

MODE-I INTERLAMINAR FRACTURE TOUGHNESS OF UNIDIRECTIONAL CARBON FIBRE EPOXY COMPOSITE

Yeo Kiam Beng @ Abdul Noor¹ & Mohd. Noh Dalimin²

¹School of Engineering and Information Technology, Universiti Malaysia Sabah,
Locked Bag 2073, 88999 Kota Kinabalu Sabah

²School of Science and Technology, Universiti Malaysia Sabah,
Locked Bag 2073, 88999 Kota Kinabalu Sabah

ABSTRACT. *Mode-I fracture toughness of unidirectional high tensile carbon fibre epoxy composite, Fibredux 913C-XAS of CIBA-Geigy, is investigated. An autoclave production method is performed to produce the composite using the manufacturer recommended curing cycle. A fracture mechanics analysis based on the strain-energy release rate, G_{IC} (J/m²), the rate of transfer of energy from the elastic stress field of a cracked structure to the localise inelastic process of crack extension, has been adopted for the calculation of Mode-I interlaminar fracture toughness. Popular standard double-cantilever beam (DCB) test geometry has been used to characterize the interlaminar fracture toughness of carbon fibre epoxy composite. The calculation of the DCB fracture toughness is formulated from the local values of bending moments and loads for a cracked laminated composite. The experimental results of mode-I fracture toughness, G_{IC} , as a function of crack length has been obtained. It is found that the interlaminar fracture toughness is independent of the crack length and has an approximate value of $G_{IC} \approx 135.5$ J/m² with about 7.4% coefficient of variation. Reproducibility of the DCB test results has been very consistent. The fractured interlaminar surfaces does not exhibit gross fibre pullout between the surfaces, which is ideal for a Mode-I critical fracture toughness calculation.*

KEYWORDS. Carbon Fibre Composite, Crack, Fracture, Mode-I, Toughness

INTRODUCTION

Most of the advanced composite materials are filamentary with continuous fibres that possess more complex structural behaviour than metals. Applications of composite structures provide new dimensions of design freedom that are not available with isotropic materials. Stiffness, strength, and thickness can be varied or designed within a single component. Carbon and glass fibre composites are known for their ultimate stiffness and/or weight performances due to their exceptional specific stiffness and specific strength properties (Schwartz, M. 1995). Low density and high strength or stiffness of advanced composites is becoming an important component for many modern aerospace and transport vehicle industries.

However, delamination of layered or laminated composite materials is a critical problem. Delamination or interlaminar failure of composite during routine services is a major concern in structural composite design. The delamination in the composite panel will result in losses of stiffness, and hence the design performances in structural application of fibre composite materials. The resistance or toughness to delamination and propagation of interlaminar defects or micro-cracks in fibre reinforced composites is thus of extreme importance to manufacturer and users. Interlaminar fracture in composite is identified by the interlaminar separation subjected to no fibre breakage, pullout and fibre bridging, which is a material property independent of test-specimen geometry and ply orientations that constitute the delaminating interface. Mode-I delamination (Whitney, J.M. et al., 1982; Williams, J.G. 1988) is the weakest mode of interlaminar failure in the composite, which requires extreme attention. The edge delamination due to layered composite laminates is a common phenomenon, which is controlled by the fracture toughness property of the fibre composite panel.

The Mode-I critical toughness value that allows crack propagation and fracture is the fracture toughness, G_{IC} (J/m²), of the material (Hashemi, S. et al., 1989; Williams, J.G. 1990). Fracture toughness or resistance to Mode-I interlaminar failure is a key identification parameter of the most common mode in composite delamination that can be regarded as the propagation of an interlaminar crack. This type of Mode-I failure, which has the weakest mode of fracture toughness associated to the matrix material and the lowest energy mode. Thus, the Mode-I critical interlaminar fracture toughness value of composites is an important guide for material improvement and design consideration purposes. The contribution of the critical delamination property of composites has immense importance in aerospace, transportation, and other structural applications, which has been catching up fast in the usage of various composite materials.

EXPERIMENTAL TECHNIQUES

As the behaviour of laminated composite structures are more complicated than that of isotropic materials, more elaborated calculations and experiments must be performed for the evaluation composites for product design. Experimental evaluation on Mode-I interlaminar quasi-static fracture of unidirectional carbon composite includes the production technique of composite panel, and the development of test method to analysis the fracture toughness of composite delamination.

Materials

Composite prepreg Fibredux 913C-XAS of treated fibre Grafil is a commercial produce of CIBA-Geigy used for the production of unidirectional composite panels. It is a low-temperature curing prepreg for the production of composite with outstanding environmental resistance against wear and tear. This prepreg is commercially formulated to produce high tensile Unidirectional Carbon Epoxy Reinforced Composite. Prepreg Fibredux comes in a form of rolls kept at a temperature of -18° C. The prepreg is a thin sheet of uniformly distributed unidirectional carbon fibre impregnated with a right amount of partially cured epoxy resin. It consist of 60% fibre and 34% resin with certain amount of moisture. Before the prepreg can be used, it has to be removed from the freezer and allowed to attain room temperature without unwrapping

to avoid moisture condensing. The prepreg comes together with release backing paper and polythene protective coverings.

Prepreg Laminate Lay-Up

Carbon-epoxy prepreg is cut from the roll into sheets of square plies for stacking. A sixteen number of plies of prepreg produce approximately 2mm thick laminate composite. While a twenty-four plies of prepreg can make up to 3mm thick of laminate composite. The stacking sequence for a unidirectional laminate can be achieved by removing the release backing paper and polythene covering in each plies.

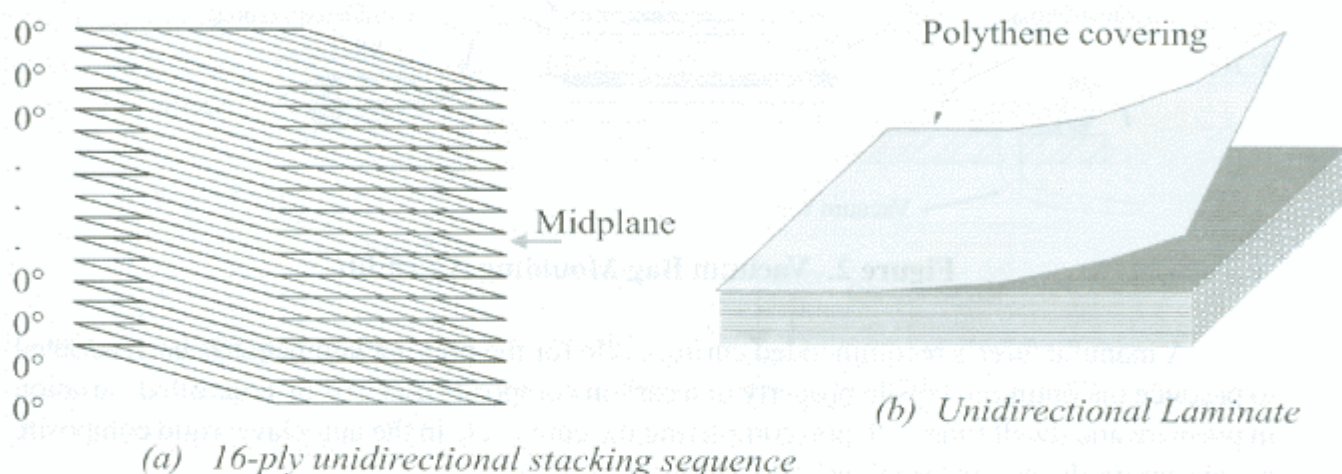


Figure 1. Unidirectional orientation of stacking and laminate prepreg

The lamination of each stacking ply is lightly pre-pressed by rolling the laminate through a mangle for every two or three plies to assure compactness and avoid major air-traps. The completed laminate prepreg without removing their last backing and polythene covering can also be properly sealed and kept in the freezer for storage before curing.

Fabrication of Delamination or Pre-crack in Prepreg Laminate

Investigation of fracture toughness in a specimen requires an initial delamination to be introduced into the midplane of the prepreg laminate before the curing process. Initial delamination can be introduced by dispersion of TYGAVAC Release Agent or Fluorocarbon particles in a solvent onto the two interfacing surfaces of the midplane prior to sacking the prepregs together. Four coatings are sprayed over 60mm section of the prepreg surfaces. The pre-fabricated delamination has to be identified throughout the process of the composite panel development.

Autoclave Lay-Up for Prepreg Laminate Curing

A typical assembly of a zero-bleed laminate and associated material set-up for autoclave curing is shown in the Fig. 2. The prepreg laminate assembly is covered by a porous peel ply on each surface followed by Melenex sheets. Since a zero-bleed prepreg laminate is considered, so no

additional bleed-cloth is necessary. Melenex sheets are used to prevent any released resin from sticking to the base table or the pressure plate. A simple piece of pressure plate acts to distribute uniform pressure over the whole surface to produce final flat surface finishing. Another layer of air breather-cloth covers up the complete lay-up to ensure continuous gas flow and exchange. Finally, vacuum-bagging material is used to seal the complete assembly to the base table in the autoclave. A vacuum vent leads to the outside of the vacuum bag for the function of regulating the pressure inside the assembly. The complete assembly is then placed in the autoclave to be cured to the appropriate cycle.

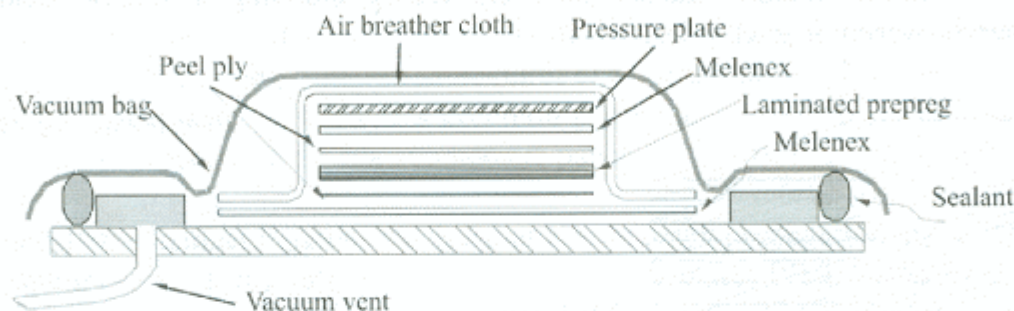


Figure 2. Vacuum Bag Moulding Assembly

A manufacturer's recommended curing cycle for the prepreg laminate has been adopted to produce the optimum tensile property of a carbon composite material by controlled variation in pressure and dwell times. Upon completing the cure cycle in the autoclave, rigid composite panels are produced for sampling and characterization.

Preparation of DCB Composite Joint

The final finished composite panel is retrieved from the autoclave for sample preparation of DCB (double cantilever beam) composite joint. The composite panel is cut into strips of dimensions of about 20mm x 190mm x 3.17mm using a diamond slitting saw. The orientation of the unidirectional fibre is along the length of each strip and its pre-fabricated delamination section of about 60mm section length is also along one end of the strip. The DCB joint requires two end-tab aluminium blocks (20mm x 20mm) to be bonded to the composite strips for the load transmission, Fig. 3. A commercial adhesive Perma-Bond is used for the bonding.

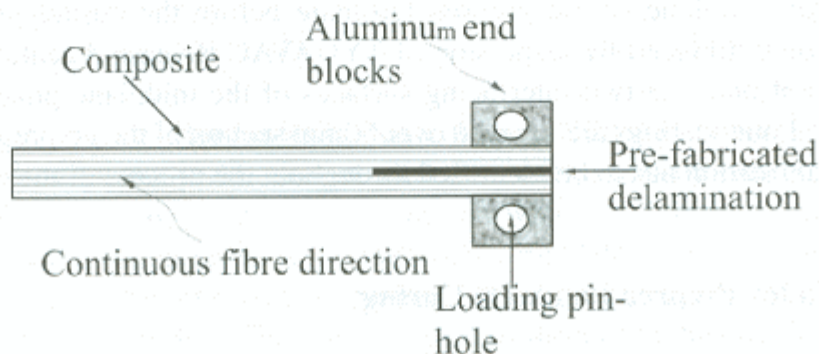


Figure3. DCB (Double Cantilever Beam) composite joint.

Mode-I Fracture Toughness Test Method

Investigation of Mode-I interlaminar quasi-static fracture toughness of unidirectional carbon epoxy composite is conducted using a servo-hydraulic Universal Tensile test machine. Before the testing of DCB composite specimen, the length along the edge of the sample is marked with 5mm intervals from the center point of the loading pin. Usually a thin layer of white correction fluid is applied along the edge for clear identification of crack length propagation or intervals during the testing. The DCB sample can be mounted on the test machine together with a travelling microscope for observing crack propagation and the identification of crack length reached. For each 5mm interval of crack propagation reached, signal is input to the data acquisition system for record, Fig. 4. Eventually, the characteristics of load, displacement and crack length can be obtained for the analysis of Mode-I fracture toughness values. A constant test rate of 5mm/min is adopted for each 6-batches of the DCB samples.

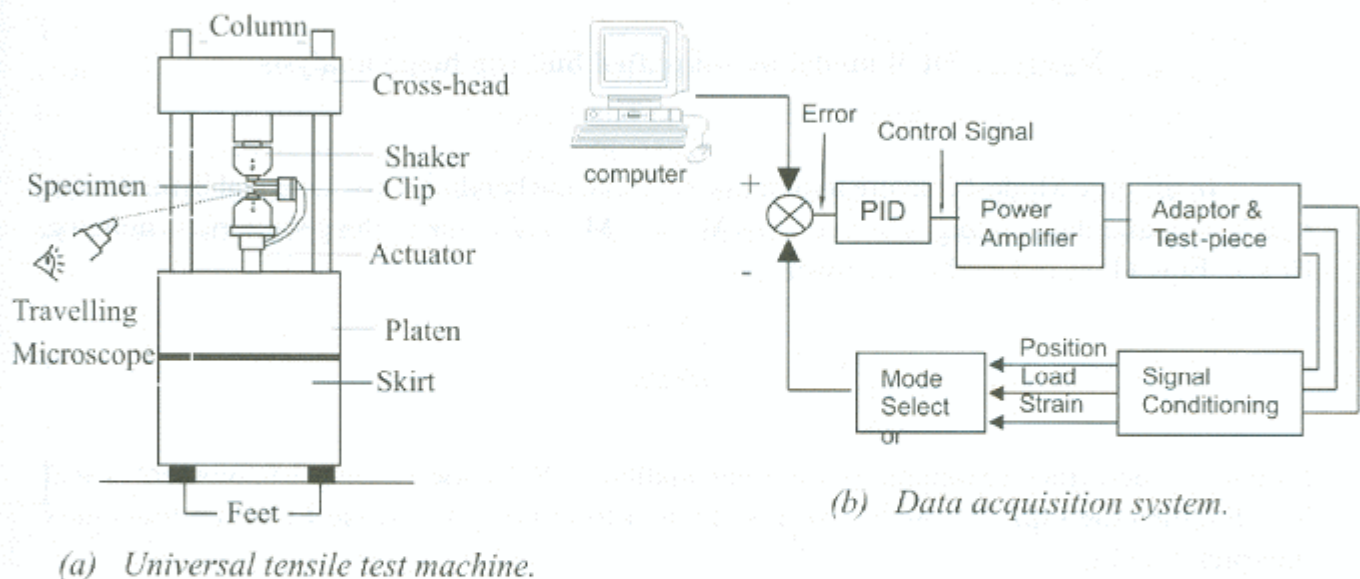


Figure 4. Test system and setup for Mode-I fracture toughness characterization.

THEORY OF FRACTURE TOUGHNESS BY GLOBAL ENERGY APPROACH

The fracture mechanics by global energy approach for the fracture toughness analysis, G_c in general, due to bending arms of thickness h_1 , h_2 and M_1 , M_2 , respectively, for a known specimen width B and elastic stiffness E , can be derived from the beam theory (Williams, J.G. 1988) Fig.5, yields

$$G_c = \frac{6h_1^3}{B^2 E h_2^3 (h_1^3 + h_2^3)} \left[M_2 - \left(\frac{h_2}{h_1} \right)^2 M_1 \right]^2 \quad (1)$$

Equation (1) can be used for the modeling of Mix-Mode I/II, Mode-I and Mode-II fracture toughness evaluation.

The linear elastic fracture mechanics (LEFM) methodology for determining the fracture energy of a structure containing sharp cracks or flaws has been the principle for the derivation of Eqn. (1) above. The analysis applied in interpreting data recorded by double-cantilever beam (DCB) specimen, as shown in Fig. 5, has been one of the most popular for fracture toughness, G_c , measurements. One advantage of the specimen geometry is that it permits measurements of Mode I, Mode II or mixed Mode fracture toughness.

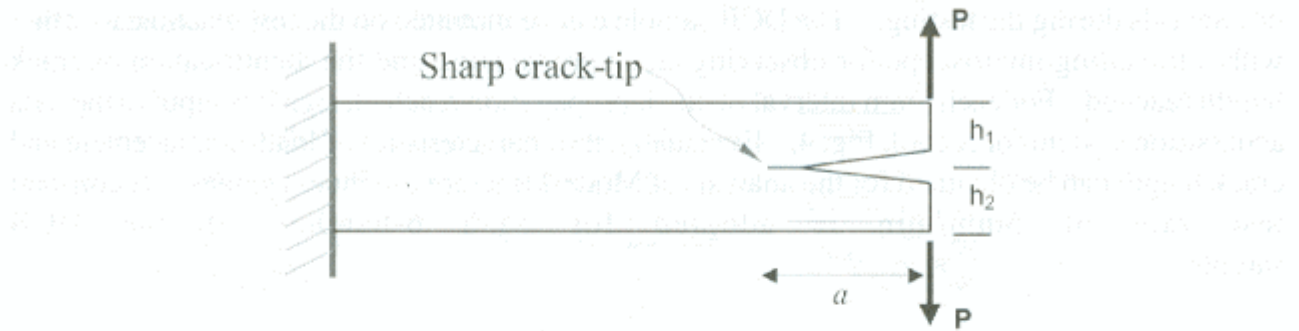


Figure 5. DCB model by simplified build-in beam analysis.

In the pure Mode-I fracture toughness, G_{IC} , test, the bending arms are equal in thickness, $h_1 = h_2 = h$, and the bending arm moments $M_2 = -M_1 = M$ due to the geometric symmetry. Hence, Eqn. (1) is reduced to the form

$$G_{IC} = \frac{12M^2}{B^2 E h^3} \quad (2)$$

for pure Mode-I fracture toughness value calculation. Since the bending arm moment is also $M = Pa$, then the Eqn. (2) can be expressed into a form ready for Mode-I fracture toughness interpretation by

$$G_{IC} = \frac{12P^2 a^2}{B^2 E h^3} \quad (3)$$

as a function of crack length from purely geometric consideration and the elastic material properties of the composite, (where B , E and h are all known constants).

RESULTS AND DISCUSSION

The pre-fabricated delamination in the DCB composite joint has been observed and found to produce a thin cracked line of about 7mm ~10mm near the crack-tip regions. Figure 6 illustrates the delamination line at the front edge of the specimen, far away from the crack-tip. The order of crack line thickness near the crack-tip is reasonably sufficient for the assumption of sharp crack-tip requirement in the LEFM's application. Hence, the appropriate calculation and evolution of the Mode-I fracture toughness in carbon fibre epoxy composite by beam analysis.

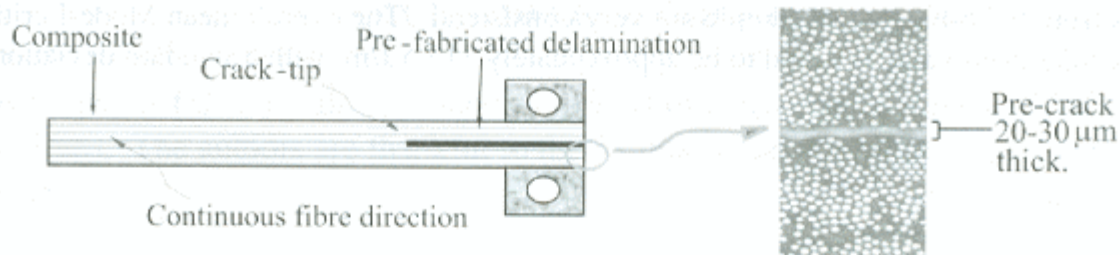


Figure 6. Delamination of DCB composite joint.

As the DCB composite specimen is loaded, the pre-fabricated delamination section did not indicate any fibre crossing or pullouts. Delamination opens up and initiation of crack growth and propagation are observed and monitored through the travelling microscope mounted in front of the specimen. Crack initiation and propagation are clearly visible in the thin layer of correction fluid. The process showed regular smooth crack propagation, where the crack is essentially moving constantly as the Mode-I opening displacement increases with falling load. This behaviour is continued till the cantilever arms are completely separated, producing a characteristic load and displacement curve as in Fig. 7. The steady crack growth length estimated to the nearest 0.1mm is also identified and recorded as the tests proceeds. Gross fibres crossing between peeled surfaces during the tests are not observed. However, fibre breaking and uneven fracture surfaces can be seen visually and under a microscope. Thus, the true or absolute flat fracture surface area in the theory is only an ideal consideration.

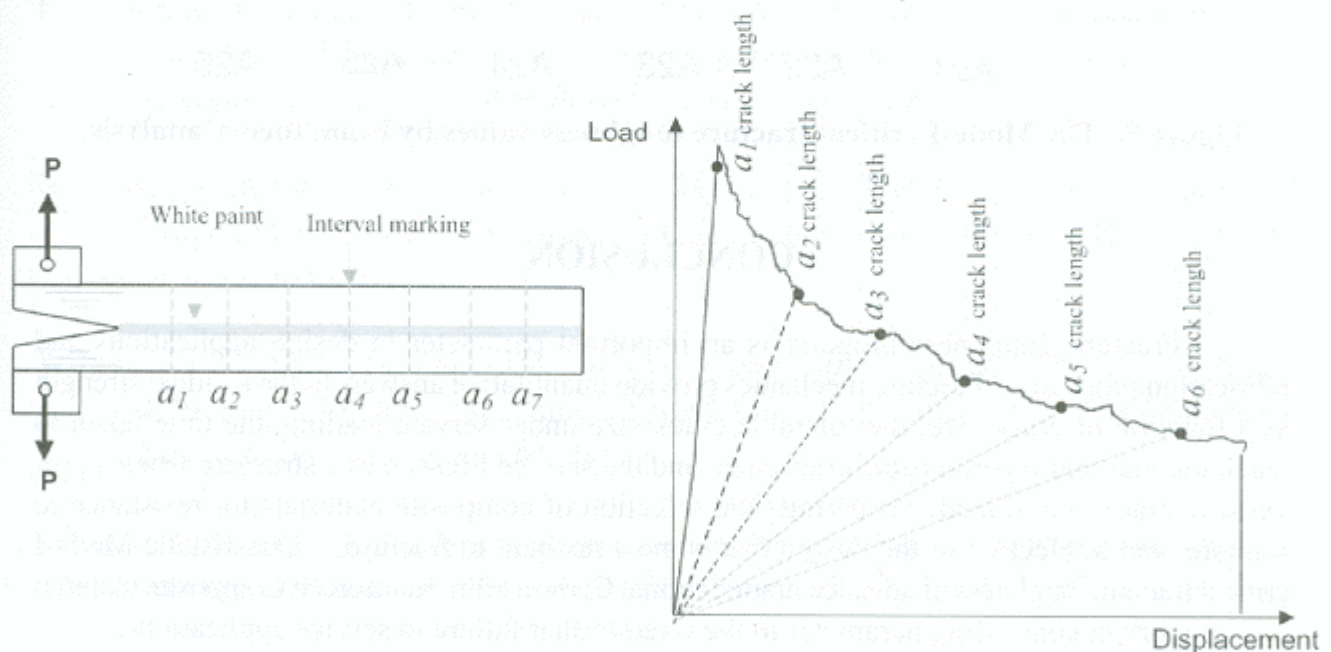


Figure 7. Load-Displacement curve of a steady state crack propagation.

Reduction of data for the calculation of opening Mode-I fracture toughness as a function of crack length is obtained from the Eqn. (3). The geometric parameters $B = 19.852\text{mm}$ and $h = 1.598\text{mm}$, and the elastic stiffness $E = 133\text{ GPa}$ are obtained for the evaluation of G_{IC} . Mode-I fracture toughness calculation from Eqn. (3) is performed on 6-batches of samples (A21, A22, A23, A24, A25 & A26) consisting of five specimens per batch. Average Mode-I G_{IC} and the standard deviation for each sample batch are obtained and plotted in Fig. 8.

Results from the 6-batches of sample are very consistent. The overall mean Mode-I critical fracture toughness value is found to be approximately 315.5 J/m^2 with a standard deviation of 7.4%.

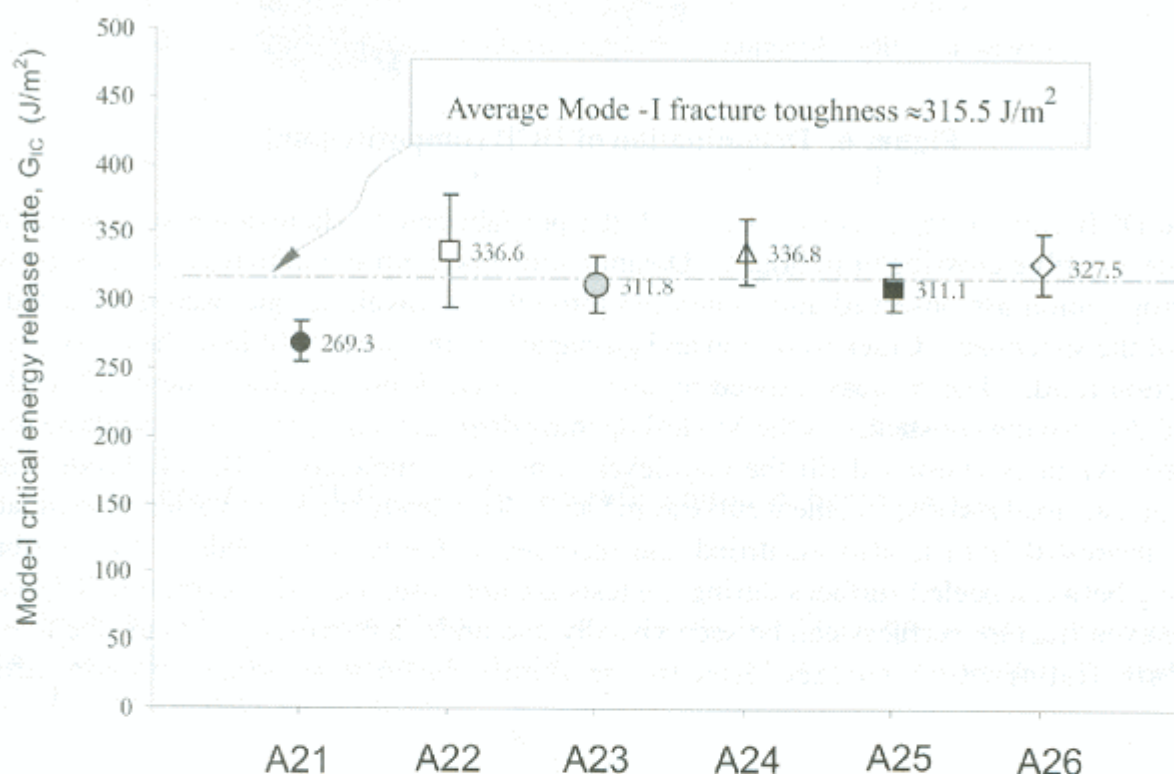


Figure 8. The Mode-I critical fracture toughness values by beam theory analysis.

CONCLUSION

Fracture Toughness property is an important parameter in design applications and fabrication processes. Fracture mechanics provide quantitative answers to the residual strength as a function of crack size, the tolerable crack size under service loading, the time taken to reach the maximum permissible crack size, and the service lifespan of a structure when a pre-existing crack is assumed. It permits the selection of composite materials for resistance to fracture, and a selection of the design that is most resilient to fracture. Quasi-static Mode-I critical fracture toughness of advance unidirectional Carbon Fibre Reinforced Composite material is an important controlling parameter to the interlaminar failure in service applications.

The experimental technique employed in the evaluation of Mode-I fracture toughness using DCB geometry is very popular. However, actual crack-tip observation may not be precisely observed or recorded, the absolute fracture surface area cannot be identified, and that the quantity of fibre breaking or damages cannot be truly known. These factors can grossly affect the calculation of a higher value of G_{IC} in the beam theory of Eqn. (3). Nevertheless, the characteristic of localised losses at the crack tip can be generally defined in the calculation of a G_C value instead of the actual intrinsic parameter of G_{IC} .

ACKNOWLEDGEMENT

This project is funded with the financial support of *Universiti Malaysia Sabah – UMS* (No. 8/98). The authors are thankful to their support and contribution in this research project.

REFERENCES

- Whitney, J.M., Browning, C.E., and Hoogsteden, W. 1982. A Double Cantilever Beam Test for Characterizing Mode-I Delamination of Composite Materials. *Journal of Reinforced Plastics and Composites*, **1**: 297.
- Williams, J.G. 1988. On the Calculation of Energy Release Rates for Cracked Laminates. *International Journal of Fracture*, **36**: 101-119.
- Chai, H. 1984. The Characterization of Mode-I Delamination Failure in Non-Woven, Multidirectional Laminates. *Composite*, **15**(4): 277.
- Hashemi, S., Kinloch, A.J., and Williams, J.G. 1989. Corrections Needed in Double-Cantilever Beam Tests for Assessing the Interlaminar Failure of Fibre-Composites. *Journal of Materials Science Letters*, **8**: 125.
- Hashemi, S., Kinloch, A.J., and Williams, J.G. 1989. The Analysis of Interlaminar Fracture in Uniaxial Fibre-Polymer Composites. *Proceedings of Royal Society of London*, C2093.
- Williams, J.G. 1990. *Fracture Mechanics of Composites Failure*. The Twenty Sixth John Player Lecture, Mechanical Engineering Department, Imperial College of Science, Technology and Medicine.
- Schwartz, M. 1995. *Composite Designs and Joint Criteria, Properties, and Quality Assurance*. *Composite Materials Handbook*. 3.1-3.5. USA: McGraw-Hill, Inc.
- Gros, X.E. and Pecorari, C. 2001. *Ultrasonic and Microscope Investigation of Impact Damage in GFRP Composites*. *Res Nondestructive Evaluation*.: 23-36.