EFFECTS OF TEST CONDITIONS ON MODE II INTERLAMINAR FRACTURE TOUGHNESS OF FOUR-POINT ENF SPECIMENS

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SUMMARY: Mode II interlaminar fracture toughness of laminated composites has risen importance to design criteria and material selections for advanced composite structures. Recently, Martin and Davidson have proposed four-point ENF (4ENF) test, which requires no special control system or complex loading fixture. In the present paper, effects of test conditions, such as specimen dimensions, loading conditions, friction between delamination surfaces, and data reduction methods on Mode II interlaminar fracture toughness at initiation and during delamination growth have been discussed by experimentally and theoretically. An improved test procedure and new data reduction method have been proposed based on the results and discussions. The 4ENF test has been considered one of the candidates of international standard test method for Mode II interlaminar fracture toughness.

KEYWORDS: Interlaminar Fracture Toughness, Delamination, Mode II, 4 point ENF, Energy Release Rate, Friction, Standardization.

INTRODUCTION

Mode II interlaminar fracture toughness of laminated composites has risen importance to design criteria and material selections for advanced composite structures. End notched flexure (ENF) test [1] has been proposed for characterization of Mode II interlaminar fracture toughness, but it has a serious problem that delamination growth is unstable under usual loading condition. It is very difficult for ENF test to evaluate interlaminar fracture toughness during delamination propagation. To overcome the instability of conventional ENF test, Stabilized ENF test [2] and End loaded split (ELS) test [3] have been proposed. Delamination growth is stable when both test methods are applied, though special control system and complex loading fixture are required with stabilized ENF and ELS tests, respectively. Recently, Martin and Davidson [4,5] and Tanaka [6] have proposed four-point ENF (4ENF) test and Over Notched Flexure (ONF) test, respectively, in which delamination growth is stable with simple specimen setup. ONF and 4ENF tests require no special control system or

complex loading fixture. The 4ENF test has been considered one of the candidates of international standard test method for Mode II interlaminar fracture toughness. In the present paper, effects of the conditions of 4ENF test, such as specimen dimensions, loading conditions, friction between delamination surfaces, and data reduction methods on Mode II interlaminar fracture toughness at initiation and during delamination growth have been discussed by experimentally and theoretically.

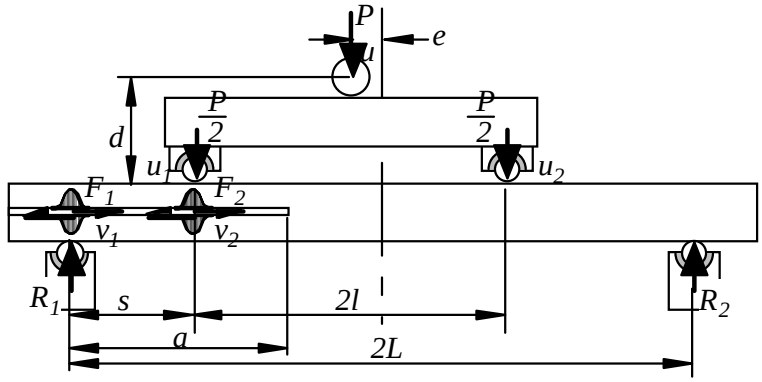


Fig. 1: Schematic figure of four- point ENF (4ENF) specimen

ANALYSIS OF 4ENF Specimen

Energy Release Rate of 4ENF Specimen

Figure 1 schematically shows 4ENF specimen subjected to eccentric load, P. Friction forces, F_1 and F_2, between upper and lower delamination surface are considered. Displacement, u. at loading point, shear slips, v_1 and v_2, with friction are given by linear function of P, F_1 and F_2.

$$\begin{Bmatrix} u \\ v_1 \\ v_2 \end{Bmatrix} = \begin{bmatrix} \lambda_{11} & \lambda_{12} & \lambda_{13} \\ \lambda_{12} & \lambda_{22} & \lambda_{23} \\ \lambda_{13} & \lambda_{23} & \lambda_{33} \end{bmatrix} \begin{Bmatrix} P \\ F_1 \\ F_2 \end{Bmatrix} \tag{1}$$

Change of total mechanical energy $d\Pi$ (potential of external loading system + elastic energy of specimen) with delamination growth, da, under fixed load condition;

$$d\Pi = -\frac{1}{2}(Pdu + F_1 dv_1 + F_2 dv_2) \tag{2}$$

Energy release rate, G, is defined by Eqn (3)

$$G = -\frac{1}{2B}\frac{d\Pi}{da} \tag{3}$$

Under the symmetric loading (e = 0 in Fig. 1), $R_1 = R_2 = P/2$, then F_1 and F_2 are equal to $\mu P/4$, where μ is coefficient of friction. Substituting Eqns (1) and (2) into Eqn (3), we obtain Eqn (4).

$$G_{II} = \frac{P^2}{2B}\left[\frac{d\lambda_{11}}{da} + \frac{\mu}{2}\left(\frac{d\lambda_{12}}{da} + \frac{d\lambda_{13}}{da}\right) + \frac{\mu^2}{16}\left(\frac{d\lambda_{22}}{da} + 2\frac{d\lambda_{23}}{da} + \frac{d\lambda_{33}}{da}\right)\right] \tag{4}$$

Assuming that λ_{22}, λ_{23} and λ_{33} are much smaller than λ_{11}, λ_{12} and λ_{13}, the higher order terms of μ can be neglected.

$$G_{II} = \frac{P^2}{2B}\frac{d}{da}(2C - \lambda_{11}) = \frac{P^2}{2B}(2m - m_0) \tag{5}$$

$$m = dC/da \quad , \quad m_0 = d\lambda_{11}/da \tag{6}$$

Where C is the compliance of 4ENF specimen with friction under symmetric loading (e = 0). By applying elementary beam theory to 4ENF specimen as shown in Fig. 1, m and m_0 can be estimated by Eqns (7) and (8), respectively.

$$m = \frac{9s^2}{8EBh^3}\left(1 - \frac{4\mu h}{3s}\right) \tag{7}$$

$$m_0 = \frac{9s^2}{8EBh^3} \tag{8}$$

Geometrical Nonlinearity

Because of unsymmetrical distribution of bending stiffness of 4ENF specimen with respect to loading line, rotation of loading noses results in change of length s.

$$\Delta s = d(u_1 - u_2)/(2l) \tag{9}$$

Relation between e and a is calculated to satisfy Δs = 0, and plotted in Fig. 2 for $2L$ = 100 mm, $2h$ = 3 mm and $2l$ = 50 mm and 70 mm. The figure indicates that eccentricity, e, of 7 mm and 5 mm reduces the effect of geometrical nonlinearity (Δs) for $2l$ of 50 mm and 70 mm, respectively.

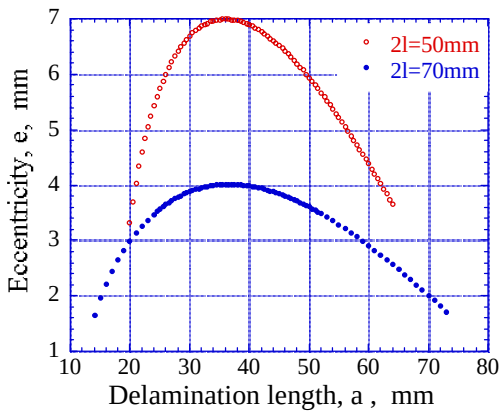


Fig. 2: Relation between eccentricity and delamination length which satisfies Δs = 0

Compliance and Energy Release Rate under unsymmetrical loading

Compliance, λ_{11} , of 4ENF specimen without friction under unsymmetrical loading is given by Eqn (10) as a function of delamination length, a.

$$\lambda_{11} = \frac{3}{8EBh^3}\left\{\frac{e^2a^3}{L^2} + \frac{3esa^2}{L} + 3s^2a + f(s,e)\right\} \tag{10}$$

Where f(s,e) is a function which is independent of *a*. $m_0 = d\lambda_{11}/da$ is not constant but as a function of a. Energy release rate is given by Eqn (11).

$$G_{II} = \frac{9P^2}{16EB^2h^3}\left(\frac{ea}{L}+s\right)^2 = \frac{3\lambda_{11}P^2\left(\frac{ea}{L}+s\right)^2}{2B\left(\frac{e^2a^3}{L^2}+\frac{3esa^2}{L}+3s^2a+f(s,e)\right)} \tag{11}$$

dG_{II}/da of unsymmetrical loading is always negative under fix grip condition, and delamination growth is expected to be stable.

EXPERIMENTAL METHOD

Material and Specimens

Material tested was a unidirectional $[0]_{22T}$ carbon/epoxy laminate produced from Mitsubishi Rayon TR340H150 prepreg and cured at 125C. The starter film was 13 μm thick PTFE film inserted into the mid-plane of the laminate. Nominal thickness of the laminates was 3 mm. Specimens were cut from the laminate panels. Nominal length and width of the specimen are 155 mm and 20 mm, respectively. Average value of elastic modulus, *E*, was 102 GPa.

Loading Fixture and Test Condition

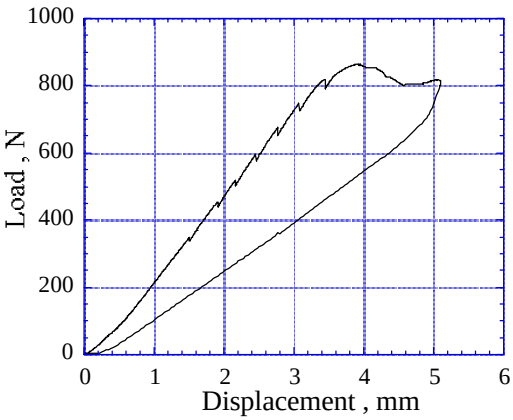
Conventional four-point-bend fixture A (d = 56 mm) and specially designed fixture B (d = 12 mm) were used to apply the four-point bending load to the specimen. PTFE films were placed at loading and supporting noses to reduce the friction between the specimen and the noses. PTFE films were inserted on the starter films of some test specimens in order to reduce the friction between delamination surfaces. Outer span length, *2L*, was fixed to be 100 mm, and inner span length, *2l*, was chosen to be 50 mm and 70 mm. Initial delamination length from supporting nose, a_0, was 40 or 45 mm. The load was applied with a testing machine at constant displacement rate of 0.1 mm/min. Unsymmetrical load was applied to some specimens by using the conventional fixture A in order to examine the reduction of geometrical nonlinearity.

Load versus displacement curves were recorded and delamination length was measured with travelling microscope. AE signal was monitored during the test in order to detect the initiation of delamination. Ultrasonic C san was applied to measure the through-the–width delamination length.

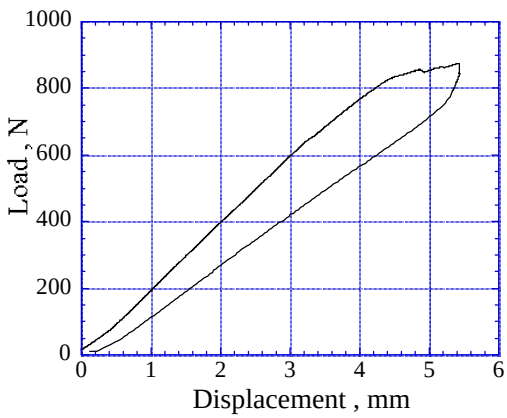
EXPERIMENTAL RESULTS

Symmetric Loading

Figures 3 (a) and (b) show the load versus displacement curves obtained by using fixture A (*d* = 56 mm). Stick-slip was observed as shown in Fig. 3 (a) when PTFE films were not placed at loading and supporting noses. Movement of specimen on the supporting noses was 2 – 3 mm in the case of Fig. 3 (b), when PTFE film was placed at the loading and supporting noses and inserted between delamination surfaces. Effect of geometrical nonlinearity was clearly observed when fixture A was used.



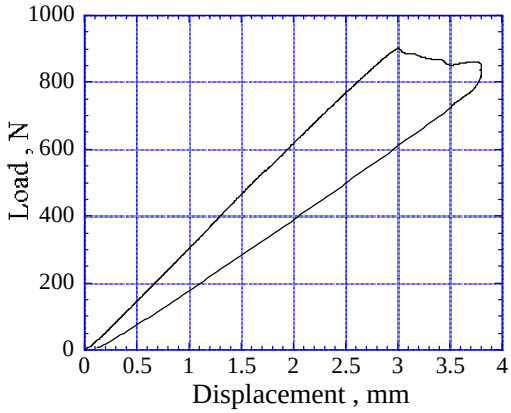
(a) PTFE film inserted between delamination surfaces



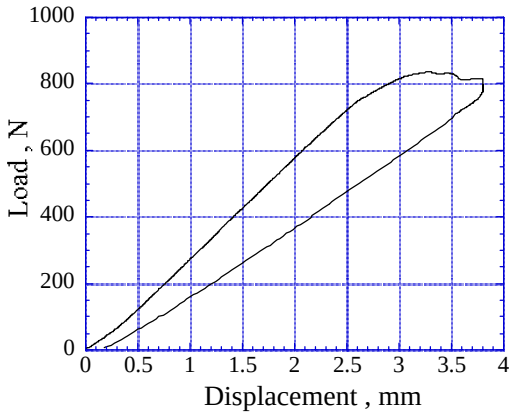
(b) PTFE films placed at loading and supporting noses and between delamination

Fig. 3: Load versus displacement curves obtained by using fixture A (d = 56 mm)

The following tests were carried out by using fixture B which can minimize geometrical nonlinearity, Δs, because of applying smaller d values (d = 12 mm). Fig. 4 (a) and (b) show the load versus displacement curves in the case of $2l$ = 50 mm and PTFE films placed at the loading and supporting noses. Linear relations are observed at initial stage of loading and stick-slips did not occurred. Delamination growth is always stable for all test specimens.



(a) PTFE film not inserted between delamination surfaces



(b) PTFE films inserted between delamination surfaces

Fig. 4: Load versus displacement curves obtained by using fixture B (d = 12 mm)

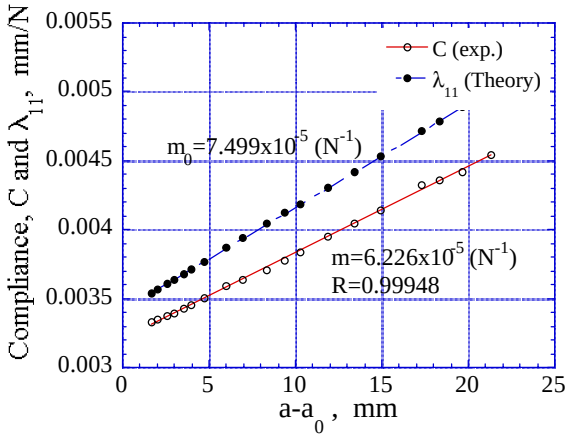
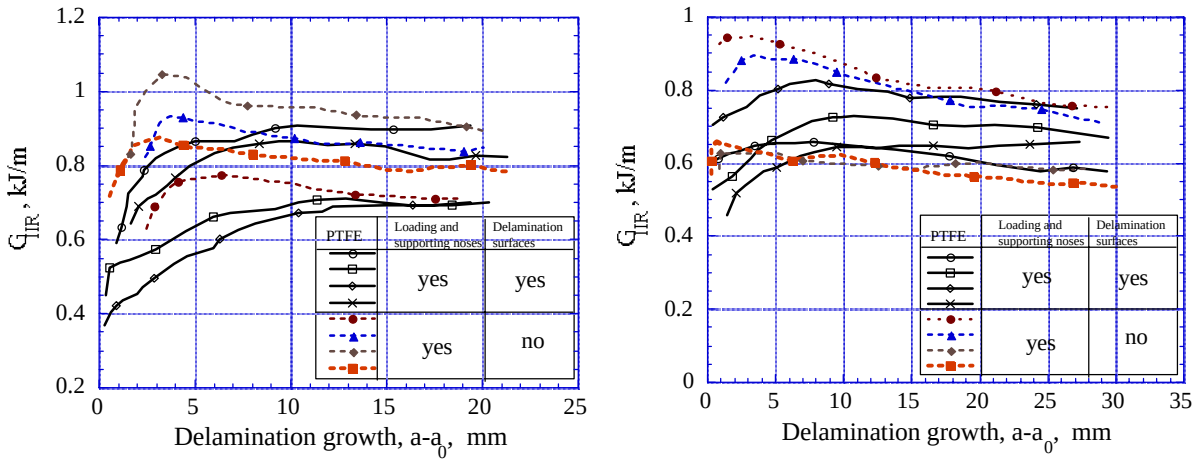


Fig. 5:Relation between compliance and delamination length

A relation between compliance versus delamination length is shown in Fig. 5. Experimental value of m is smaller than theoretical value of m_0 because of frictional effect as predicted by Eqns (7) and (8).



(a) 2l = 50 mm *(b) 2l = 70 mm*

Fig. 6: R-curves of 4ENF specimens

Figs. 6 (a) and (b) indicate R-curve of Mode II delamination growth. Scatters of data points are rather large during delamination growth. PTFE films inserted between delamination surface reduces fracture toughness values at initial stage of delimitation growth.

Time history of AE events is plotted with corresponding load versus displacement curve in Fig. 7. Onset of rapid increase of AE events (AE point) might coincide with an initiation point of delamination detected by using ultrasonic C scan method.

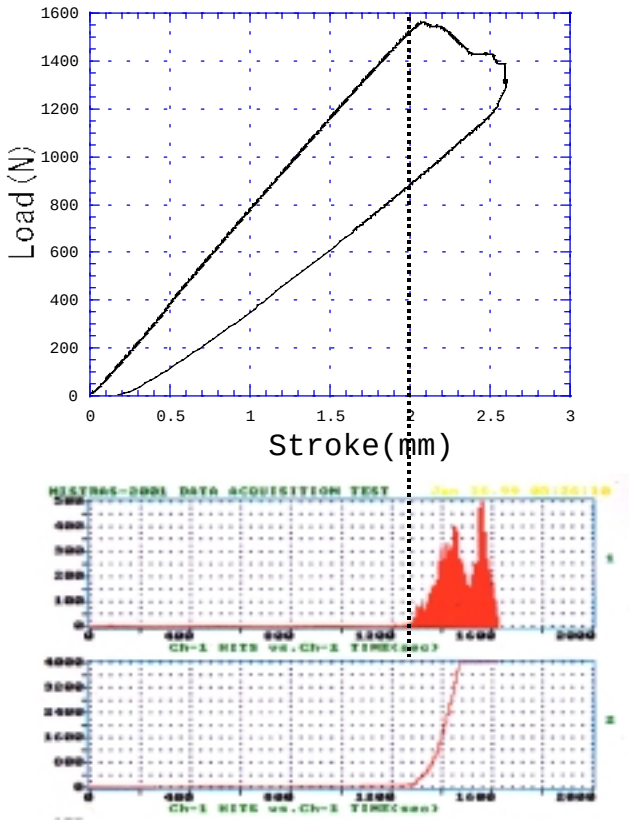


Fig. 7: AE event history and load versus displacement curve.

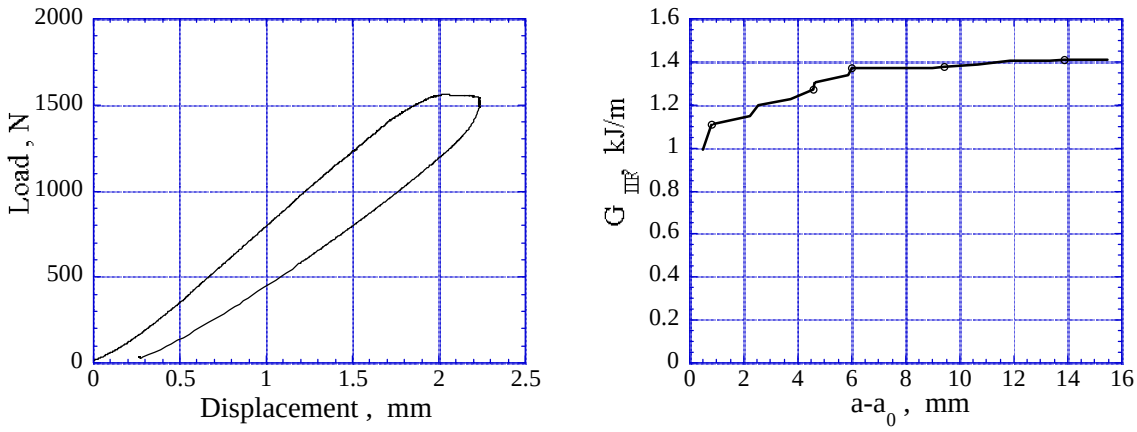
Critical loads at nonlinear point, AE point, 5% offset and max load were defined on load versus displacement curves, and Mode II fracture toughness values, G_{IIc}, were evaluated. The results are summarized in Table 1, in which the averaged results of the 4ENF specimens with PTFE films at loading and supporting noses and between delamination surfaces are compared with that obtained by stabilized ENF test under CSD control [2,7] according to JIS K 7086 Annex III.

Table 1: Critical values of Mode II interlaminar fracture toughness of 4ENF specimens (Unit: kJ/m^2)

Method	Condition	NL	AE	5% or Max	Prop.
Martin & Davidson[5]	$2l$ = 50 mm	0.682	0.781	0.902	1.002
	$2l$ = 70 mm	0.854	0.930	1.011	1.047
Present method	$2l$ = 50 mm	0.525	0.601	0.692	0.767
	$2l$ = 70 mm	0.563	0.612	0.666	0.690
Stabilized ENF [2,7]		1.041	------	1.261	1.225

Unsymmetrical Loading

Unsymmetrical load with eccentricity of 4 mm was applied to 4ENF specimens for $2l$ of 70 mm. Fig. 8 (a) shows a load versus displacement curve, which indicates stable delamination growth. G_{II} values were calculated from Eqn (11), by assuming that λ_{11} is nearly equal to experimental data of compliance. This assumption means that effect of friction is ignored and results in the higher values of G_{IIR}. The calculated R-curve is shown in Fig. 8(b).



(a) Load versus displacement curve of *(b) R-curve*

Fig. 8 Experimental results of 4ENF specimen under unsymmetrical loading

DISCUSSIONS

G_{IIc} values listed in Table 1 indicate that the present method gives most conservative values among three different data reduction methods. Loading conditions, such as inner span length, $2l$, have smaller effects on the results of present method. It might imply the advantage of the present method.

Fig. 5 indicates that the experimental value of compliance does not agree well with the theoretical curve. Assuming that the difference is due to friction between delamination surfaces, we can estimate the coefficient of friction. The estimated value of μ was 2.1 for $2l$ of 50 mm, and the value is higher than expected. Though, as elementary beam theory gives smaller value of λ_{11} than the exact elastic solution, the effect of friction might be larger than

that estimated in the present paper. Present method can take account of the effect of friction of 4ENF specimen, ant it indicated that the friction gives larger effect on 4ENF specimen. Accuracy of the proposed method directly depends on the accuracy of theoretical value of λ_{11}. The terms of order of μ^2 in Eqn (4) was neglected in order to obtain the simple expression of Eqn (5). It is an important problem to be investigated in the future study.

Unsymmetrical loading is one of the solutions to geometrical nonlinearity, but data reduction is too complicated to be applied. Distance, *d*, between loading point and loading noses should be as small as possible when symmetrical load is applied to the 4 ENF specimen. Special attention should be paid to 4-point bending fixture for 4ENF test in order to satisfy the condition.

CONCLUSIONS

Effects of loading nose distance, *d*, inner span length, 2*l*, and friction, μ, on the deformation and fracture of 4ENF specimen were investigated theoretically and numerically. A data reduction method was proposed in order to consider the effect of friction on the compliance data. Four-point ENF tests of unidirectional carbon/epoxy laminates were carried out and the proposed method applied to data reduction. The results were compared with conventional method and stabilized ENF test results. Proposed method gives the most conservative values among them. Unsymmetrical loading can reduce effect of geometrical nonlinearity, but data reduction method becomes very complicated. The length of *d* should be as small as possible in order to avoid the effect of large deformation.

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