Mixed-Mode Fracture Test of CFRP Laminates*

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Mixed-mode (mode I and mode II) interlaminar fracture toughness of unidirectional reinforced and woven carbon fiber-reinforced plastic (CFRP) is evaluated using DCB specimens. A new testing apparatus is made in order to change the ratio of mode I to mode II across a wide range. The fracture toughness value is evaluated based on beam theory, and the deformation of the specimen is analyzed by the finite element method (FEM). The relationship between compliance and crack length obtained in the experiment agrees with the results obtained by FEM. The constant fracture toughness value, G_c , which is independent of crack length, is obtained. Due to the decrease of the G_I/G_{II} ratio, the fracture toughness value increases. It is shown that the role of mode II changes largely due to the change in the ratio of mode I to mode II, though the mode I component maintains a nearly constant value.

Key Words: Fracture, Fracture Toughness, Mixed-Mode Fracture, CFRP, DCB Specimen, Finite Element Method

1. Introduction

The fracture of CFRP (carbon fiber-reinforced plastic) laminates occurs mainly due to the delamination between laminates. This indicates that the evaluation of the delamination toughness of CFRP plates is very important from the practical viewpoint.

In recent years, fracture behavior of CFRP plates has been studied by many authors and fracture toughness has been measured experimentally^{(1)~(6)}. Through these studies, it has been shown that the delamination between laminates is the most effective factor in the fracture of CFRP plates. Due to the strong anisotropy of this material, the fracture of CFRP plates occurs in the mixed-mode condition. Thus, the study of the mixed-mode fracture behavior is recognized to be important.

In this study, a new testing apparatus is made for the mixed-mode fracture test of CFRP specimens.

With this apparatus, unidirectional reinforced and woven CFRP specimens are tested. The fracture toughness of the plates under mixed-mode conditions is measured experimentally and numerically.

2. Specimen and Testing Apparatus

2.1 Specimen

In the experiment, two kinds of specimens are used. One is unidirectional reinforced carbon/epoxy laminate, which consists of 11 plies of HTA 1200/# 113 prepregs. The other is a woven plate consisting of 16 plies of T 400/# 2500 crossed prepregs. The thickness of the two plates is 3 mm, and the nominal fiber volume fractions are 67.2% and 64%, respectively.

Elastic constants of both plates used in the FEM analyses are shown in Table 1. They are measured by four-point bending, in-plane shear, and transverse tension tests. In the unidirectional specimen, the mechanical properties along the T and Z axes are assumed to be equal, and the following relations are used.

$$E_T = E_Z, \quad G_{LT} = G_{LZ}, \quad \nu_{LZ} = \nu_{LT}.$$

In Fig. 1, the shape and size of specimens are shown. A DCB (double cantilever bending) specimen

* Received 17th, April, 1992. Paper No. 91-0251 A

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is used. The length of the specimen, $2L$, is 160 mm and 120 mm for the unidirectional specimen, and 160 mm for the woven specimen. The fiber orientation of the unidirectional specimen coincides with the longitudinal direction (L direction) of the specimen. In the woven specimen, both fiber orientations coincide with the L and T directions. At the edge of the specimen, aluminum hinges are attached using Araldite Standard for pin loading.

Thirty-millimeter Kapton film is inserted as a starter crack. The crack is carefully wedged open and extended about 5 mm beyond the insert in order to

Table 1 Elastic modulus of CFRP specimen

	E_L (GPa)	E_T (GPa)	G_{LT} (GPa)	ν_{LT}	Fiber	Matrix	Vf (%)
Unidirectional CFRP	13.4	9.46	3.57	0.31	HTA1200	#113	67.2
Woven CFRP	74.1	74.1	4.27	0.054	T400	#2500	84.0

Table 2 The ratio of mode I to mode II of unidirectional CFRP

l/L	0.625	0.75	1.00	1.25	1.50	1.75
G_I/G_{II}	0.38	0.68	1.33	1.99	2.61	3.18

Table 3 The ratio of mode I to mode II of woven CFRP

l/L	0.75	1.00	1.25	1.68
G_I/G_{II}	0.68	1.33	1.99	2.90

Fig. 1 Test specimen

Fig. 2 Testing apparatus

introduce a natural crack.

2.2 Experimental method

Figure 2 shows an apparatus for the mixed-mode fracture test⁽⁹⁾. With application of the load P at the right side of the figure, opening at the crack tip and the bending of the specimen at the center of the plate occurs simultaneously. This indicates that the mode I and mode II tests are mixed. With changes in the loading position (location of load point P), the ratio of mode I to mode II is changed across a wide range. When l in Fig. 2 is large, mode I becomes dominant, and when l is small, mode II is dominant. Tables 2 and 3 show the ratios of mode I to mode II used in the experiments of each specimen. These ratios are calculated using Eq. (7) which appears in the following section. Five ratios are used for the unidirectional specimen, and 4 values are used for the woven specimen. Fracture tests are conducted by controlling the displacement, and the cross-head speed is 0.05 mm/sec. All experiments are recorded using a CCD camera. The change in the crack length is measured by playing back the film after the tests.

3. Analysis of Mixed-Mode Energy Release Rate

The energy release rate can be calculated by considering the change in the compliance during the fracture test. In the following section, four kinds of different methods, which are originally based on beam theory, are used to obtain the energy release rate of the specimen.

(1) In mode I loading, the compliance is expressed by the following equation⁽¹⁰⁾.

$$\lambda = \frac{u}{P} = \frac{8a^3}{E_L B H^3} \quad (1)$$

where λ is the compliance, a is the crack length, B is the width of the specimen, $2H$ is plate thickness and u is the crack opening displacement.

In mode II loading, the compliance of the ENF (end notched flexure) specimen is expressed as follows⁽¹⁾:

$$\lambda = \frac{v}{P} = \frac{2L^3 + 3a^3}{8E_L B H^3} \quad (2)$$

where v is the deflection of the specimen at the loading point.

The relation between the compliance and the energy release rate is given by the following equation.

$$G = \frac{P^2}{2B} \frac{\partial \lambda}{\partial a} \quad (3)$$

By the use of Eqs. (1) ~ (3), energy release rates of mode I and mode II are obtained as follows.

$$G_I = \frac{3a^2 P^2}{4B^2 H^3 L^2 E_L} (3l - L)^2 \quad (4)$$

$$G_{II} = \frac{9a^2 P^2}{16B^2 H^3 L^2 E_L} (l + L)^2 \quad (5)$$

Then the total energy release rate and the ratio of mode I to mode II are given by the following equations.

$$G = \frac{3a^2 P^2 (4(3l-L)^2 + 3(l+L)^2)}{16B^2 H^3 L^2 E_L} \quad (6)$$

$$\frac{G_I}{G_{II}} = \frac{4(3l-L)^2}{3(l+L)^2} \quad (7)$$

(2) With consideration of the effect of the shear deformation, Eqs.(4) and (5) are modified as follows⁽⁹⁾.

$$G_I = \frac{3P^2(3l-L)^2}{4B^2 H^3 L^2 E_L} \left[a^2 + \frac{2a}{\gamma} + \frac{1}{\gamma^2} + \frac{H^2 E_L}{10G_{LT}} \right] \quad (8)$$

$$G_{II} = \frac{9P^2(l+L)^2}{16B^2 H^3 L^2 E_L} \left[a^2 + \frac{0.2H^2 E_L}{G_{LT}} \right] \quad (9)$$

$$G = G_I + G_{II} \quad (10)$$

$$\frac{G_I}{G_{II}} = \frac{4(3l-L)^2}{3(l+L)^2} \frac{\left[a^2 + \frac{2a}{\gamma} + \frac{1}{\gamma^2} + \frac{H^2 E_L}{10G_{LT}} \right]}{\left[a^2 + \frac{0.2H^2 E_L}{G_{LT}} \right]} \quad (11)$$

where

$$\gamma = \frac{1}{H} \left(\frac{6E_T}{E_L} \right)^{1/4}$$

(3) The energy release rate can be calculated using the loading point displacement δ . The compliance of the specimen used in the experiments is expressed by Eq.(12). Then, with Eqs.(3) and (12), G is given as follows.

$$\lambda = \frac{\{4(3l-L)^2 + 3(l+L)^2\} a^3 + 2L^3(l+L)^2}{8BH^3 L^2 E_L} \quad (12)$$

$$G = \frac{4(3l-L)^2 + 3(l+L)^2}{\{4(3l-L)^2 + 3(l+L)^2\} a^3 + 2L^3(l+L)^2} \times \frac{3Pa^2 \delta}{2B} \quad (13)$$

In this case, the decomposition of G into mode I and II components is carried out using Eq.(11).

(4) It is important to note that the compliance is proportional to the cubic of crack length a . The compliance and the crack length can be obtained experimentally. Then, with the use of the experimental results, the relation between the compliance and the cubic of crack length is approximated by Eq.(14).

Fig. 3 Mesh pattern for FEM analysis

$$\lambda = \lambda_0 + ma^3 \quad (14)$$

$$G = \frac{3ma^2 P^2}{2B} \quad (15)$$

where m is determined experimentally. By the use of this equation and Eq.(3), the energy release rate is also calculated using Eq.(15). The decomposition of G into mode I and II components is conducted by means of Eq.(11).

The results of these four methods are compared after the test.

FEM analyses are also carried out. Figure 3 shows one example of the mesh pattern of the specimen. An eight-noded isoparametric element is used. The element number is 257 and the node number is 969. The plane strain condition is assumed. As the crack growth occurs in the elastic stress state, the crack growth is simulated easily by moving the near tip region along the crack growth direction. The loading jig is made of steel. Thus, the weight of the jig is considered in the FEM analysis.

The energy release rates, G_I and G_{II} are calculated using the nodal reaction force F_x , F_y and nodal displacement u_i and v_i at the crack tip as follows.

$$G_I = \frac{1}{2\Delta a} F_y (v_1 - v_2) \quad (16)$$

$$G_{II} = \frac{1}{2\Delta a} F_x (u_1 - u_2) \quad (17)$$

The J integral is also calculated. In the elastic state, the J integral coincides with total energy release rate, $G_I + G_{II}$. These values are compared with those obtained by the four methods mentioned above.

4. Experimental Results and Discussion

In Figs.4 and 5, the load-displacement relationships of both specimens are shown. In the unidirectional specimen, the curve during crack growth is smooth, which means that the crack growth occurs in the steady state. Similar results are obtained in other tests with changing mixed-mode ratios. In the woven specimen, the crack growth does not occur smoothly. As the ratio of mode I to mode II increases, the roughness of this curve during crack growth becomes large. However, in the mode II dominant region, the crack growth occurs smoothly.

The relationship between the compliance and the crack length is shown in Figs.6 and 7. The abscissa is the cubic of crack length, and the ordinate is the compliance. The results of FEM analyses are also shown in the same figures by the solid lines. Although a slight scatter of the experimental data is observed, the agreement of experimental results with numerical ones is good. Almost all data can be plotted on straight lines. It is also confirmed that the compliance is proportional to the cubic of the crack length.

Fig. 4 P - δ curve (Unidirectional CFRP, 160 mm, $G_I/G_{II} = 1.99$)

Fig. 5 P - δ curve (Woven CFRP, $G_I/G_{II} = 2.90$)

Fig. 6 The relation between compliance and crack length (Unidirectional CFRP, 160 mm)

Fig. 7 The relation between compliance and crack length (Woven CFRP)

Energy release rates obtained by four kinds of conventional equations (Eq.(6), Eq.(10), Eq.(13) and Eq.(15)), by Eqs.(16) and (17), and by the J integral are compared in Figs.8 and 9. The results of Eq.(13) give values larger than the other obtained values. This depends largely on the displacement δ . The results of Eq.(15) give the minimum value, which is 10-15% smaller than the other values. The reason for this result is unclear. The results of Eqs.(16) and (17), and the J integral agree with each other very well. Results of Eqs.(10) and (13) give similar results to those obtained by FEM analyses. Reference (9) suggests that the results of Eq.(10) may be preferable for evaluating the energy release rate. Consequently, the results of Eq.(10) are used in the following discussion.

Figures 10 and 11 show the changes in energy release rates due to the change in the mixed-mode ratio. As they are measured during the crack growth test, they are considered to be G_c values. In both figures, the G_c values do not change due to the crack growth. This indicates that the crack growth occurs under constant conditions. In both specimens, G_c values increase due to the decrease in mixed-mode ratio. This indicates that as the mode II fracture becomes dominant, the mixed-mode fracture tough-

Fig. 8 Energy release rate evaluated by conventional equation and by FEM (Unidirectional CFRP, 160 mm, $G_I/G_{II} = 0.38$)

Fig. 9 Energy release rate evaluated by conventional equation and by FEM (Woven CFRP, $G_I/G_{II} = 1.33$)

Fig. 10 The relation between energy release rate and crack length (Unidirectional CFRP, 160 mm)

Fig. 11 The relation between energy release rate and crack length (Woven CFRP)

Fig. 12 G_I - a relation (Unidirectional CFRP, 160 mm)

Fig. 13 G_{II} - a relation (Unidirectional CFRP, 160 mm)

ness increases. In the woven specimen, the data become slightly scattered as the mode I fracture becomes dominant.

Figures 12 and 13 show the G_I and G_{II} of the unidirectional specimen. Similar to the G_c values, both G_I and G_{II} values maintain nearly constant values during crack growth. Although the G_{II} value changes largely due to the change in the mixed-mode ratio, the G_I value does not change markedly. The change in the G_I value is not proportional to the change in the mixed-mode ratio; it reaches the maximum when the ratio is 0.68.

The relationships between G_I and G_{II} for both specimens are shown in Figs. 14 and 15. In Fig. 14, both results of 160 mm and 120 mm are shown. The dotted lines in Fig. 14 show G_{Ic} and G_{IIc} values obtained by Tanaka* in pure mode I and pure mode II fracture tests. When the rate of mode II is small, the results of this study agree well with that obtained by Tanaka. As mode II increases, it seems that the G_{II} value stays nearly constant, and only the G_{II} value increases. Tanaka et al.⁽¹¹⁾ conducted mixed-mode fracture tests by changing the fiber orientation, and obtained the relation between K_I and K_{II} . It is reported that the K_I agrees well with the K_{Ic} value obtained

Fig. 14 G_I - G_{II} relation (Unidirectional CFRP)

Fig. 15 G_I - G_{II} relation (Woven CFRP)

* Private communication.

by the pure mode I test, and K_{II} also agrees with K_{IIC} of the pure mode II test. The relation between K_I and K_{II} is expressed by square lines similar to Fig. 14. In Fig. 14, the G_I value increase slightly due to the increase in the mixed mode ratio, but it may be considered that these results agree with those of Tanaka et al. There is an insufficient amount of data for the woven specimen, but obtained results are very similar to those of Fig. 14.

5. Conclusions

The testing method of mixed mode fracture for CFRP specimens is studied experimentally and numerically.

(1) A new apparatus to conduct mixed-mode fracture test is made, and a mixed-mode test of mode I and mode II is carried out.

(2) In the mixed-mode condition, stable crack growth occurs and G_c , G_{IC} and G_{IIC} stay nearly constant during crack growth.

(3) Due to the change in mixed-mode ratios, the G_{II} value changes substantially but the G_I value does not show such a change.

Acknowledgments

The authors wish to express their sincere thanks to Professor Kageyama of Tokyo University for his

useful discussions. Mr. Tanaka at Shinnittetu Ltd. and Mr. Mouri at Nihon Sekiyu Ltd. are also appreciated for the supply of testing specimens.

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