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Interfacial Fracture Toughness of Multilayer Composite Structures

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The interfaces in multilayer composite structures are susceptible to delamination due to the combination of active tensile and shear loads under operating conditions. A four-layer center crack composite beam in four-point bending is simulated to determine the interfacial fracture energy of the multilayer structure. The crack is propagating along the interface between the second and third layers. Based on the Euler–Bernoulli theory, the strain energy of the four-layer composite beam is derived. Strain energies before and after the propagation of the interfacial crack are calculated, which results in determining strain energy release rates. Analytical results for those rates are validated with the numerical data obtained by the finite element method. The effect of layer thickness of the composite beam on the interfacial fracture toughness is investigated through a parametric study.

Keywords: interfacial fracture toughness, multi-layered structure, strain energy release rate.

Introduction. Multi-layered composite structures have received substantial attention in a variety of engineering applications, such as wear resistant materials, microelectronic devices and composite laminates used in aircraft structures. While multi-layered composites are widely used in structural components due to their favorable mechanical properties, such as high stiffness-to-weight and strength-to-weight ratios, the main drawback of such materials is their low interlaminar fracture toughness, which usually causes delamination when subjected to impact. Delamination or interlaminar separation is the most predominant and life-limiting failure mechanism in composite structures. Delaminations may develop during manufacturing; it may also result from impact damage, or from three-dimensional interlaminar stresses at stress-free edges and other discontinuities. In general, delamination corresponds to a crack-like discontinuity between the plies and it may typically extend during application of mechanical or thermal loads, or both during service life of composites [1, 2]. Fracture toughness is usually used as a generic term for measures of material resistance to extension of a crack. Fracture toughness testing has been recognized as the key to provide accurate toughness values needed in the linear elastic fracture mechanics [3]. A number of experimental and analytical techniques have been proposed to estimate the fracture toughness. Double cantilever beam (DCB) test is nowadays standardized for the measurement of the mode I interlaminar critical strain energy release rate [4]. For mode II there are several tests proposed in the literature [5–7]: end notched flexure (ENF), end loaded split (ELS), and four-point end notched flexure test (4ENF). Mode III interlaminar fracture of carbon/epoxy laminates was evaluated using the edge crack torsion (ECT) test and four-point bending plate test (de Morais and Pereira) [8, 9].

The aim of this paper is to investigate the interfacial fracture toughness of a four-layer composite structure with an interfacial crack. A four-point bending test is used to evaluate the interfacial fracture energy of a four-layer beam. An analytical expression for the strain energy release rate is presented as a function of the material properties and thickness of the four-layer structure. The effect of thickness ratio between the adjacent layers of the interfacial crack is studied by performing a parametric study.

1. Strain Energy Release Rate of a Four-Layer Composite Beam. In this study, the procedure for evaluation of the interfacial fracture energy of a four-layer composite beam is preceded in two steps. Firstly, the strain energy release rate of a four-layer composite beam is derived on the basis of the Euler–Bernoulli beam theory. Then, the analytical expression for the strain energy release rate is validated using the finite element method.

1.1. Modeling of the Strain Energy Release Rate. A four-layer composite beam consists of four different materials subjected to four point bending adopted in this work to investigate the interfacial fracture toughness. A central notch is cut through the thickness of the top two layers, and a symmetric crack is situated along the interface between the second and third layers as shown in Fig. 1. The four-layer beam width is b. The thicknesses of four layers are h_1, h_2, h_3, and h_4, respectively. The Young moduli of the four layers are E_1, E_2, E_3, and E_4, respectively. The crack length is $2a$. The specimen is subjected to four-point bending. The interfacial crack between the two supports is under constant moment conditions. The strain energy release rate should exhibit steady state characteristics, at least when the crack length significantly exceeds the thickness of the cut layer. Figure 2 shows the free-body diagram of the right half of the specimen subjected to a moment M that produces pure bending.

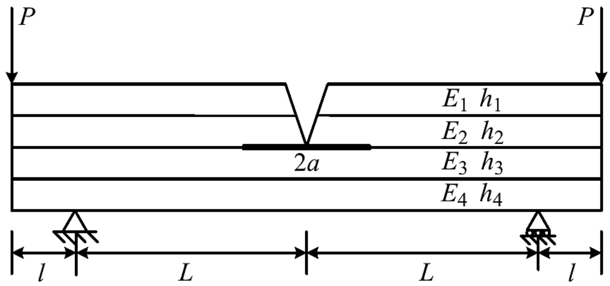

Fig. 1. Four-point bending test.

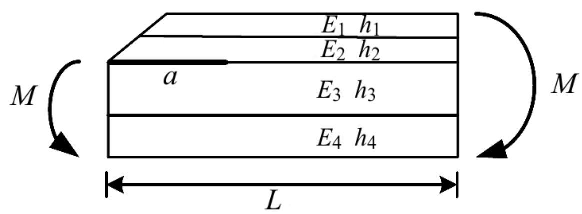

Fig. 2. Free-body diagram for the right half of four-point bending test specimen.

In the right-hand side of Fig. 2 the bending stresses in four layers can be written as

$$\sigma_1 = \frac{ME_1}{\overline{EI}}\, y, \qquad \sigma_2 = \frac{ME_2}{\overline{EI}}\, y, \qquad \sigma_3 = \frac{ME_3}{\overline{EI}}\, y, \qquad \sigma_4 = \frac{ME_4}{\overline{EI}}\, y, \tag{1}$$

$$\overline{EI} = E_1\left[\frac{1}{12}bh_1^3 + \left(\frac{1}{2}h_1 + h_2 + h_3 + h_4 - \bar{y}\right)^2 bh_1\right] +$$

$$+ E_2\left[\frac{1}{12}bh_2^3 + \left(\frac{1}{2}h_2 + h_3 + h_4 - \bar{y}\right)^2 bh_2\right] +$$

$$+ E_3\left[\frac{1}{12}bh_3^3 + \left(\frac{1}{2}h_3 + h_4 - \bar{y}\right)^2 bh_3\right] + E_4\left[\frac{1}{12}bh_4^3 + \left(\frac{1}{2}h_4 - \bar{y}\right)^2 bh_4\right],$$

$$\bar{y}=\frac{E_1 h_1 (h_1+2h_2+2h_3+2h_4)+E_2 h_2 (h_2+2h_3+2h_4)+E_3 h_3 (h_3+2h_4)+E_4 h_4^2}{2(E_1 h_1+E_2 h_2+E_3 h_3+E_4 h_4)},$$

where σ_1, σ_2, σ_3, and σ_4 are the bending stresses in the first, second, third, and fourth layers, respectively, $\overline{EI}$ and $\bar{y}$ are the flexural stiffness and neutral axis of the four-layer composite beam, and y is the distance measured from the neutral axis of the four-layer composite beam.

The strain energy stored of the right-hand side of Fig. 2 is as follows:

$$W=\frac{1}{2}\int \sigma_{ij}\varepsilon_{ij}\,dV=\frac{M^2}{2\overline{EI}}\int dx. \tag{2}$$

In the left-hand side of Fig. 2 the bending stresses in the top two layers are assumed to be negligible, and bending stresses in the bottom two layers can be expressed as

$$\sigma_3=\frac{ME_3}{\overline{EI}'}\,y, \qquad \sigma_4=\frac{ME_4}{\overline{EI}'}\,y, \tag{3}$$

$$\overline{EI}'=\frac{b}{12}\left[E_3 h_3^3+E_4 h_4^3+2E_3 E_4 h_3 h_4 \frac{(h_3+h_4)^2}{E_3 h_3+E_4 h_4}\right], \qquad \bar{y}'=\frac{E_3 h_3 (h_3+2h_4)+E_4 h_4^2}{2(E_3 h_3+E_4 h_4)},$$

where σ_3 and σ_4 are the bending stresses in the third and fourth layers, respectively, $\overline{EI}'$ and $\bar{y}'$ are the flexural stiffness and neutral axis of the bottom two-layer composite beam, and y is the distance measured from the neutral axis of the bottom two-layer composite beam.

Since there is negligible strain energy in the top two layers above the crack, the strain energy of the left-hand side of Fig. 2 is deduced from the bottom two layers as follows:

$$W=\frac{1}{2}\int \sigma_{ij}\varepsilon_{ij}\,dV=\frac{M^2}{2\overline{EI}'}\int dx. \tag{4}$$

As the crack length is extended from a to $a+\delta a$, the difference of the strain energy in the specimen before and after crack propagation is recognized to be the difference of the strain energy stored in the left-hand side of Eq. (4) and right-hand side of Eq. (2) of Fig. 2,

$$\delta W=\frac{M^2}{2\overline{EI}'}\int_0^{\delta a} dx-\frac{M^2}{2\overline{EI}}\int_0^{\delta a} dx=M^2\delta a\left[\frac{1}{\overline{EI}'}-\frac{1}{\overline{EI}}\right]. \tag{5}$$

The strain energy release rate is defined as

$$G=\lim_{\delta A\to 0}\left|\frac{\delta W}{\delta A}\right|, \qquad \delta A=b\delta a, \tag{6}$$

where δW represents the variation of the strain energy in the specimen and δA is the change of the crack area.

Substituting Eq. (5) into Eq. (6) leads to obtaining the strain energy release rate as follows:

$$G = \lim_{\delta A \to 0} \left| \frac{\delta W}{\delta A} \right| = \frac{M^2}{2b} \left[\frac{1}{\overline{EI}'} - \frac{1}{\overline{EI}} \right]. \tag{7}$$

1.2. Validation of Analytical Model Using Finite Element Method. As it is mentioned above, the interfacial fracture energy is studied on the basis of the Euler–Bernoulli beam theory. To verify the analytical model, numerical calculation based on the finite element method is employed. The finite element analysis has been carried out under plane stress conditions using ANSYS code. A two-dimensional regular element PLANE82 with 8 nodes is adopted for the entire structure. To model stresses around the crack tip accurately, a fairly fine mesh is required. In the finite element analysis the boundary conditions are specified as shown in Fig. 1. The displacements in the y-direction are zero at the two supports, and forces in the y-direction are specified at the two loading points. According to the expression for the strain energy release rate Eq. (6), it is necessary to calculate the difference of strain energy in the specimen before and after crack propagation. ANSYS is used to calculate strain energy. In this paper, the numerical value of the crack extension is taken as 1% of the initial crack length, i.e., $\delta a = a/100$. The material properties and thickness of the four-layer composite beam are listed in Table 1. The width, length, and crack length of the test specimen are 0.2, 60, and 20 mm, respectively. The bending moment applied to the specimen is $M = 200\ \text{N}\cdot\text{mm}$. A typical finite element mesh used in this study is shown in Fig. 3. The strain energy values in the four-layer beam before and after the crack extension are calculated by finite element method. Substituting the difference of the strain energy δW into Eq. (6) results in obtaining the strain energy release rate $G = 2.01\cdot 10^5$ J/m^2. The strain energy release rate is obtained using the analytical prediction shown in Eq. (7) is $G = 2.02\cdot 10^5$ J/m^2. Difference between the analytical solution and finite element result is less than 1%, which demonstrates the accuracy of the present prediction.

T a b l e 1

Material Properties and Thickness of the Four-Layer Beam [10]

Parameter of beam	Layer			
	first	second	third	fourth
Material	glass	copper	globtop	glass
Young modulus (GPa)	80	130	7	80
Poisson's ratio	0.3	0.3	0.3	0.3
Thickness (mm)	0.5	0.4	0.53	0.57

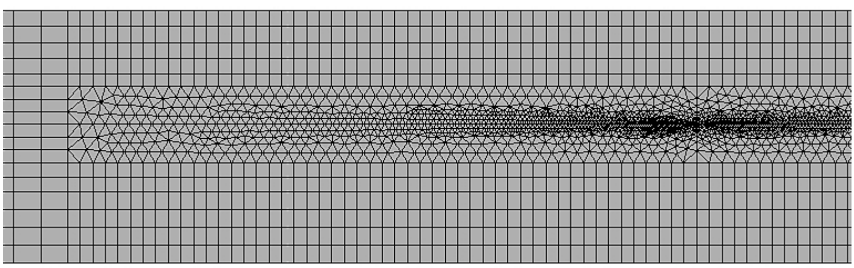

Fig. 3. Finite element mesh.

2. Numerical Results and Discussion. The analytical prediction of strain energy release rate has been proven to be accurate. The aim of the numerical study is to investigate the influence of layer thickness on the fracture energy. Considering the material properties listed in Table 1 the effect of layer 2 thickness h_2 is examined. The specimen width is $b = 7$ mm, load $P = 34$ N and load span $l = 5$ mm as it is shown in Fig. 1. The thicknesses of the first, third, and fourth layers are 1, 0.3, and 1 mm, respectively. The strain energy release rate varies with the thickness of the second layer as it is plotted in Fig. 4. It shows that the strain energy release rate increases with an increase of the thickness of the second layer. The strain energy release rate is converged to 9.7 J/m^2 as the second layer thickness reaches 5 mm. Then the effect of the first layer thickness is studied. Figure 5 illustrates the variation of the strain energy release rate at different values of thickness ratio. The strain energy release rate increases with an increase of the thickness ratio h_1/h_3. Stable strain energy release rate is found to be achieved in the region of larger h_1/h_3 and $h_1/(h_2+h_3)$ or in the region of smaller h_1/h_3 and $h_1/(h_2+h_3)$.

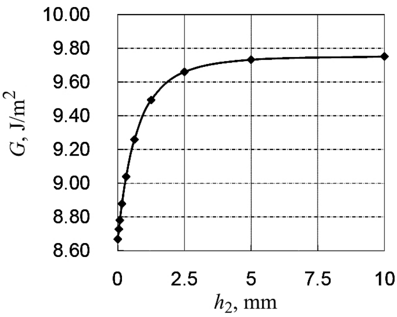

Fig. 4. Variation of strain energy release rate according to second layer thickness.

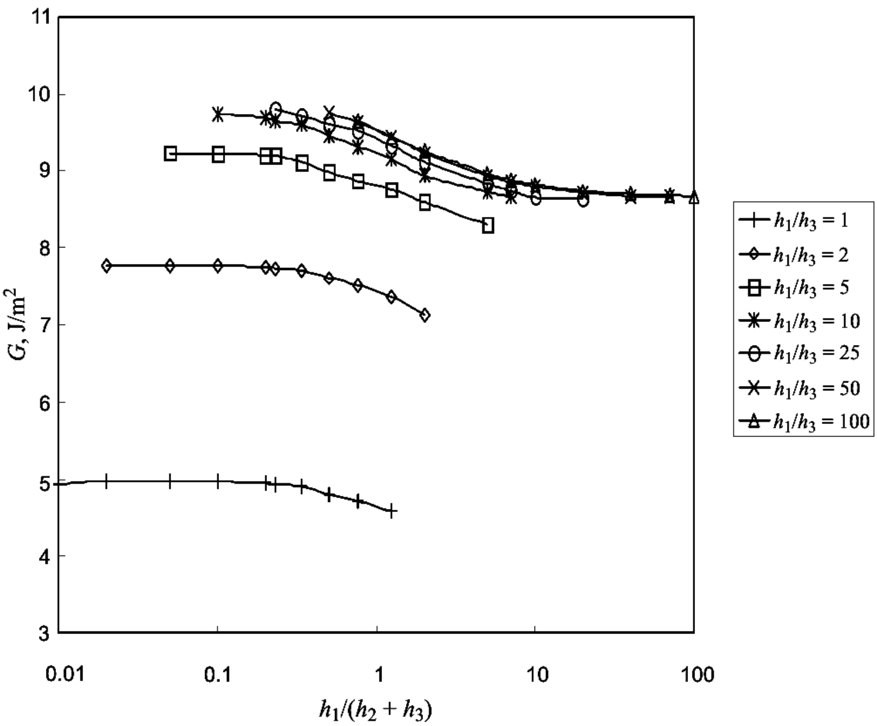

Fig. 5. Variation of strain energy release rate according to thickness ratios.

Conclusions. In this study, a four-point bending specimen was employed to determine the interfacial fracture energy of the four-layer composite beam. The strain energy release rate was studied on the basis of the Euler–Bernoulli beam theory. A simple but accurate expression relating the strain energy release rate to the thickness and material property of the four-layer composite beam is presented. A numerical validation was also performed using finite element method. The difference between the analytical solution and finite element result is less than 1%. The effect of thickness ratio on the strain energy release rate is investigated through a parametric study. Numerical results show that the strain energy release rate increases with an increase of the thickness of the second layer. The analytical prediction can be used for guidance in the physical design of four-layer structures.

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