General paper

INTRALAMINAR FRACTURE TOUGHNESS OF 90° LAYER IN CROSSPLY COMPOSITE LAMINATES

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Abstract: A new scheme for estimating the *intralaminar* fracture toughness is proposed. Recent research on the transverse cracking damage in crossply composite laminates suggests the use of the energy-release rate (ERR) of the 90° layer as the fracture toughness of the 90° layer. A brief survey of the authors' formulation of transverse cracking damage is presented, which shows that the ERR of the 90° layer is constant during damage progress in spite of the fact that the transverse cracking is a stochastic process. The ERR of the 90° layer is a constant which completely characterizes the damage evolution process. Some benefits of using the ERR of the 90° layer as a measure of the intralaminar fracture toughness are discussed in comparison with the other parameters such as the transverse strength, the crack resistance and the ERR of the whole laminate.

Key words: *Composite laminate, Fracture toughness, Energy-release rate, Transverse cracking, Damage evolution, Transverse strength, Crack resistance*

1 INTRODUCTION

Experimental determination of the strength of uni-directional (UD) composites as a material specification is obviously essential for design of structural members using advanced composite materials (ACM). However the transverse strength of UD composites is one of the most troublesome properties in experimental determination. Measurement involves many subtle technical problems to be overcome, such as the stress concentration due to gripping, the state of defects on sample edges, the specimen alignment with the testing machine etc. Moreover, even very careful testing sometimes yields discouraging scatter of the data. It is also the main reason of rather low reliability of composite materials.

This paper discusses some benefits of using the energy-release rate (ERR) of the 90° layer in crossply laminates instead of the transverse strength of UD material or other material parameters. In effect, it is not evident that the transverse strength of UD lamina is actually indispensable for design because of the recent trends of damage tolerant concept in structural design where the material parameters characterizing damage evolution processes are required. Much more severe reason is that the UD lamina can never be a structural member being subject to transverse loads and almost all ACM are used in the form of laminates with layers of various orientations of fibers. Therefore it is more reasonable to use a material specification appearing within actual laminate configurations including the effects of thermal residual stresses.

Section 2 is devoted to a brief survey of the authors' formulation of evolution law of transverse cracking damage in crossply laminates using the ERR of the cracking layer [1,2,3]. In spite of probabilistic nature of the transverse cracking, the ERR of the 90° layer can be regarded as constant during damage evolution. In section 3, the relation between the values of the ERR of the 90° layer and the edge roughness of specimen is discussed. We shall then discuss

some benefits of using the ERR of the 90° layer as the *intralaminar* fracture toughness in conjunction with the transverse strength, the ERR of the whole laminate by Nairn [4], Liu and Nairn [5] and Yalvaç et al [6] and the crack resistance of Han and Hahn [7].

2 DAMAGE EVOLUTION IN CROSSPLY LAMINATES

Nairn [4] extended Hashin's pioneering work [8] of stress analysis of crossply laminates with transverse cracks in the 90° layer to include the effects of thermal residual stresses. His results lead to the expression of ERR by a cracking in the 90° layer. We recently corrected some errors in Nairn's calculation [1] and showed experimentally that the ERR of the whole laminate is not constant but increases with the crack density [2]. We also calculated the ERR of each layer (0° and 90°) and that of the 90° layer alone has been experimentally shown to be constant during the damage evolution [1,2]. Then we formulated an evolution law for transverse cracking damage with excellent agreement with experimental results [3]. This section briefly surveys our results.

2.1 Energy -Release Rate

Suppose that a small increase of longitudinal load causes a new transverse crack in the 90° layer as is shown in Fig.1 where $2\rho s$ and 2δ are non-dimensional crack spacings and position normalized by the thickness of the 90° layer, respectively. In the case of displacement controlled tensile testing, the total energy change between the states (a) and (b) is the difference of strain energies between them since the potential energy of the external force does not change in the cracking process. One can evaluate this energy change with the aid of Nairn's results of stress analysis [4]. Then the ERR can be identified with the energy difference between (a) and (b) divided by the crack surface area. We shall call it the *energy-release rate* G_m by a cracking in spite that it is

Fig. 1. Distribution of existing cracks and position of the new crack.

slightly different from the usual fracture mechanical terminology, because the transverse cracks in crossply laminate instantaneously propagate to the width direction. The ERR of the whole laminate can be calculated as

$$G_m = \left(\frac{E_c}{E_T} \sigma_0 - \frac{\Delta\alpha\Delta\theta}{C_1} \right)^2 t_1 C_3 \frac{S}{S'} Y(\rho, \delta), \quad (1)$$

where E_c is Young's modulus of undamaged laminate and E_T is the transverse Young's modulus of UD lamina, σ_0 is the laminate stress, $\Delta\alpha$ is the difference between transverse and longitudinal thermal expansion coefficients of UD material, $\Delta\theta$ is the difference between curing temperature and test temperature ($\Delta\theta$ is negative if the test temperature is the room temperature), t_1 is the half thickness of the 90° layer. C_1 and C_3 are constants determined by the elastic stiffnesses and laminate geometry. S and S' are compliances of the laminate respectively in the states (a) and (b) in Fig.1 which is given by, as well as the function Y ,

$$\frac{S}{S'} = \frac{1 + K \sum_{i=1}^N \chi(\rho_i)}{1 + K \left\{ \sum_{i=1}^N \chi(\rho_i) + Y(\rho, \delta) \right\}}, \quad (2)$$

$$Y(\rho, \delta) = \chi(\delta) + \chi(\rho - \delta) + \chi(\rho), \quad (3)$$

$$\chi(\rho) = 2\alpha\beta (\alpha^2 + \beta^2) \frac{\cosh 2\alpha\beta - \cos 2\beta\rho}{\beta \sinh 2\alpha\rho + \alpha \sin 2\beta\rho}, \quad (4)$$

where N is the number of existing crack spacings and K , α , β are again the coefficients determined by material constants and the laminate geometry. The second term in the parentheses in the RHS of Eq.(1) is the thermal residual stress in the 90° layer, and therefore the quantity in the parentheses is in effect the total normal stress in the load direction.

A series of experiments was conducted in order to examine the dependence of the energy-release rate on the laminate configuration and the edge roughness of the specimens. Two GFRP laminates with configurations of $[0/90_4/0]_T$ and $[0/90_5/0]_T$ were used. Since the transverse cracks in GFRP can be recognized by naked eyes under an appropriate lighting, the specimens being subject to tensile loading were recorded by a video scope. The tensile testing

was stopped before the saturation of the cracking damage [9]. After the testing we measured the positions of all the cracks by a microscope. Then replaying the video scope, we identified the order and positions of all the cracks. The laminate stress at each cracking could be obtained on the load-displacement chart because the load carrying capacity is comparatively high in GFRP so that small but sharp drop of load by each cracking was easily recognized. Then all the necessary informations are obtained for calculation of the ERR of the whole laminate, i.e., Eq.(1). Note that the direct measurement of the energy-release rate is impossible because the load drops are too small to measure. Figure 2 shows examples of the test result for specimens of each edge roughness.

Fig. 2. Energy-release rate of the whole laminate. ($[0/90_4/0]_T$)

The numbers in Fig.2 indicate the sand paper numbers (in JIS notation) by which the sample edges were polished. The abscissa is the averaged crack density which can be linearly transformed to the crack count.

Nairn [4] assumed that the ERR of the whole laminate is constant during the cracking and then he formulated the damage evolution law. Although the data exhibit significant scatter at high crack density, Fig.2 clearly shows that the ERR increases with the crack density, therefore the fundamental assumption of Nairn is not appropriate. For $[0/90_5/0]_T$ samples, the results were the same.

2.2 Energy-Release Rate of Each Layer

In the case of displacement controlled quasi-static tensile testing, the potential energy of the external force does not change by cracking but only the strain energy of the sample changes. Therefore, the total energy change by a cracking is the change in the strain energy of the sample. This strain energy change then can be divided into two parts, i.e., those of the 90° and 0° layers, each of which includes the energy change due to relaxation of thermal residual stresses. Let us define the ERR of each layer as the strain energy change of each layer divided by the crack surface area just as in the case of ERR of the whole laminate which is the sum of the ERR of each layer. The ERR of the 90° layer is useful for the construction of evolution law of cracking damage. The analytical result for the ERR of the 90° layer $G_m^{(1)}$ is obtained as follows;

$$G_m^{(1)} = \left(\frac{E_T \sigma_0 - \Delta \alpha \Delta \theta}{E_C C_1} \right)^2 t_1 C_3 \times \quad (5)$$

$$\left\{ \frac{1 - \frac{\eta E_1}{h E_C} \sum \chi(\rho_i) + \frac{1}{2} K \sum \chi^{(1)}(\rho_i)}{1 + K \sum \chi(\rho_i)} Y(\rho, \delta) - \frac{1}{2} Y^{(1)}(\rho, \delta) \right\},$$

where the new functions are defined as

$$\begin{aligned} \chi^{(1)}(\rho) = & \frac{C_1^{(1)}}{C_1} \left\{ \chi(\rho) [1 + \zeta(\rho)] + \frac{C_1}{C_3} [\eta_1(\rho) + \eta_2(\rho)] \right\} \\ & + \frac{C_2^{(1)} - C_4^{(1)}}{C_2 - C_4} \left\{ \chi(\rho) [1 - 2\zeta(\rho)] - 2 \frac{C_1}{C_3} \eta_1(\rho) \right\} \\ & + \frac{C_3^{(1)}}{C_3} \left\{ \chi(\rho) \zeta(\rho) + \frac{C_1}{C_3} [\eta_1(\rho) - \eta_2(\rho)] \right\}, \quad (6) \end{aligned}$$

$$Y^{(1)}(\rho, \delta) = \chi^{(1)}(\delta) + \chi^{(1)}(\rho - \delta) - \chi^{(1)}(\rho), \quad (7)$$

$$\zeta(\rho) = \frac{\alpha^2 + \beta^2}{4\alpha^2\beta^2} \frac{\beta^3 \sinh 2\alpha\rho + \alpha^3 \sin 2\beta\rho}{\beta \sinh 2\alpha\rho + \alpha \sin 2\beta\rho}, \quad (8)$$

$$\eta_1(\rho) = (\alpha^2 - \beta^2) \frac{1 - \cosh 2\alpha\rho \cos 2\beta\rho}{(\beta \sinh 2\alpha\rho + \alpha \sin 2\beta\rho)^2} \rho, \quad (9)$$

$$\eta_2(\rho) = 2\alpha\beta \frac{\sinh 2\alpha\rho \sin 2\beta\rho}{(\beta \sinh 2\alpha\rho + \alpha \sin 2\beta\rho)^2} \rho, \quad (10)$$

where C_1, C_2 , etc. are again constants determined by material parameters. As in the case of the ERR of the whole laminate, Eq.(5) can be calculated using the experimental data. Figure 3 shows the experimental results for the same sample group as in Fig.2.

Fig.3. Energy-release rate of 90° layer ([0/90₄/0]_T).

In the later stage of the cracking evolution, the scatter of the data is rather large again but the ERR of the 90° layer can be regarded as practically constant during the damage evolution. On the other hand, the ERR of the 0° layer monotonically increases with the crack density [2], therefore the change in the ERR of the whole laminate is mainly due

to the increasing characteristics of the ERR of the 0° layer with the crack density.

2.3 Evolution Law of Cracking Damage

If we set the LHS of Eq.(5) as a constant according to experimental confirmation in the preceding section, Eq.(5) can be regarded as an evolution law. However it is not convenient that the evolution law contains positions of all the cracks. A useful evolution law should be a relation between the laminate stress and the crack density or the crack count. In order to obtain the evolution law from Eq.(5), we must take into account the probabilistic nature of cracking.

New cracks randomly occur between already existing pairs of cracks at lower crack density, however they tend to take place nearer and nearer the center of crack spacings as the crack density grows up. It is because the normal stress in the direction of external force changes its distribution from plateau like one at low crack density to one with a peak at the center of the spacing at high crack density. Therefore, we assume that a new crack always forms at the center of the existing pair of cracks, i.e.,

$$\delta = \frac{\rho}{2}. \quad (11)$$

The crack spacing in which a new crack forms is not the same as the average crack spacing, but it is almost always wider than the averaged one [3]. Figure 4 shows a result of one of our experiments for a [0/90₄/0]_T #2000 specimen

Fig. 4. Ratio of true crack spacing and averaged one.

where the ordinate indicates the ratio of actual crack spacing in which a new crack forms to the average crack spacing. From this figure, it is clear that almost all new cracks forms between crack pairs whose spacings are wider than the averaged one. Hence we assume

$$\rho = f\bar{\rho}, \quad (f \geq 1). \quad (12)$$

With these assumptions, Eq.(5) can be reduced to the desired evolution law as follows;

$$\sigma_0(D) = \frac{E_C}{E_T} \left[\sqrt{\frac{G_m^{(1)}}{t_1 C_3 g(D)}} + \frac{\Delta \alpha \Delta \theta}{C_1} \right], \quad (13)$$

where the crack density $D = 1/\bar{\rho}$, and we have set

$$g(D) = 2 \frac{1 - \frac{\eta E_T^2 C_3}{h E_c} D \left[\frac{t_2 E_L}{h E_c} \chi(1/D) + \frac{1}{2} \chi^{(1)}(1/D) \right]}{1 + \frac{\eta E_T^2 C_3}{h E_c} D \chi(1/D)} \times Y(f/D, f/2D) - \frac{1}{2} Y^{(1)}(f/D, f/2D) \quad (14)$$

The determination of the factor f can be done by comparing e.g., the experimental data of Y and the function $Y(f/D, f/2D)$. It is shown in Fig.5 for the same specimen as in Fig.4. For all specimens we have obtained $f = 1.3$, which can be regarded as constant during the damage evolution [3]. (The curve of $f=1$ is also shown in this figure for comparison.)

Fig.5. Determination of the factor f .

Examples of comparisons of the evolution law Eq.(13) and experiments are shown in Fig.6 for $[0/90_4/0]_T$ laminates and 7 for $[0/90_5/0]_T$ laminates. The correlation between the theoretical evolution law and experiments is excellent. All other specimens showed the resembling good correlations. The values of ERR of the 90° layer $G_m^{(1)}$ were taken as the average of experimental values of each specimen. Therefore all the material parameters were experimentally determined and no adjustable parameters have not used in drawing the theoretical curves, which suggests that the damage evolution law Eq.(13) is appropriate.

3 ENERGY-RELEASE RATE AS A MEASURE OF TOUGHNESS

As was noticed in the introduction, UD lamina subject to transverse load can never be a structural member, but laminates with various orientations of laminae are usual forms. This means that transverse UD properties such as the strength have their significances only as basic data when one needs to describe the off-axis property in various laminate configurations. Transverse cracking is a sequence of fracture of the 90° layer. Therefore the cracking damage evolution is closely related to transverse fracture properties of the UD

Fig.6. Comparison of theoretical and experimental evolution of cracking damage: $[0/90_4/0]_T$.

Fig.7. Comparison of theoretical and experimental evolution of cracking damage: $[0/90_5/0]_T$.

materials. We have shown that the ERR of the 90° layer in crossply laminates is the one describing the damage progress and is constant. Although it is a discrete quantity, it can be regarded as continuous just as the *interlaminar* fracture toughness in UD materials if the cracking evolution process (increase in the number of transverse cracks) is conceived as same as a single crack propagation process. We shall investigate in this section some benefits of using the ERR of 90° layer as a measure of the *intralaminar* fracture toughness.

3.1 Dependence of Energy-Release Rate on Edge Roughness

Transverse cracks propagate through the width of specimen starting from the edge. This can be recognized since a few cracks stop at intermediate position in the width direction. Observing them, we can recognize that the cracks start from the either edge of the specimen. Therefore the resistance against the crack formation will be influenced by the state of the edge. In order to investigate the dependency of the ERR of the 90° layer on the state of edge of the 90° layer, we have polished the specimen edges by sand papers with 4 roughnesses; #80, 240, 400 and 2000. Table 1 shows the maximum surface roughness $R_{\max}$ of the 90° layer of each specimen where the radius of curvature of searching needle of roughness instrument was 0.2 μm . For all the specimens tested, we could obtain $G_m^{(1)}$ as the average of experimental values. Figure 8 shows the dependence of the average values of $G_m^{(1)}$ on the surface roughness. This figure is illustrated with the abscissa of sand paper numbers, therefore note that

Table 1. Surface roughness of specimen edge and number of sand papers.

sand paper number	$R_{\max}$ (μm)
# 80	17.6
# 240	8.98
# 400	4.80
# 2000	1.38

Fig. 8. Dependence of $G_m^{(1)}$ on the surface roughness.

its scale has no physical meaning. Moreover, marks in figures merely indicate the values of different specimens. Although sample number tested is limited, it might be said that $G_m^{(1)}$ depends on the edge roughness in both laminate configurations. However, the rougher the edge, the larger the $G_m^{(1)}$, i.e., more resistant against cracking. It might seem to be a peculiar result at first sight, but it should suggest that the defects which can be nucleation sites of transverse cracks must be finer and/or more sharp than the roughness which can be detected by usual instruments for surface roughness measurement. It is strongly conceivable that finer sand paper will cause small but sharp defects on the edges of the 90° layer. More intensive investigation is necessary on this point.

The scatter of the data in Fig.8 between specimens of the same configuration and roughness must be reduced by more careful preparation of the specimens.

3.2 Comparison with UD Strength

The transverse strength of UD lamina is one of the properties having a large scatter of data. For instance, the coefficient of variation in CF/Epoxy system is about 10 % [10]. Therefore it is frequently regarded as a statistical quantity. This causes rather low reliability of composite materials and significantly restricts their wide usage. Another troublesome property of transverse strength is that it is difficult to strictly determine one value of the strength of a sample since the broken pieces of a specimen after the first strength test have different strengths, and the second strength can be either larger or smaller than the first one [10].

On the other hand, the ERR $G_m^{(1)}$ can be deterministically obtained. The number of our samples is limited, but Fig.8 suggests that the data of $G_m^{(1)}$ will be expected not to be so widely spread since a few data shown in Fig.8 could show a clear dependence of $G_m^{(1)}$ on the edge roughness. The method of measurement of $G_m^{(1)}$ adopted in the present research is simple and no extreme care for specimen preparation and setting on testing machine is necessary except for polishing specimen edges, because the laminate configuration is such that the 0° layers are on both surfaces. Also in that sense, the use of $G_m^{(1)}$ is advantageous than the transverse strength.

Our method of experiment however takes much time and efforts since precise positions of all the cracks need to be determined by replaying the recorded video scope. Concerning to this point, we are now planning a development of an automatic measurement of cracking stress and crack positions by using acoustic emission sensors. This is expected to much simplify our laborious process and will lead to an easy estimate of the intralaminar fracture toughness.

3.3 Comparison with Crack Resistance

Han and Hahn[7] calculated the surface energy γ_R of transverse crack and called the relation between γ_R and the laminate stress as the *crack resistance curve*. As they insist, γ_R can be regarded as a measure of fracture toughness of the 90° layer. However their γ_R increases with the crack density. Therefore it is effectively possible to compare γ_R curves between different materials but determination of a definite

value of γ_r is impossible. On the other hand, single value of our $G_m^{(1)}$ can be definitely specified. To be able to determine a definite value of the fracture toughness is important as a specification for the structural design.

3.4 Comparison with G_m of the Whole Laminate

The essential assumption by Nairn that the ERR of the whole laminate G_m is constant is not true. This has been experimentally confirmed also by Yalvaç et al [6]. Using AS4/3501-6 and AS4/Tactix, they measured G_m with the aid of the approximate formula of Nairn and have shown that the change in G_m with the crack density is divided into three regions. In the second region G_m can be regarded as constant in their materials, so that they propose a remedy that the G_m value in the second region can be used as the fracture toughness. However, in each of our specimens of GFRP, G_m is a monotonically increasing function of the crack density. It is impossible to find a constant region of G_m .

Moreover, the matrix resins used in [6] are toughened epoxys in which plastic deformations might be large when the cracking damage progresses, therefore to such a case, the applicability of the elastic-brittle damage theory as ours and Nairn's should be argued.

4 CONCLUDING REMARKS

A new method is proposed for evaluation of the intralaminar fracture toughness using the constant $G_m^{(1)}$ which characterizes the transverse cracking damage in crossply composite laminates. Benefits of use of the ERR of the 90° layer as a measure of the fracture toughness are

presented in comparison with other parameters such as the transverse strength of UD materials, the crack resistance curve etc. Advantageous points are summarized as follows;

- (1) $G_m^{(1)}$ can be definitely determined. This is a better feature in compared with other measures picked up in this paper.
- (2) $G_m^{(1)}$ is a damage characterizing parameter. It is useful in the actual design process of structural members of laminates.
- (3) To measure $G_m^{(1)}$ is much easier than the transverse strength of UD lamina. A future development of automatic measurement is expected to much simplify the measuring process.

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