EVALUATION OF MODE III INTERLAMINAR FRACTURE TOUGHNESS OF LAMINATED COMPOSITES

Shinji Ogihara* and Katsuhiro Matsuda**
***Department of Mechanical Engineering, Tokyo University of Science**
****Graduate Student, Tokyo University of Science**

Keywords: *Mode III Interlaminar Fracture Toughness, CFRP, Delamination, Energy Release Rate*

Abstract

Mode III interlaminar fracture toughness in CFRP is evaluated experimentally by using the Edge Crack Torsion (ECT) test. A material system used is T700S/2500 carbon/epoxy system. Laminate configuration is $[90/(+45/-45)_3/(-45/+45)_3/90]_s$ *with a delamination introduced by a 25μm-thick kapton film at the mid-plane along one edge. The specimen size is 90mm long, 40mm wide and 4.2mm thick. The film lengths were 0, 5, 10 and 15 mm. A natural crack is produced with a wedge from the film edge. The resulting crack lengths are from 8mm to 18mm. Two data reduction methods are used to calculate mode III interlaminar fracture toughness* G_{IIIC} *at the maximum load and load at onset of nonlinearity. Soft X-ray radiograph is used to observe delamination propagation. Three-dimensional finite element analysis is performed to calculate the distribution of mode I, mode II, and mode III energy release rate along the delamination front. The validity of the experimental method is also discussed.*

1 Introduction

It is known that when fiber reinforced plastics such as CFRP often used as laminates are subjected to loading, the resin matrices between the plies can often fail resulting in ply separation or delamination failure. Therefore, to understand the initiation and the propagation behavior of delamination, analysis and experiment evaluation in the fracture mechanics approach have been performed.

The test techniques for interlaminar fracture toughness in mode I and mode II has been well established by double cantilever beam (DCB) test and end notched flexure (ENF) test, respectively [1]. However, there is no standard test method of mode III at the present stage because of the experimental difficulties in introducing pure mode III loading. However, the establishment of the experiment evaluation of mode III is also important, because the delamination is actually caused in these mixed modes.

A method for measuring mode III interlaminar fracture toughness, called the edge crack torsion (ECT) test, has been proposed by Lee [2, 3]. Suemasu proposes the method of calculating mode III interlaminar fracture toughness based on the torsion theory of Saint-Venant [4]. Recently, ECT test which uses the results of a round robin exercise by the ASTM D30 committee is performed by Ratcliffe [5]. However, the examination of its coverage and the data accumulation are not well conducted.

In the present study, mode III interlaminar fracture toughness in CFRP is evaluated experimentally by using the Edge Crack Torsion (ECT) test. T700S/2500 carbon/epoxy system is used. The validity of the experimental method is also discussed by using FEM.

2 Experimental Procedure

2.1 Material and Specimen

A material system used is T700S/2500 carbon/epoxy system. The mechanical properties of T700S/2500 is shown in Table I. An ECT specimen is a rectangular laminate as shown in Figure 1. Dimensions of the specimen are also provided in the Figure 1. Laminate configuration is $[90/(+45/-45)_3/(-45/+45)_3/90]_s$ with a delamination introduced by a 25μm-thick kapton film at the mid-plane along one edge. Specimen with different crack lengths are manufactured and tested. A natural crack is produced with a wedge from the film edge. The resulting crack lengths are 0mm, from 8mm to 18mm (The film lengths were 0, 5, 10 and 15 mm.)

2.2 ETC Test

The ECT specimen is tested in a fixture with three fixed supporting points and one loading point as shown in Figure 1. The ECT specimen is subjected to torsional loading by these pins. The crosshead speed is 0.5 mm/min. The Load P and crosshead displacement δ are recorded during each test using date acquisition software on a computer connected to the test machine. The test is performed until the propagation of an initial crack. The specimen compliance C is calculated by taking the slope of the load-displacement plot.

2.3 Data Reduction Methods

Two data reduction methods are used to calculate mode III interlaminar fracture toughness G_{IIIC}. The first data reduction method is based on the laminated plate theory which was proposed by Lee [2]. In this paper, the method is called LPT method. Compliance and fracture toughness are calculated using the following expressions.

$$C=\frac{\delta}{P}=\frac{W^2L}{4\{B-(1-2s)a\}(D_{66})_{\mathrm{I}}} \tag{1}$$

$$G_{\mathrm{IIIC}}=\frac{P_{\mathrm{C}}^2C(1-2s)}{2LB\{1-(1-2s)(a/B)\}} \tag{2}$$

where, W is moment arm length, L is effective specimen length, B is specimen width, a is initial crack length, P_{c} is critical load, $(D_{66})_{\mathrm{I}}$ and $(D_{66})_{\mathrm{II}}$ are torsional stiffness terms for the uncracked laminated and cracked half laminate, $s = (D_{66})_{\mathrm{II}}$ / $(D_{66})_{\mathrm{I}}$. Calculated $(D_{66})_{\mathrm{I}}$, $(D_{66})_{\mathrm{II}}$ and s are shown in Table II.

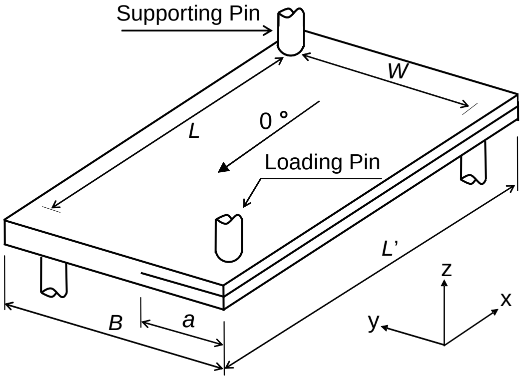
The second data reduction method is the compliance calibration method which employs a multi-specimen compliance calibration procedure [3]. In this paper, the method is called CC method. Compliance of each specimen is plotted as a function of crack length. Linear regression analysis is performed to determine the constants, A and m. Compliance and fracture toughness are calculated using the following expressions.

$$\frac{1}{C}=A\left[1-m\left(\frac{a}{B}\right)\right] \tag{3}$$

$$G_{\mathrm{IIIC}}=\frac{P_{\mathrm{C}}^2}{2L}\frac{dC}{da}=\frac{mP_{\mathrm{C}}^2C}{2LB[1-m(a/B)]} \tag{4}$$

TABLE I. MECHANICAL PROPERTIES OF T700S/2500

E_{11}(GPa)	E_{22}(GPa)	ν_{12}	G_{12}(GPa)
105	8.72	0.34	4.02



L'= 90mm L = 78mm
B = 40mm W = 34mm
Thickness 4.2mm
0° : Principle fiber direction

Figure 1. Schematic of ECT specimen

TABLE II. PARAMETERS OF TORSIONAL STIFFNESS

$(D_{66})_{\mathrm{I}}$ (Nm)	$(D_{66})_{\mathrm{II}}$ (Nm)	s
125.9	12.98	0.103

2.4 Finite Element Method

Three-dimensional finite element analysis is performed to calculate the compliance, the distribution of mode I, mode II, and mode III energy release rate along the delamination front. Three-dimensional finite element models with four different crack lengths are constructed using the MSC.Marc2001 and a model with crack length 17mm is shown in Figure 2a. The four crack lengths are 0, 7, 12 and 17mm. The eight-node solid elements are used. The number of elements of the model without crack and one with crack are 18160 and 16192, respectively. Geometrically nonlinear analysis is performed. The edge crack is modeled by introducing elements with double nodes on the plane of the crack. Material properties used are shown in Table III. The constant distributed load and the fixed displacement are applied in a circle of 0.5mm in the radius as shown in Figure 2b.

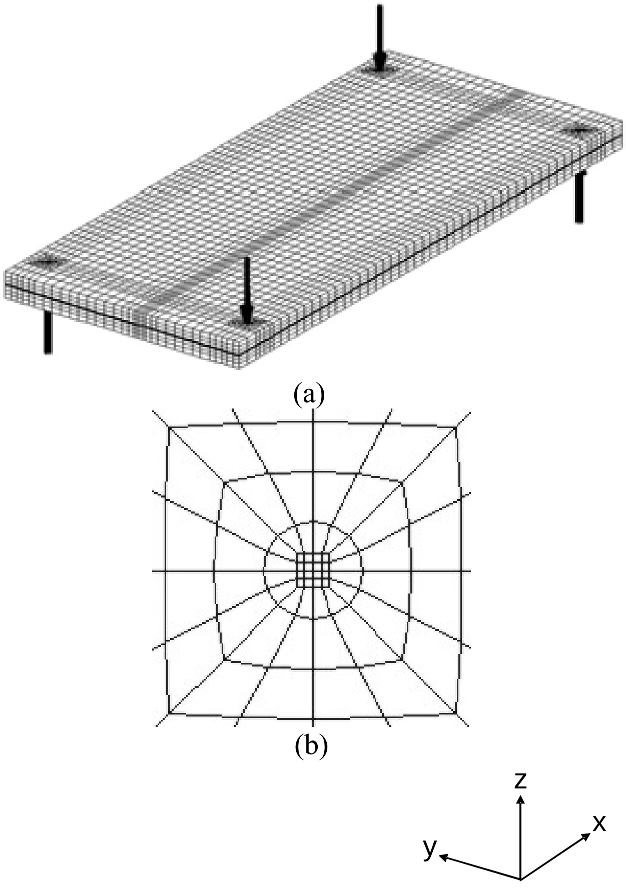
The virtual crack closure method (VCCM) is used to calculate the energy release rate. The energy release rate is calculated using the following expressions.

$$G_{\mathrm{I}} = \frac{F_{\mathrm{zj}}\delta_{\mathrm{zi}}}{2\Delta a \Delta x} \quad (5)$$

$$G_{\mathrm{II}} = \frac{F_{\mathrm{yj}}\delta_{\mathrm{yi}}}{2\Delta a \Delta x} \quad (6)$$

$$G_{\mathrm{III}} = \frac{F_{\mathrm{xj}}\delta_{\mathrm{xi}}}{2\Delta a \Delta x} \quad (7)$$

where, F_{xj}, F_{yj} and F_{zj} are the nodal forces in the x, y, and z-direction at node j, δ_{xi}, δ_{yi} and δ_{zi} are the relative crack face displacements between nodes i and i', Δa is the one element length, Δx is the sum of one-half the element lengths on either side of node j as shown in Figure 3. The nodal force is calculated by introducing the three high stiffness springs (10^{10}N/mm) with independent degree of freedom in the x, y and z-direction respectively between the double nodes in the crack tip.


(a)

(b)

Figure 2. Finite element model with crack length 17mm
(a) Finite element model (b) Loading point and supporting point

TABLE III. MATERIAL PROPERTIES USED IN THE ANALYSIS

Young's modulus (MPa)	Poisson's ratio	Shear modulus (MPa)
$E_{11} = 105000$	$\nu_{12} = 0.34$	$G_{12} = 4020$
$E_{22} = 8720$	$\nu_{23} = 0.5$	$G_{23} = 2910$
$E_{33} = 8720$	$\nu_{31} = 0.028$	$G_{31} = 4020$

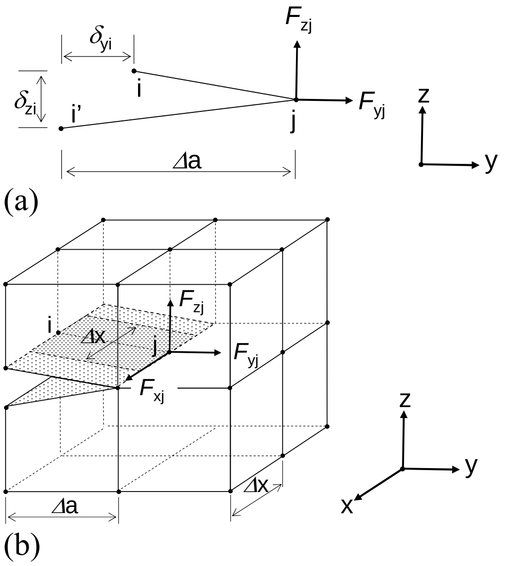


Figure 3. VCCM for three-dimensional eight-node solid elements
(a) Two-dimensional view (b) Three-dimensional view

3 Results and Discussion

Experimentally-measured load-displacement response is presented in Figure 4. The curve exhibits a nonlinear response after a linear response region until a sudden load drop. Figure 5 presents relation between the crack length and the compliance (experiment, LPT method and FEM). Table IV shows experimentally-measured constants A and m in CC method. A difference in compliance is seen between LPT method values and experimental results, and as crack length becomes long, the difference becomes larger. FEM analysis and experimental compliance show a good agreement. Figure 6 shows displacement in z-direction for specimens from the FEM analysis (crack length of 0mm and 17mm). This implies that a local deformation in the crack region is a cause of the difference in compliance. Therefore, it is thought that deriving G_{IIIC} from LPT method is unsuitable. G_{IIIC} at the maximum load by two deriving methods is shown in Figure 7.

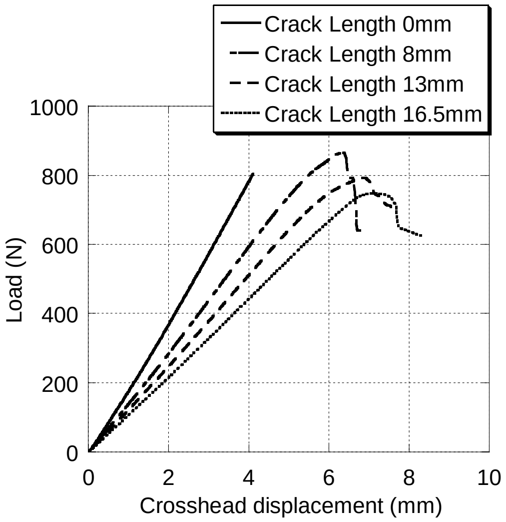


Figure 4. Load-displacement curves

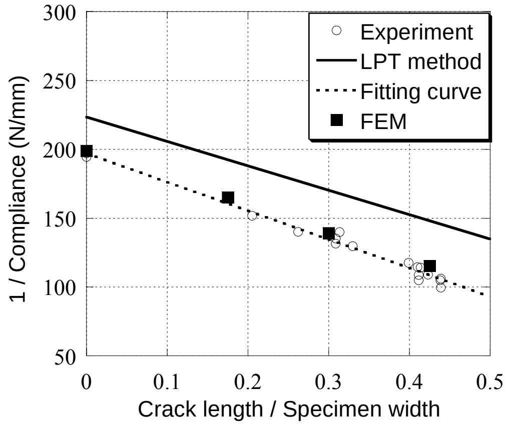


Figure 5. Relation between the crack length and compliance (experiment, LPT method and FEM)

TABLE IV. COEFFICIENT OF FITTING CURVE

A (N/mm)	*m*
197.13	1.0675

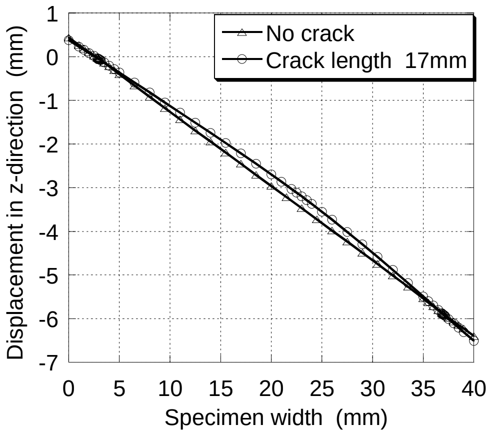


Figure 6. Displacement in z-direction for specimens with crack length of 0mm and 17mm

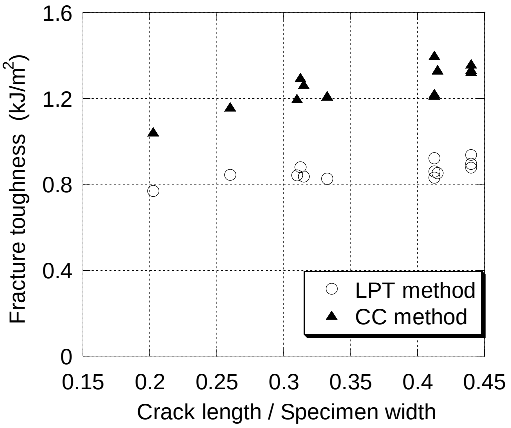


Figure 7. Fracture toughness versus crack length at the maximum load by two deriving methods

Figure 8 and 9 contains soft X-ray radiographs of the ECT specimens at the sudden load drop and in the nonlinear region (initial part), respectively. It is seen that the crack propagation is not uniform and large delamination propagation is seen in Fig.8. The initial crack propagation is seen in Fig.9. Therefore, it can be considered that the evaluation of G_{IIIC} at the maximum load is not appropriate. In the present study, G_{IIIC} at onset of nonlinearity is evaluated. To determine the load at onset of nonlinearity, a linear regression analysis is performed to estimate the linear fit corresponding to the linear portion as shown in Fig.10. The difference between the linear fit load P_{LR} and the experimental load P_{EXP} is plotted as a function of displacement as shown in Fig.11. The load at onset of nonlinearity is then determined by recording difference of load begins to diverge as shown in Fig.11. G_{IIIC} of load at onset of nonlinearity by two deriving methods is shown in Fig.12. Figure 13 presents comparison of G_{IC} by

DCB test and G_{IIC} by ENF test and G_{IIIC}. Each column is an average value and a bar shows a maximum and a minimum value in data.

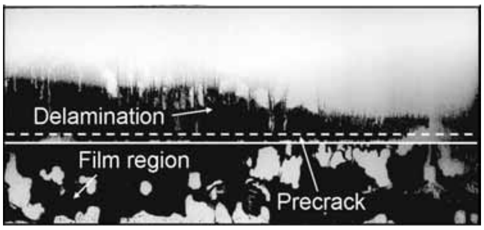


Figure 8. Soft X-ray radiograph after a sudden load drop (crack length 16.5mm, maximum load 743N)

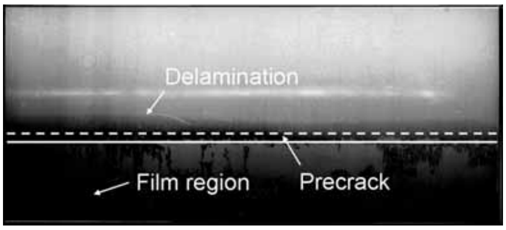


Figure 9. Soft X-ray radiograph of nonlinearity region (crack length 17mm, load 620N).

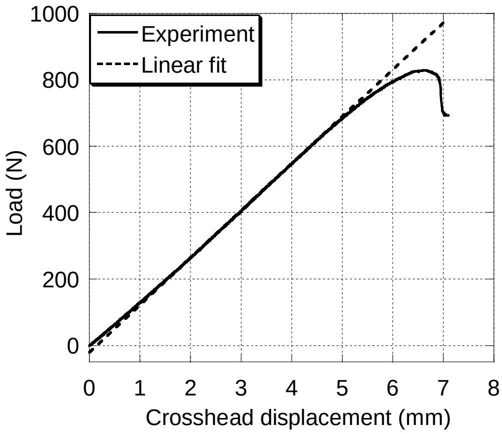


Figure 10. Load-displacement curves (experiment and linear fit)

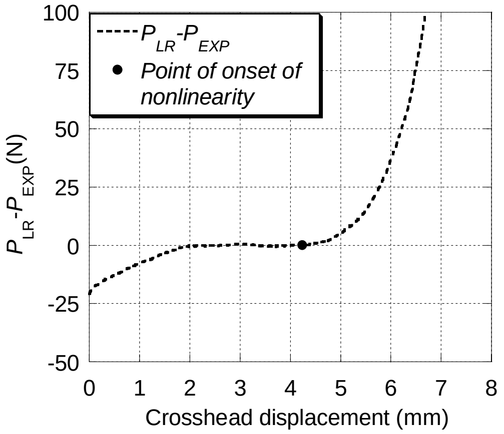


Figure 11. P_{LR} - P_{EXP} versus displacement

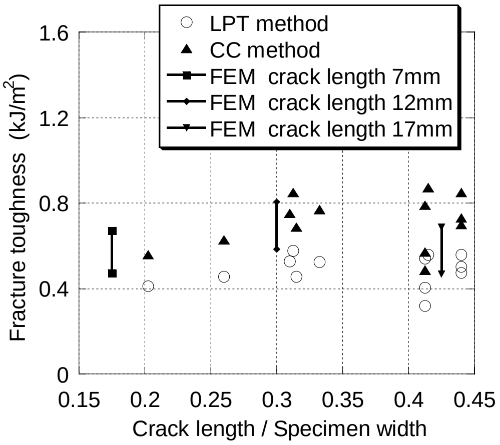


Figure 12. Fracture toughness versus crack length (Load point at onset of nonlinearity, comparison of LPT method and CC method and FEM)

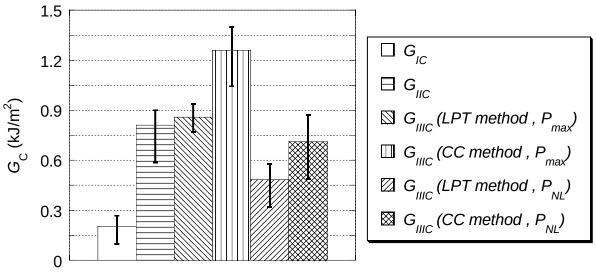


Figure 13. Comparison of G_{IC}, G_{IIC} and G_{IIIC}

Load used in FEM is determined within a certain range as shown in Fig.14 because some scatter is seen in the experimental data. The load used in FEM is shown in Table 5. The VCCM was used to calculate the Mode I, Mode II and Mode III energy release rate components. In the comparison of G_{IIIC} of experiment and FEM, G_{IIIC} of FEM is calculated as an average value of the mode III energy release rate component of each point. Figure 15 presents relation between plots of G_{I}, G_{II} and G_{III} and distance along the delamination front. It is found that mode III energy release rate is the largest component. It is also found that pure mode III is realized within inner part of specimens and that when crack length becomes long, the mode III component becomes almost constant within inner part of specimens. At the edge of specimens, mode II component appears. When crack length becomes long, mode II component at both ends increases. The comparison of G_{IIIC} of experiment and FEM is also shown in Fig.12. It is found that fracture toughness by FEM indicates a value which is closer to CC method than LPT method.

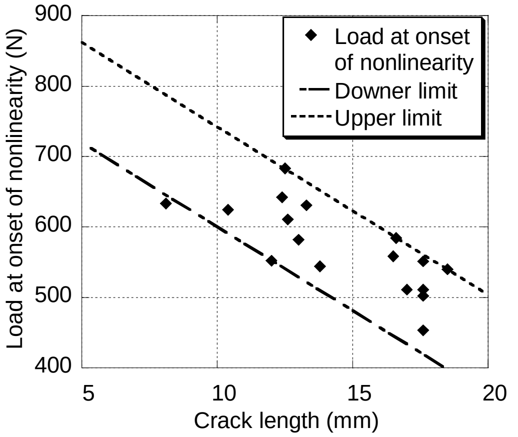


Figure 14. Load at onset of nonlinearity versus crack length

TABLE 5. CRITICAL LOAD USED IN FEM

Crack length (mm)	Min load (N)	Max load (N)
7	673	815
12	553	695
17	434	576

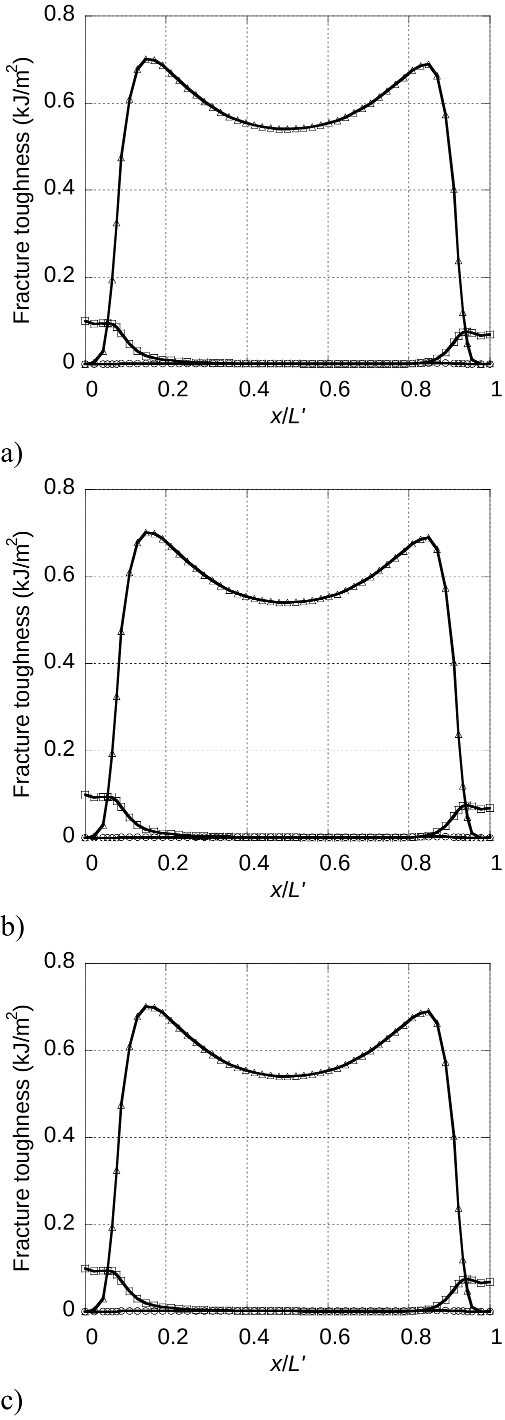


Figure 15. Fracture toughness distribution across delamination front

(a) Crack length 7mm

(b) Crack length 12mm

(c) Crack length 17mm

4 Conclusion

The validity of the ECT test as a test method of mode III interlaminar fracture toughness is discussed. Analytical procedure gives poor prediction of compliance. However, FEM analysis and experimental compliance shows a good agreement. Therefore, it is expected that a more realistic G_{IIIC} value can be calculated by using experimentally-obtained relation between the crack length and the compliance. Evaluation of G_{IIIC} at the maximum load may not appropriate because the propagation of an initial crack is seen before reaching the maximum load. By using FEM, it is found that mode III energy release rate is the largest component and that pure mode III is realized within the inner region. Mode II component appears at the edge. When crack length becomes long, mode II component at both ends increases.

References

[1] JIS K 7086. "Testing Methods for Interlaminar Fracture Toughness of Carbon Fibre Reinforced Plastics," 1993

[2] Lee, S. M. "An Edge Crack Torsion Method for Mode III Delamination Fracture Testing," Journal of Composites Technology & Research, JCTRER, Vol.15, No.3, 1993, pp.193-201

[3] Li, J., Lee, S. M., Lee, E. W., and O'Brien, T. "Evaluation of the Edge Crack Torsion (ECT) Test for Mode III Interlaminar Fracture Toughness of Laminated Composites," Journal of Composites Technology & Research, JCTRER, Vol.19, No.3, 1997, pp.174-183.

[4] Suemasu, H. "An Experimental Method to Measure the Mode-III Interlaminar Fracture Toughness of Composite Laminates," Composites Science and Technology, 1999, pp.1015-1021

[5] Ratcliffe, J. G. "Characterization of the Edge Crack Torsion (ECT) Test for Mode III Fracture Toughness Measurement of Laminated Composites," NASA/TM-2004-213269, 2004