three approaches for calculating the energy release rate(G_{IC}) were used and fracture toughness of foam core sandwich structures formed by autoclave, vacuum bagging and hotpress were compared and analyzed. Experiment, analysis using nonlinear beam bending theory, and numerical work by FEM method were performed. Bonding surface compensation and equivalent moment of inertia were used to calculate the energy release rate in nonlinear analytical work. Conclusions of experimental, nonlinear analytical and FEM results was compared.

2. Elastica (large deflection)

In this paper, numerical analysis is performed using Elastica theory by Bernoulli, Lagrange, Euler and Planar to analyze foam core sandwich.

Upper laminates(carbon/epoxy) and lower laminates (foam core + carbon/epoxy) was analysed by applying Elastica theory.

$$k = \frac{d\theta}{ds} = -\frac{M}{EI} \qquad (1)$$

where, k is a deformation ratio of angle of rotation of the deflection curve to measured distance. $d\theta$ is a angle of rotation of the deflection curve and ds is a distance of curvature.

Differential equation for deflection curve can be represented by the following equation:

$$\frac{\frac{d^2v}{dx^2}}{[1+(\frac{dv}{dx})^2]^{(3/2)}} = -\frac{M}{EI} \qquad (2)$$

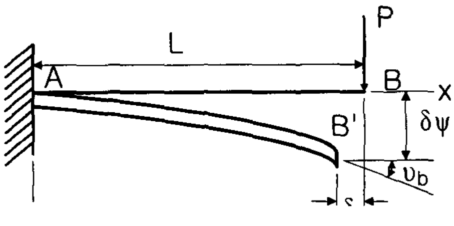


Fig. 1 Large deflection of a cantilever beam

In Fig. 1, the δ_v and δ_h denote to vertical and horizontal displacements, respectively. The elliptic function for deflection angle in a cantilever beam, θ_b, can be represented by the following equation:

$$F(k) - F(k,\phi) = \sqrt{\frac{PL^2}{EI}} \qquad (3)$$

where,

$$k = \sqrt{\frac{1+\sin\theta_b}{2}}$$

$$\phi = \arcsin\frac{1}{k\sqrt{2}}$$

$$F(k) = \int_0^{\pi/2}\frac{dt}{\sqrt{1-k^2\sin^2 t}} \qquad (4)$$

: complete elliptic integral of the first kind

$$F(k,\Phi) = \int_0^{\phi}\frac{dt}{\sqrt{1-k^2\sin^2 t}} \qquad (5)$$

: incomplete elliptic integral of the first kind

The vertical displacement, δ_v, is represented by the following equation:

$$\delta_v = 1 - \sqrt{\frac{4EI}{PL^2}}[E(k) - E(k,\phi)] \qquad (6)$$

where,

$$E(k) = \int_0^{\pi/2}\sqrt{1-k^2\sin^2 t}\,dt \qquad (7)$$

: complete elliptic integral of the second kind

$$E(k,\Phi) = \int_0^{\phi}\sqrt{1-k^2\sin^2 t}\,dt \qquad (8)$$

: incomplete elliptic integral of the second kind

The horizontal displacement, δ_h, is represented by the following equation:

$$\frac{\delta_h}{L} = 1 - \frac{\sqrt{2EI\sin\theta_b}}{PL^2} \qquad (9)$$

3. Equivalent moment of inertia

In Fig. 2, the equivalent moment of inertia is applied to get the deflection Δ_2. By using a ratio of modulus of elasticity, $n = \frac{E_c}{E_f}$, equivalent moment of inertia was calculated. E_c is the ratio of modulus of elasticity of carbon/epoxy and E_f is the ratio of modulus of elasticity of form core.

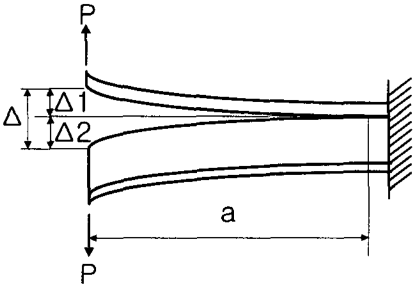


Fig. 2 Deflection of foam core sandwich

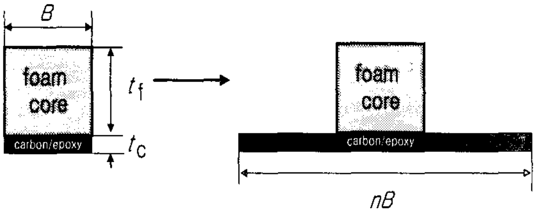


Fig. 3 Equivalent moment of inertia

In Fig. 3, centroid of equivalent area from the bottom, y, is represented by

$$y = \frac{\frac{t_c}{2} \cdot nB \cdot t_c + t_f \cdot B \cdot (t_c + \frac{t_f}{2})}{Bt_f + nBt_c} \tag{10}$$

where, B = width
tf = thickness of foam core
tc = thickness of carbon/epoxy
n = ratio of Ec/Ef

moment of inertia, I_e, is represented by:

$$\begin{aligned} I_e = &\frac{1}{12} B\, t_f^3 + Bt_f(t_c + \frac{t_f}{2} - y)^2 \\ &+ \frac{1}{12} nB\, t_c^3 + nBt_c(\frac{t_c}{2} - y)^2 \end{aligned} \tag{11}$$

Using Eq.(11), energy release rate of foam core sandwich can be written as:

$$G_I = \frac{P^2}{2B} \cdot \frac{\partial C}{\partial a} \tag{12}$$

where, P is a applied load, B is the specimen width and C is the compliance.

4. Bonding surface compensation

Due to the difference of stiffness between upper laminates(carbon/epoxy) and lower laminates(foam core+carbon/epoxy), bonding surface rotates to smaller stiffness side. Because of the rotation, it is difficult to get exact deflection value.

Hence, bonding surface compensation must be considered. In fig. 4, foam core sandwich rotates around the virtual hinge because of vertical displacement, δ_v, and horizontal displacement, δ_h, of upper laminates (carbon/epoxy).

The increment of exact deflection value owing to the rotation of bonding surface is proportional to the angle of rotation, θ. So, the exact deflection has to include the deflection owing to the angle of rotation, θ.

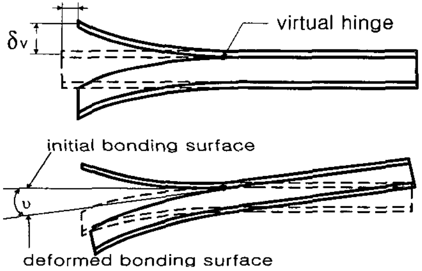


Fig. 4 Bonding surface compensation

5. Specimen

Face material of foam core sandwich structure is CF3327 prepreg(made by HanKuk fiber), and core material of foam core sandwich structure is Airex® R82.80. Specimens were made by autoclave forming, vacuum bagging forming and hotpress forming.

Loading hinge configuration shown in fig. 5 is as recommended in the ASTM standard. The DCB specimen should be 15cm long and 2.5cm wide. To provide a starter crack, thin teflon film which has 10μm thickness was placed between the mid-plane of the upper cabon/epoxy and foam core.

Carbon/epoxy laminates employed four plies. In order to confirm the propagation of crack visually, markings were made on the surface of the specimen at the interval of 2mm up to 7cm beyond the starter crack. For autoclave forming, Specimen was cured at 140℃ and at 9,62MPa of high pressure for 30 minute and 60 minutes, respectively.

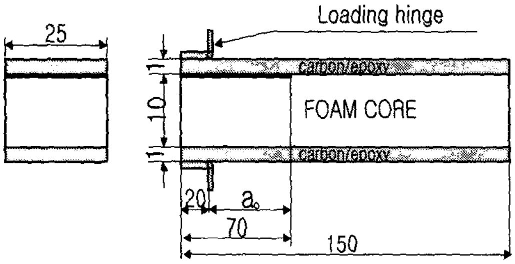


Fig. 5 Foam core sandwich DCB specimen

Autoclave forming is the most commonly used method of applying heat and pressure simultaneously.

Vacuum bagging is a less expensive fabrication method than autoclave molding since only vacuumizing is needed without external pressure and heat can be supplied by an unpressurized heated oven.

Hotpress forming is used to fabricate composite component by matched die tools which are composed of upper and lower plates that can apply heat and pressure simultaneously .

6. Experiments

DCB test method is shown schematically in fig. 6. The mechanical properties of foam core material(Airex® R82.80) used in this study are shown in table 1.

The properties of foam core sandwich made by autoclave forming, vacuum bagging forming and hotpress forming are shown in table 2.

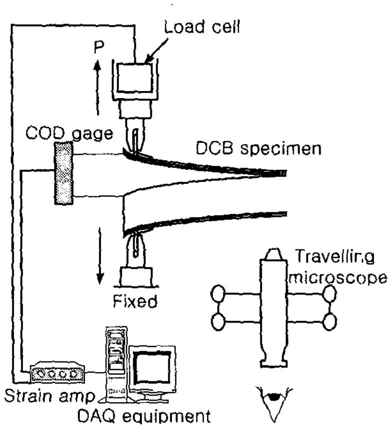


Fig. 6 Schematic diagram for DCB test

Table 1 Mechanical properties of foam core material

Density	0.085 $\mathrm{g/cm^3}$
Shear strength	0.9 MPa
E-modulus	52 MPa
Shear modulus	18 MPa
Maximum temp.	190℃
Poisson's ratio	0.444

Table 2 Comparison of mechanical properties

Mechanical property	Autoclave	Vacuum bagging	Hotpress
E_{11}(GPa)	66.42	56.55	40.93
E_{22}(GPa)	66.42	56.55	40.93
G_{12}(GPa)	4.352	3.602	2.962
ν_{12}	0.05367	0.0689	0.0756

Table 3 Variation of thickness & density in foam core

	Initial thickness	Deformed thickness	Change of density
Autoclave	10 mm	6.68 mm	0.13 $\mathrm{g/cm^3}$
Vacuum bagging	10 mm	9.71 mm	0.0875$\mathrm{g/cm^3}$
Hotpress	10 mm	9.93 mm	0.0856$\mathrm{g/cm^3}$

Fig. 7 Solid modeling for DCB specimen of foam core sandwich

The variation of thickness and density in foam core made by different method and it's dimensions are shown in table 3.

Also, the numerical calculation for this study are carried out with the finite element code ANSYS.

A solid95 model in ANSYS 5.3 was used for finite element modeling and laminates was assumed to be a isotropic material.

7. Experimental result and Discussion

7.1 Energy release rate and bonding surface compensation

Fig. 8 shows the result by the proposed bonding surface compensation theory versus experimental results. Rotation angle varies very little with the increase of load, crack growth, and opening displacement. There are 13% discrepancies between experimental and theoretical results.

We can see the results of crack length vs. energy release rate in the autoclave forming from fig. 9. The experimental and theoretical energy release rate are nearly the same at about 900J/m².

Fig. 10 shows crack length vs. energy release rate in vacuum forming. From this figure, we can see some discrepancies between experimental and theoretical energy release rate.

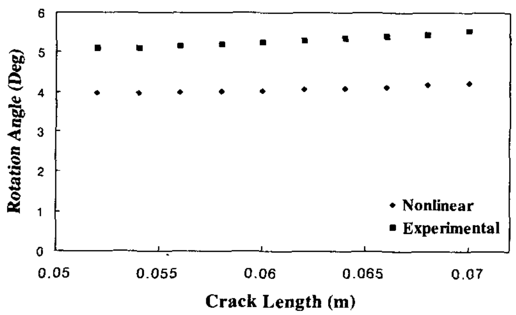


Fig. 8 Crack length vs. rotation angle of specimen

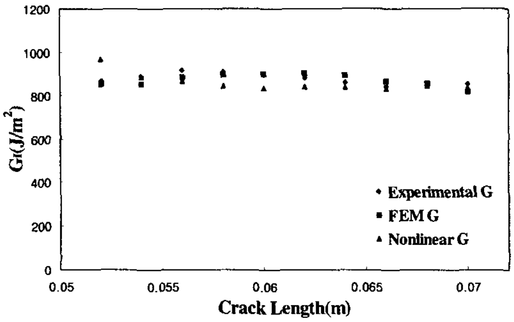


Fig. 9 Crack length vs. energy release rate (Autoclave)

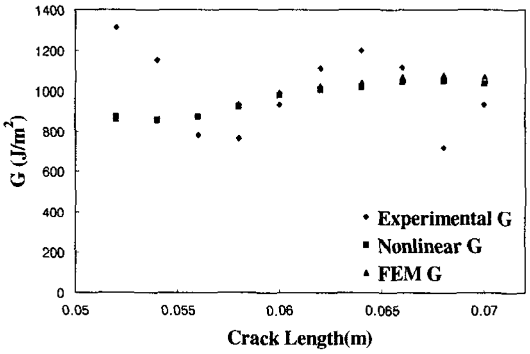


Fig. 10 Crack length vs. energy release rate (Vacuum)

The change of density in vacuum bagging is smaller than that in autoclave forming. The crack propagated into the core because bonding strength increase in autoclave forming.

We can see the results of crack length vs. energy release rate in hotpress forming in Fig. 11. The difference among three results decreases with the increment of crack growth.

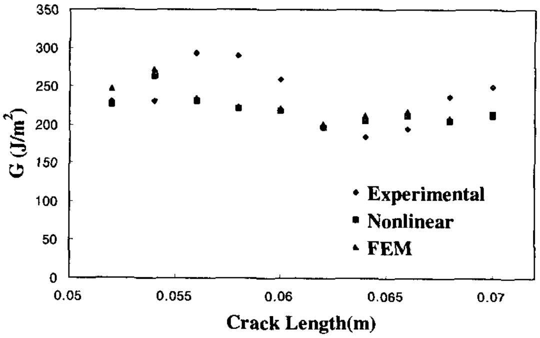


Fig. 11 Crack length vs. energy release rate (Hotpress)

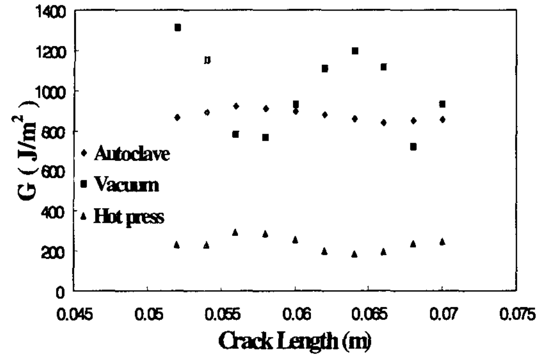


Fig. 12 Comparison of energy release rate (Experimental)

Energy release rates by three different forming methods are compared in Fig. 12. Autoclave forming and vacuum forming are more superior than hotpress forming in energy release rate. Fig. 13 show a measuring of specimen rotation.

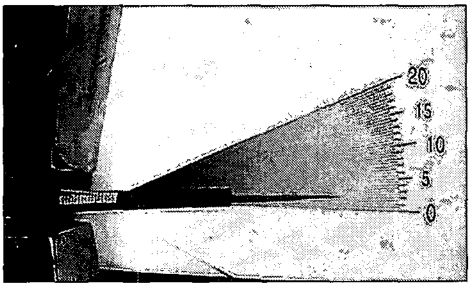


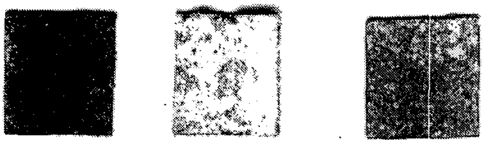
Fig. 13 Measurement of specimen rotation

7.2 Comparison of delamination of DCB specimens according to manufacturing form core sandwich

In Fig. 14, delamination surfaces of foam core sandwich by different forming method are shown.

In case of autoclave forming, typical delamination between form core and carbon/epoxy is shown. But in case of vacuum bagging, crack propagated into core because the bonding strength between carbon/epoxy is stronger than that of form core.

Debonding appears due to the low bonding strength between upper laminates(carbon/epoxy) and lower laminates(foam core + carbon/epoxy) in hotpress forming(a).



(a) Hotpress (b) Vacuum bagging (c) Autoclave

Fig. 14 Delamination surface of DCB specimens

8. Conclusions

The following results have been obtained from the numerical and experimental investigations for Mode I delamination of Foam Core Sandwich Structures.

1. In the analysis of energy release rate on non-symmetric DCB test by using proposed bonding surface compensation and equivalent moment of inertia method, experimental results of autoclave forming and vacuum bagging methods agreed well with those of FEM and Elastica theory.
2. Vacuum bagging method can be substituted in stead of autoclave forming method, because energy release rate of Foam Core Sandwich by expensive autoclave forming is nearly equal to that of economical vacuum bagging method.
3. In case of autoclave forming, crack of form core sandwich propagates along the bonding surface because of change of density. But in case of vacuum bagging, crack of form core sandwich propagates into core part because there is no change of density. In this case, energy release rate is described by fracture strength of core.

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