Experimental Characterization of Interlaminar Fracture Behavior in Polymer Matrix Composites under Low-Velocity Impact Loading*

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Novel experimental methods were proposed to easily and precisely evaluate the mode I, II and I+II fracture toughness of polymer matrix composite laminates under low-velocity impact loading. A ramped incident stress wave was applied to suppress the flexural vibration of the specimen. A strain-based formula was employed to improve the accuracy of evaluation of the dynamic energy release rate. The validity of the proposed method was confirmed by the results of finite element analyses and dynamic experiments. The effects of loading rate and mode mixture on the interlaminar fracture behavior of carbon-fiber/epoxy composite laminates were investigated over a very wide range of loading rate from static to impact. The macroscopic fracture toughness clearly showed loading rate dependence regardless of mode ratio, and consequently the mixed mode fracture criterion varied with loading rate. The microscopic fracture morphology also showed loading rate dependence; cohesive fracture of matrix resin itself was a dominant fracture mechanism at higher loading rate, whereas debonding of fiber/matrix interface was a dominant fracture mechanism at lower loading rate.

Key Words: Composite Material, Delamination, Fracture Mechanics, Dynamic Fracture, Mixed Mode Fracture, Fracture Criterion, Low Velocity Impact

1. Introduction

Characterizing the initiation and growth of delamination is one of the most important issues for the structures made of polymer matrix composite laminates such as aircrafts or space structures. A number of works have been, therefore, carried out on this subject since the 1980's⁽¹⁾.

The macroscopic fracture behavior of polymer matrix composite laminates is basically governed by the microscopic factors such as the strength of fiber/matrix interface, toughness of matrix resin or volume fraction of fibers to matrix resin. Hence, the investigation of the rate dependence of fracture behavior is essential, considering the visco-elasticity of the matrix resin⁽²⁾. Especially, the characterization at

high loading rate is vitally important, because the delamination frequently occurs under low-velocity impact loading such as the bird-strike⁽³⁾.

It is, however, quite difficult to estimate the fracture behavior under impact loading with high accuracy owing to the influence of inertia forces both in the specimen and measurement system⁽⁴⁾. The authors have, therefore, continued a series of works on the development of experimental method for evaluating impact fracture toughness and on the characterization of rate dependence of fracture behavior of polymer matrix composite laminates⁽⁵⁾⁻⁽⁹⁾.

In the present paper, novel experimental methods are proposed to characterize the interlaminar fracture behavior of polymer matrix composite laminates under low-velocity impact loading, $\delta=10^0-10^1$ m/s. In addition, the effects of loading rate and mode mixture on the interlaminar fracture behavior of carbon-fiber/epoxy composite laminates are investigated by applying the experimental methods.

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2. Theoretical Basis

2.1 Specimen configuration

The WIF (Wedge Insert Fracture), ENF (End Notched Flexure) and MMF (Mixed Mode Flexure) specimens were employed to evaluate the mode I, II and I+II energy release rate, G_I , G_{II} and G_{III} , respectively^{(5),(10),(11)}. Configurations of the specimens were shown in Fig. 1.

2.2 Dynamic energy release rate

The dynamic energy release rate, G^{dyn} , is generally given by the following equation⁽¹²⁾;

$$G^{\text{dyn}} = \frac{dW}{dA} - \frac{dU}{dA} - \frac{dT}{dA}, \quad (1)$$

where A is the area of the crack. W is work done by external force. U and T are the strain and kinetic energy of the specimen, respectively.

On the other hand, the dynamic energy release rate, G^{dyn} , is theoretically equivalent to the $\hat{J}$ -integral given by the following equation for elastic bodies⁽¹³⁾;

$$\hat{J} = \int_{\Gamma} (W_e n_1 - T_i u_{i,1}) d\Gamma + \iint_{\Omega} \rho \ddot{u}_i u_{i,1} d\Omega, \quad (2)$$

where W_e , T_i , n_i and u_i are the strain energy density,

traction vector, outer normal vector and displacement vector, respectively. Γ and Ω are the boundary involving the crack tip and the region inside the boundary. ρ is the mass density of the body.

As for a stationary crack, the integrand of the second integral of Eq. (2) always has finite value, whereas the integrand of the first integral becomes infinity at the crack tip. Hence, Eq. (2) can be reduced as the following form by limiting the integration path to the region neighboring the crack tip⁽¹⁴⁾;

$$\hat{J} = \lim_{\Gamma \rightarrow 0} \int_{\Gamma} (W_e n_1 - T_i u_{i,1}) d\Gamma, \quad (3)$$

which is the same form as the static J -integral except for the limitation of $\Gamma \rightarrow 0$. However, the integrand of Eq. (3) is indeed different between static and dynamic cases owing to the inertia force.

Let us consider a short beam element containing the crack tip in the specimen, as shown in Fig. 2. The inertia force can be considered to affect only the flexural vibration in the x - y plane, when the longitudinal stress wave propagation in x , y and z directions can be neglected. In this case, the difference of the integrands of Eq. (3) between static and dynamic cases can be neglected, if the length of the beam, ΔL , is sufficiently smaller than the wave length of the caused vibration, and consequently the dynamic energy release rate, G^{dyn} , can be evaluated by the same equation as the static energy release rate⁽¹⁵⁾, G^{sta} ;

$$G^{\text{dyn}} \simeq G^{\text{sta}} = \frac{8M_U^2 + 8M_L^2 - (M_U + M_L)^2}{16bEI}, \quad (4)$$

where b , $2h$, a , $I (=bh^3/12)$ and E are the width, thickness, crack length, moment of inertia of area and Young's modulus of the specimen, respectively. M_U and M_L are the bending moments applied to the upper and lower beams, respectively.

Summarizing the above discussion, the following conditions must be satisfied to precisely evaluate the dynamic energy release rate, G^{dyn} , by Eq. (4) ;

(a) The area considered for evaluating the energy release rate must be sufficiently small; the distance between the points of measurement and the crack tip must be small enough.

(b) The impact loading must be applied not to

Fig. 1 Specimens for the mode I, II and I+II fracture toughness tests (unit: mm)

Fig. 2 Cracked beam subjected to bending moment

cause the high-order vibration of the specimen; the acceleration of the specimen must be appropriately controlled during the duration of loading.

3. Numerical simulation

3.1 Finite element model

Transient responses of the WIF, ENF and MMF specimens under low-velocity impact loading were analyzed with a finite element code, MARC K7, to study the validity of the discussion described in the previous section. The specimens were discretized with 4-nodes plane strain elements and considered as an orthotropic body with elastic moduli, $E_L=150$ GPa, $E_T=10$ GPa, $G_{LT}=4$ GPa, $\nu_{LT}=0.3$ and $\nu_{TL}=0.02$, as exemplified in Fig. 3. Nonlinear boundary conditions in conjunction with a contact algorithm were applied to the supporting points and crack interface.

To study the validity of the assumption (b), two different types of impact loadings were modeled and applied to the specimens as the forced displacement, $\delta(t)$, as shown in Fig. 4. One is the stepped input shown by the solid line, which corresponds to the condition of large acceleration. The other is the ramped input shown by the dotted line, which corresponds to the condition of less acceleration.

To study the validity of the assumption (a), two different types of evaluation formulae were derived on the basis of the beam theory. One is a load-based formula deduced by determining the bending

Fig. 3 Finite element model for the MMF specimen

Fig. 4 Time histories of displacement rate used in finite element analysis

moments, M_U and M_L , from the reaction force of the loading point, P , which corresponds to the condition of large integration path, $I \gg 0$ ($\Delta L = a$ or $L - a$). The other is a strain-based formula deduced by determining the bending moments, M_U and M_L , from the surface strain of the specimen, ϵ , which corresponds to the condition of small integration path, $I \approx 0$ ($\Delta L = 0$). The above formulae are, for example, given by the following equations for the MMF specimen, respectively⁽⁷⁾;

$$G_M^{\text{load}} = \frac{42C}{b(2L^3 + 7a^3)} \cdot \left(\frac{Pa}{2}\right)^2, \quad (5)$$

$$G_M^{\text{strain}} = \frac{42C}{b(2L^3 + 7a^3)} \cdot \left(\frac{\epsilon}{D}\right)^2, \quad (6)$$

where $C (= \delta/P)$ is the compliance of the specimen. $D (= \epsilon/M)$ is a coefficient depending on the section modulus and elastic moduli of the specimen.

3.2 Finite element results

Figure 5, where (a) and (b) are respectively the results for the stepped and ramped inputs, shows the results of finite element analysis for the MMF specimen. The abscissa represents the displacement of loading point, δ . The ordinate represents the energy release rate, G_M . The thick solid lines are the apparent values, G_M^{load} , obtained by Eq. (5). The thick broken lines are the apparent values, G_M^{strain} , obtained by Eq. (6). The thin solid lines are the $\dot{J}$ -integral.

In the case of stepped input, high-order vibration occurs as the consequence of large acceleration at the beginning of loading, and consequently the dynamic energy release rate, G_M^{dyn} , largely oscillates, as shown in Fig. 5(a). However, the strain-based value, G_M^{strain} , agrees well with the dynamic energy release rate, G_M^{dyn} , whereas the load-based value, G_M^{load} , does not agree with it at all.

In the case of ramped input, extremely less vibration occurs than the case of stepped input, and consequently the dynamic energy release rate, G_M^{dyn} , hardly oscillates, as shown in Fig. 5(b). In addition, the strain-based value, G_M^{strain} , agrees very well with the dynamic energy release rate, G_M^{dyn} , whereas the load-based value, G_M^{load} , slightly disagrees.

The above results lead to the conclusion that the combination of the ramped input and the strain-based formula enables to easily and precisely evaluate the dynamic energy release rate, G_M^{dyn} , as suggested in the previous section. The similar conclusions are also reached for the WIF and ENF specimens.

4. Dynamic Experiments

4.1. Materials

Two types of carbon-fiber/epoxy composite materials were investigated in the present study. One is a conventional composite of 120°C curing tempera-

(a) Stepped input

(b) Ramped input

Fig. 5 Finite element results for the low-velocity impact MMF test

ture, HTA/112 (Toho Tenax). The other is a toughened composite of 180°C curing temperature, IM600/133 (Toho Tenax). Unidirectional panels of 20 plies were fabricated according to the prepreg manufacturer's recommended cure cycle. A thin PTFE film was inserted between the mid-plane of the panels to provide an artificial starter slit. The specimens were carefully precracked about 1–2 mm to diminish the effects of the resin-rich region at the film's tip.

4.2 Experimental procedure

Fracture toughness tests at high displacement rates, $\dot{\delta} = 10^0 - 10^1$ m/s, were carried out with a SHPB (Split Hopkinson Pressure Bar) system, as shown in Fig. 6. A small column of tin alloy was utilized as a buffer to generate the ramped incident stress wave.

Fig. 6 SHPB system for the low-velocity impact MMF test (unit: mm)

The dynamic load and displacement were calculated from the outputs of strain gauges attached on the input and output bars on the basis of the one-dimensional wave propagation theory. Fracture toughness tests at low displacement rates, $\dot{\delta} = 10^{-7} - 10^{-2}$ m/s, were carried out with a screw-driven testing machine.

4.3 Macroscopic fracture toughness

Figure 7 shows the loading rate dependence of fracture toughness for the HTA/112. The abscissa represents the loading rate (time derivative of energy release rate⁽⁵⁾), $\dot{G}$. The ordinate represents the fracture toughness (critical energy release rate at the onset of crack growth), G_c . $\blacktriangle$ and $\triangle$ are the mode I fracture toughness, G_{Ic} , obtained by the DCB and WIF tests. $\blacktriangledown$ and $\triangledown$ are the mode II fracture toughness, G_{IIc} , obtained by the ENF test. $\blacksquare$ and $\square$ are the mode I+II fracture toughness, G_{Mc} , obtained by the MMF test. $\bullet$ are the mode I+II fracture toughness, G_{Mc} , obtained by the MMB test⁽¹⁶⁾. $\blacktriangle$, $\blacktriangledown$, $\blacksquare$ and $\bullet$ are the static test results obtained with the screw-driven testing machine. $\triangle$, $\triangledown$ and $\square$ are the impact test results obtained with the SHPB system.

As shown in Fig. 7, the mode I fracture toughness, G_{Ic} , decreases with increasing loading rate in $\dot{G}_I = 10^1 - 10^3$ J/m²/s. However, it keeps a constant value in the other region. The mode II fracture toughness, G_{IIc} , increases with increasing loading rate in $\dot{G}_{II} < 10^2$ J/m²/s. However, it decreases with increasing loading rate in $\dot{G}_{II} > 10^2$ J/m²/s. Consequently, a local maximum value exists at $\dot{G}_{II} \approx 10^2$ J/m²/s. The mode I+II fracture toughness, G_{Mc} , shows a similar tendency to the mode II fracture toughness, G_{IIc} . However, for $G_{II}/G_I = 0.58$ and 0.78, the mode I+II fracture toughness, G_{Mc} , is remarkably higher than the mode I fracture toughness, G_{Ic} , in $\dot{G} > 10^3$ J/m²/s. The above results for the HTA/112 are similar to those for the IM600/133, as shown in Table 1.

Fig. 7 Effect of loading rate on interlaminar fracture toughness(HTA/112)

Table 1 Summary of fracture toughness tests

	HTA/112		IM600/133	
	(Static)	(Impact)	(Static)	(Impact)
Mode I	153 [10 ⁰]	100 [10 ⁵]	499 [10 ⁰]	353 [10 ⁵]
Mode II	494 [10 ²]	418 [10 ⁷]	1430 [10 ²]	1030 [10 ⁷]
Mode I+II	211 [10 ³]	189 [10 ³]	745 [10 ³]	—

G_{IC} , G_{IIC} , G_{MC} (J/m²), $[\dot{G}_I]$, $[\dot{G}_{II}]$, $[\dot{G}_M]$ (J/m²/s)

4.4 Mixed mode fracture criterion

Figure 8, where (a) and (b) are respectively the results for lower and higher loading rates, shows the loading rate dependence of mixed mode fracture criterion for the HTA/112. The abscissa represents the mode I component of mixed mode fracture toughness, $G_{MC}^{(I)}$, normalized by the pure mode I fracture toughness, G_{IC} . The ordinate represents the mode II component of mixed mode fracture toughness, $G_{MC}^{(II)}$, normalized by the pure mode II fracture toughness, G_{IIC} . ●, ▲ and ▼ are the static test results at $\dot{G}=10^{-1}$, 10^0 and 10^1 J/m²/s, respectively. ○, △ and ▽ are the static test results at $\dot{G}=10^2$, 10^3 and 10^4 J/m²/s, respectively. ⊙ are the impact test results at $\dot{G}=10^6$ J/m²/s. The broken lines represent the linear fracture criterion given by the following equation⁽¹⁶⁾;

$$f = \frac{G_{MC}^{(I)}}{G_{IC}} + \frac{G_{MC}^{(II)}}{G_{IIC}} = 1. \quad (7)$$

At lower loading rate, the mode I+II fracture toughness, G_{MC} , agrees with the linear fracture criterion regardless of mode ratio, as shown in Fig. 8(a). However, at higher loading rate, the mode I+II fracture toughness, G_{MC} , does not agree with the linear fracture criterion for lower mode ratio, as shown in Fig. 8(b). The tendency at higher loading rate is similar to the results obtained by Reeder⁽¹⁶⁾.

4.5 Microscopic fracture morphology

Figures 9 and 10, where (a), (b) and (c) are respectively the results of mode I, II and I+II fracture

(a) Low loading rate

(b) High loading rate

Fig. 8 Effect of loading rate on mixed mode fracture criterion(HTA/112)

(Static)

(Impact)

(a) Mode I (DCB, WIF tests)

(Static)

(Impact)

(a) Mode I (DCB, WIF tests)

(Static)

(Impact)

(b) Mode II (ENF test)

(Static)

(Impact)

(b) Mode II (ENF test)

(Static)

(Impact)

(c) Mode I+II (MMF test)

(Static)

(Impact)

(c) Mode I+II (MMF test)

Fig. 9 Scanning electron micrographs of fracture surface (HTA/112, crack propagation →)

Fig. 10 Scanning electron micrographs of sectional area (HTA/112, crack propagation ⊗)

toughness tests, show the fracture surfaces and sectional areas of the specimens, respectively.

As shown in Figs. 9 and 10, the fracture surfaces are rough at lower loading rate; the profiles of carbon fibers can be clearly observed in the micrographs of sectional area. However, the fracture surfaces are relatively smooth at higher loading rate; the carbon fibers are embedded in the matrix resin.

The above trends, which does not depend on mode ratio, suggest that the debonding of fiber-matrix interface is a dominant fracture mechanism at lower loading rate but that the cohesive fracture of matrix resin itself is a dominant fracture mechanism at higher loading rate. The transition of microscopic fracture morphology almost coincides with that of macroscopic fracture toughness discussed in the previous

section. The above results for the HTA/112 are similar to those for the IM600/133.

5. Conclusions

Novel experimental methods were proposed to characterize the interlaminar fracture behavior of polymer matrix composite laminates under low-velocity impact loading. In addition, the effects of loading rate and mode mixture on the interlaminar fracture behavior of carbon-fiber/epoxy composite laminates were investigated by applying the experimental methods. The results are summarized as follows.

(1) The dynamic energy release rate can be easily and precisely evaluated by combining the ramped input and the strain-based formula.

(2) The mode I, II and I+II fracture toughness

clearly depends on loading rate.

(3) The mixed mode fracture behavior does not agree with the linear fracture criterion at higher loading rate, whereas it agrees at lower loading rate.

(4) The dominant fracture mode is cohesive fracture of matrix resin at higher loading rate, whereas it is debonding of fiber/matrix interface at lower loading rate.

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