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Mode-I Toughness and Curing Pressure Characteristic of Symmetrical Lay-Up of Plain-Weave Woven GFRP Composites

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Abstract: This study describes an experimental study on the interlaminar Mode-I fracture toughness behavior of hand lay-up plain-weave woven GFRP laminate by using a fracture energy method of evaluation. Mode-I Double Cantilever Beam (DCB) tests were performed on woven GFRP unsaturated polyester composite, E-Glass EWR 600 NISER, specimens. The specimen design and test procedure are performed with reference to the BS ISO 15024 and ASTM D5528. Various curing uniform pressure distribution has been investigated at 35.8, 70.1, 104 and 138.2 kg m^{-2}, with respect to the toughness value. The lay-up laminates designed with symmetrical arrangement at the center-plane of the composite are also investigated. The experimental results of mode-I fracture toughness as a function of crack length has been obtained. Experimental data obtain are analyzed using the modified beam theory, MBT method. The delamination-resistance curve or the R-curve effect has been found as the general characteristics of the laminate system. Fiber bridging phenomenon with slow and stable crack propagation and extensive half-arm fiber bridged are also observed with lower curing pressure found to produce higher G_{IC} propagation values.

Key words: Mode-I, fracture toughness, curing pressure, lay-up, woven, GFRP

INTRODUCTION

In recent years, Fiber Reinforced Polymers (FRP) have emerged as a potential solution to the tribulations associated with materials technology. Lightweight composite materials have gained increasing interest for applications in aeronautical, transports and sports industries and in many other fields of engineering. The aerospace industry has capitalized the use of reinforced composites, known for their extensive outstanding material properties, for decades. The high strength to weight ratio, stiffness to weight ratio, corrosion and fracture resistance of FRP composites make them an attractive structural component for use in many applications. Bader (2002) reported that composite materials based glass fiber in thermosetting resins has been widely utilized in industry for more than 50 years. Woven GFRP composite is a classic example of a synthetic composite that combines the strength of small diameter glass fibers with the ductility of the polymeric matrix, the outcome of which is superior to either component alone. This supremely characteristic is due to the proper selection of fabrication process and this is also agreed by Avila and Morais (2005), which confirmed that performance is directly related to the manufacturing process used to produce the composite.

A good understanding of the mechanical performance of composite materials and the influence of production methods on their performance is vital in achieving the full potential of these materials in structural applications. However, a number of technical issues remain that must be addressed before the engineering practitioners can develop confidence in structural design with composite members. These issues include, but are not limited to, low stiffness, connection details, cost, confirmation of improved durability and toughness to fracture failure. However, delamination of laminated composite materials is a critical problem, whereby interlaminar failure during routine services becomes a major concern in structural composite design. The delamination in the composite panel will result in looses of stiffness and hence the design performances in structural application of fiber composite materials. The resistance or toughness to delamination and propagation of interlaminar defects or micro-cracks in fiber-reinforced composite is identified by the interlaminar separation subjected to no fiber breakage, pullout and fiber bridging. This defines a material property independent of test-specimen geometry and ply orientation that constitute the delaminating interface (Yeo and Dalimin, 2001).

The purpose of this study is to study on the mode-I interlaminar fracture toughness by established standard

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(ASTM, 2001; BS ISO 15024, 2001) due to symmetrical ply arrangement and various curing pressure of the reinforced woven glass fiber material. In the interest of this matters, the discussion is limited to composite based mainly on thermosetting (unsaturated polyester) resin with E-glass plain weave woven fiber.

Many workers specializing on fracture mechanics approach to investigate the interlaminar failure of fiber composite materials can be found. As detailed by earlier workers (Faizal *et al*., 2006), commonly employed standard test geometry, ASTM D5528 and BS/ISO 15024, can be used for characterization of Mode-I interlaminar toughness. However, many practical applications usually involve only multidirectional laminates. Therefore, it is essential to study the interlaminar fracture toughness of multidirectional and woven composites (Morais *et al*., 2002). The Double Cantilever Beam (DCB) geometry has been widely used in this study for the characterization of delamination resistance or fracture energy of laminates (Blackman *et al*., 1991; Todo and Jar, 1997). This is also shown by Robinson *et al*. (1995) that, the conventional DCB specimen is most widely used in determining Mode-I critical interlaminar strain energy release rate (G_{IC}) for unidirectional laminates. However, if this specimen is used for measuring G_{IC} between plies of dissimilar fiber orientation then extensive fiber bridging and crack jumping can result, which prevents measurement of the critical energy release rate for pure delamination growth.

Toughness is a quantitative term that describes the energy consumed or work done in rupturing a specimen. Toughness is a material property independent of crack length, geometry or loading system. Therefore, fracture toughness is a generic term for measuring a resistance to extension of a crack (ASTM, 1996). The material is said to have a high toughness when it is hard to make a crack propagate into the system or body. Pinho *et al*. (2006) study on fracture toughness of the tensile and compressive fibre failure modes in laminated composites reported that lower value of G_{IC} is associated with an initial planar fracture from the pre-crack plane without any significant fiber pullout and if this is the case, then the initiation value would be lay-up independent. Robinson *et al*. (1995) reported that laminated fiber reinforced plastic composites are particularly susceptible to failure by delamination initiation and growth owing to the relatively low tensile strength of the matrix. Schön *et al*. (2000) studied on the fracture mechanical properties of DCB specimens, reported that by comparing different types of damages, manufacturing or service induced, delamination growth occur as a consequence of interlaminar stresses. Perrin *et al*. (2003), has also reported that DCB specimen employed for studying interlaminar fracture toughness expressed, critical energy release rate, is very sensitive to fiber-matrix interface in composite laminates.

Focus on the present work is to undertake a detailed investigation of the interlaminar fracture toughness of woven E-glass fiber/Unsaturated polyester composite material using the fracture mechanics approach. By using DCB specimen the critical mode-I energy release rate, G_{IC}, can be measured and this information can then be used to increase the understanding of interlaminar toughness in composite materials. In particularly, to investigate the effects of curing pressure to symmetrical ply arrangement, which induces matrix variation and the relationship with the interlaminar fracture toughness energy value, G_C.

MATERIALS AND METHODS

The experimental method describes in detail the materials and its fundamental constituents, the specimen preparation for the fabrication of GFRP composite panels and the experimental test method that has been carried out.

Material: Plain-weave type woven glass fiber, commercial code: NISER (EWR-600B) had been used as the GFRP material for the purpose of this study. The basis of EWR-600B was the glass fabric of E-glass, based according to the 0.5% content of $Na_2 + K_2O$. The E-glass plain weave had been produced by interlacing warp thread and weft thread and was mainly used in hand lay-up processes. The EWR-600 had a round cross sectional shape approximately 9 μm and chemically contains less than 1% alkali. The basic physical properties of EWR-600B were described in Table 1.

The package of the woven roving was stored horizontally as recommended by reference (BS 3396-1, 1991; BS 3396-2, 1987; BS 3396-3, 1987) in order to avoid distortion of the fabric weaves and the physical outlook of the woven roving EWR-600B as shown in Fig. 1. Before cutting the fabrics, it was ensured that uniformly woven,

Table 1: Physical properties of EWR-600B

Code	Width (mm)	Linear density (tex) Warp	Linear density (tex) Weft	Fabric density (end cm^{-1}) Warp	Fabric density (end cm^{-1}) Weft	Area weight (g m^{-2})	Moisture content (%)	Warp size (mm)	Weft size (mm)	Yarn spacing (mm)	Dry thickness (mm)
EWR 600B	1000	1750	1750	1.97	1.57	620	< 0.15	2.48	2.10	1.08	0.467

selvedges were well made, straight and even, free yarn defects and free from streaks, stains and also other contaminations and permanent distortions.

Laminate composite panel: Woven laminates had been prepared by hand lay-up at room temperature. Four experimental composite panels were fabricated with symmetry arrangement of E-glass fiber cloth/ply. A plain weave woven roving with fibers at 0° and 90° direction, were symmetrically layered up about a central plane as shown in the Fig. 2.

An average mass of 71g woven roving ply was positioned manually in a rectangular open mold. The polyester resin was then poured into the mold and the ply flattens using brush or flat stick. The plain weave woven E-glass fabric was stacked into ten layers symmetrically as mentioned earlier. A panel of 10 ply laminates had been fabricated for different curing pressure of 35.8 kg m^{-2}, 70.1 kg m^{-2}, 104 kg m^{-2} and 138.2 kg m^{-2}. The stacked plies for each group of laminate were then allowed to cure for 24 h at room temperature at 23°C/297.15 K.

DCB sample: The geometry of the DCB specimen consists of a rectangular uniform thickness as illustrated in the Fig. 3. The DCB specimen contains a thin, non-adhesive starter film embedded at the mid-plane, which was used to simulate an initial delamination (BS ISO 15024, 2001). From the Fig. 3, b was the specimen width, h the specimen thickness, a_0 the initial delamination length, a the total delamination length, A the insert length, l the specimen length, l_1 the distance from center of loading pin to mid-plane of specimen, l_2 the distance from center of loading pin to edge of end block, l_3 the end block length and H the end block thickness.

In this study, dimensions of the specimen had been selected in accordance with the standard test method BS ISO 15024 (2001) specifications and as well as other publications were referred. The Fig. 3 shows the summary of DCB specimen design according to established test standards and other researchers work. Perrin *et al.* (2003) reported that improper selection of thickness of the DCB specimens could cause the need for large deflection correction, which was due to large displacement of end block rotation.

Test method: The testing was undertaken in accordance with the ASTM D5528-01 (2001) and British test method BS ISO 15024 (2001). All tests were conducted at room temperature 23°C/297.15 K, with dry laminates using an axial loading servo-hydraulic test machine, INSTRON Series 8801, under displacement control, as shown in the Fig. 4. Prior to testing, a thin layer of white correction fluid is applied along the edge of the DCB specimen for clear identification of crack position or intervals during the testing. The specimen edge was marked with initial 1mm interval up to 5mm from the starter crack end and thereafter at 5mm intervals. All specimens were not pre-cracked before the testing in order to obtain an initiation value free of fiber bridging. All tests were conducted under displacement control at constant crosshead speed of 3 mm min^{-1}.

DATA REDUCTION SCHEME

The Linear Elastic Fracture Mechanics (LEFM) analysis for analyzing the data obtained in the load-displacement traces can be tackled by different approaches. However, the various methods available for calculating mode-I strain energy release rate from DCB geometries could result in different values (Ashcroft *et al.*, 2001). In this study however, a load/displacement plot provided the data for each crack length used for the calculation of G_{IC} by adopting the experimental modified beam theory method (Stevanovic *et al.*, 2000).

Modified Beam Theory, MBT: The experimental beam theory expression for G_I assumes perfectly built-in (clamped at the delamination front) of DCB specimen that can be derived as

$$G_I = \frac{3P\delta}{2ba} \quad (1)$$

where, P is the load, **δ** the load point or opening displacement, b the specimen width and a the delamination length. However, this equation could over estimate the G_I by imperfect built-in assumption, which could be affected by the rotation at the delamination front. Correction of this rotation is to treat the DCB as if it contains a slightly longer delamination and this led to the introduction of Modified Beam Theory (MBT) method. For this data reduction strategy, then the critical energy release rate is resolved as

$$G_I = \frac{3P\delta}{2b\left(a+|\Delta|\right)} \quad (2)$$

where, **Δ** is determined experimentally by generating a least square plot of the cube root of compliance, $C^{1/3}$, as a function of delamination length as shown in the Fig. 5. The parameter-C is the compliance or also the ratio of the load point displacement to the applied load, **δ**/P and N is the loading block correction.

Parameter **Δ**, is the crack length correction factor which, in a real specimen, accounts for the effects of

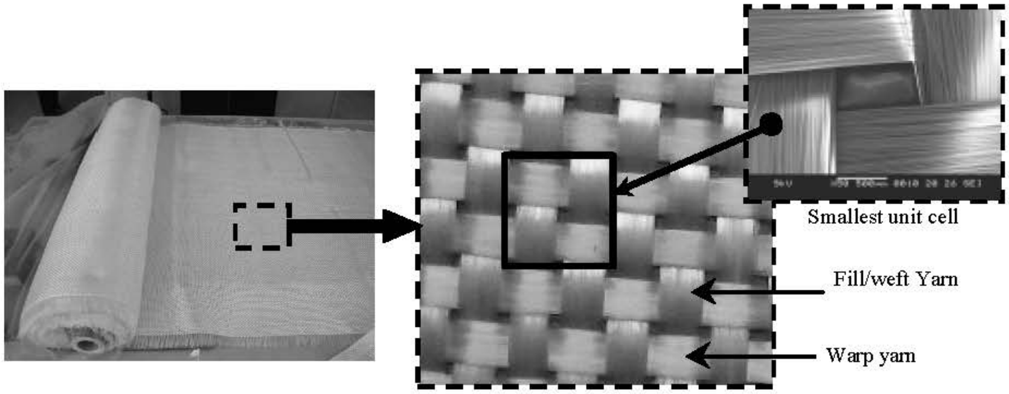

Fig. 1: Typical plain-weave E-glass woven roving, EWR-600B

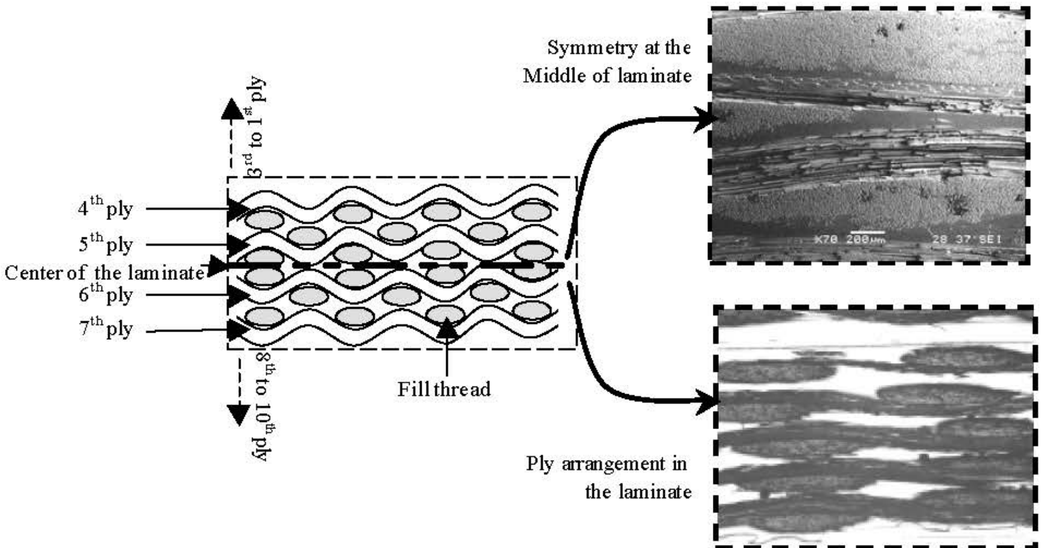

Fig. 2: Symmetry arrangement of E-glass woven ply

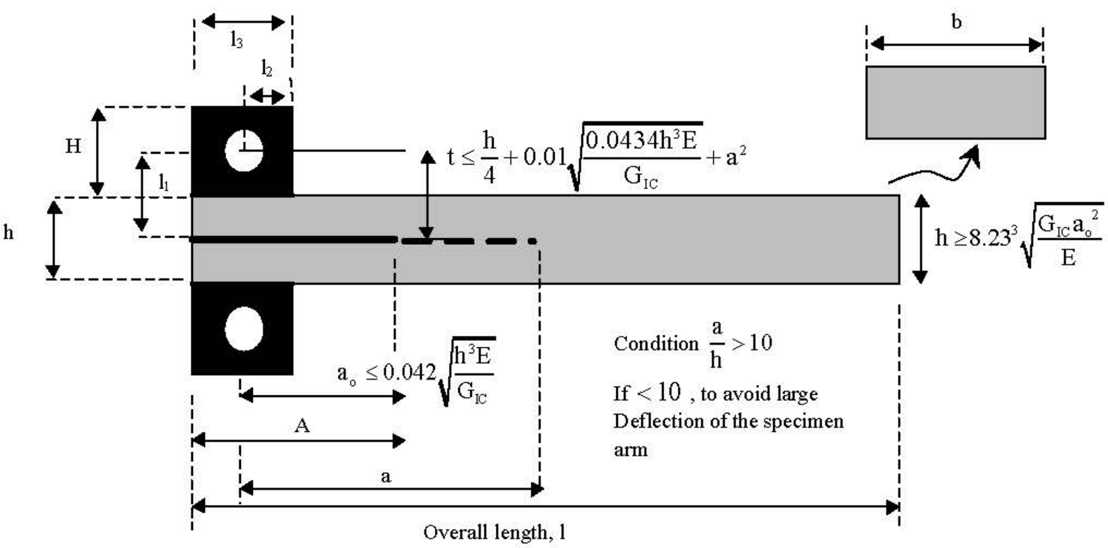

Fig. 3: Specimen geometry and parameters

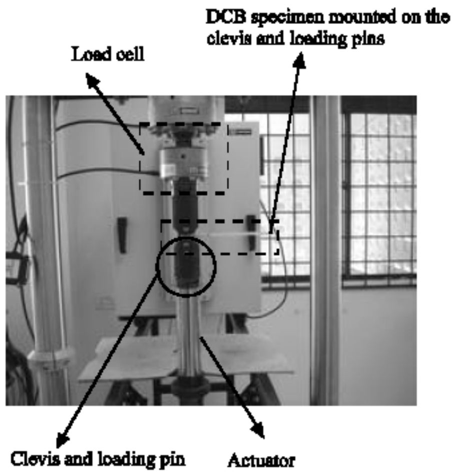

Fig. 4: Servo hydraulic testing machine, INSTRON

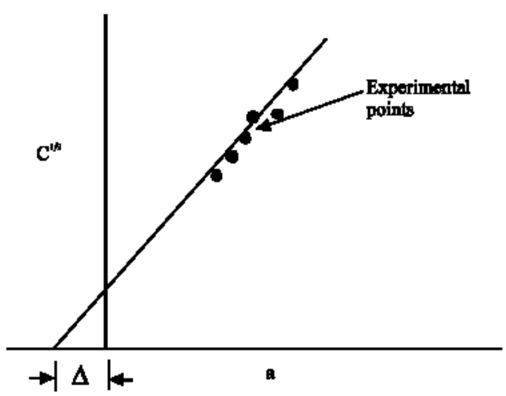

Fig. 5: Determination of the Δ-correction

rotation at the crack tip. The correction to the crack length ensures that the opening displacement δ can be related to the corrected crack length (a+|Δ|), by the simple beam theory expression for a cantilever (Robinson *et al*., 2004), given by;

$$\delta = \frac{2P(a+\Delta)^3}{3EI} \quad (3)$$

If the Δ is negative, ESIS recommends that it should be set to zero whereas ASTM D5528-01 recommends that the modulus should be used. As reported by Robinson *et al*. (2004), neither of these recommendations is followed since a negative value of Δ is physically appropriate due to the existence of the bridging stress.

As a result, the critical energy release rate G_{IC} is determined by multiplying the F/N factor to the G_I in Eq. 2, such that;

$$F = 1 - \frac{3}{10}\left(\frac{\delta}{a}\right)^2 - \frac{2}{3}\left(\frac{\delta l_1}{a^2}\right) \quad (4)$$

$$N = 1 - \left(\frac{l_2}{2}\right)^3 - \frac{9}{8}\left[1 - \left(\frac{l_2}{a}\right)^2\right]\frac{\delta l_1}{a^2} - \frac{9}{35}\left(\frac{\delta}{a}\right)^2 \quad (5)$$

where F is the large displacement effect and N is the loading block correction.

RESULTS AND DISCUSSION

A successful curing process of composite fabrication will be determined by its outstanding properties. The variation of curing cycle and curing pressure could contribute to the variation in the material properties. As a result, the characteristic standard curing cycle and pressure variation, toughness and fractographic analysis of the fabricated composite would reviewed any such distinction and correlation.

Physical characteristic: Micrographs of through thickness cross-section of the woven has been obtained to determine its fiber and matrix characteristic via the JEOL JSM 5610LV scanning electron microscope (SEM), as shown in Fig. 6. Generally, voids are found in small quantities about 1 to 4% across the thickness section that appears as black dots in the micrographs. The voids formed are found to cause local rearrangement of tows, which reflects the non-uniform stress distribution through the thickness. However, the fiber weight fraction (%) has shown a variation increasing from 50 to 56% and remains about constants with respect to increasing curing pressure. As a result, the quality of these composites produced can be classified as of a mediocre quality (Berthelot *et al*., 1999).

Toughness characteristic: A typical load-displacement curve for the symmetrical lay-up system has a distinct decreasing load shift with increasing curing pressure, as shown in the Fig. 7. By increasing the curing pressure, resin depletion characteristic at the interlaminar fracture interface has been identified. This depletion of resin at the interlaminar interface reduces the localized volume of plastic strain absorption, thus resulting in a lower load necessary to fracture the specimen.

The Fig. 8 shows the failure mechanisms that occur during initial elastic loading that develops into initiation and damage growth of the DCB specimen. This initial microscopic fracture was observed before the characteristic macroscopic fracture or delamination during

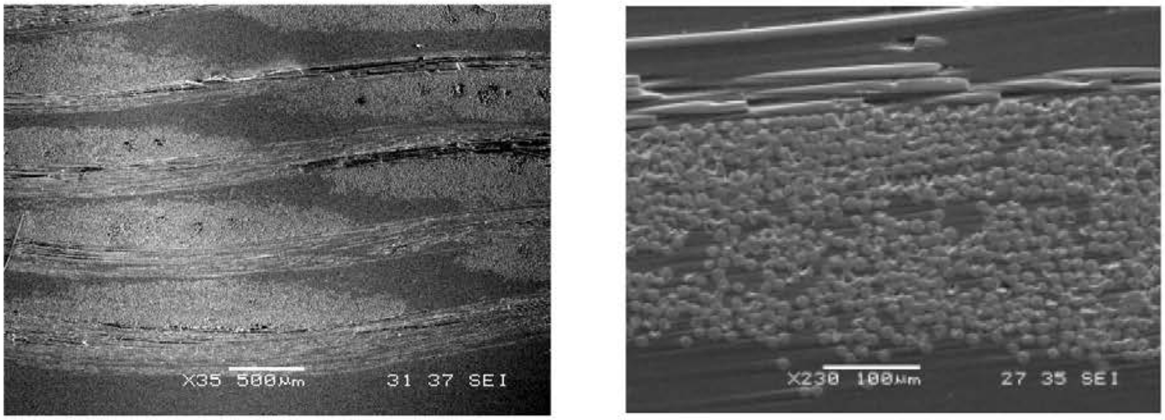

Fig. 6: SEM micrograph of through thickness cross-section of laminate

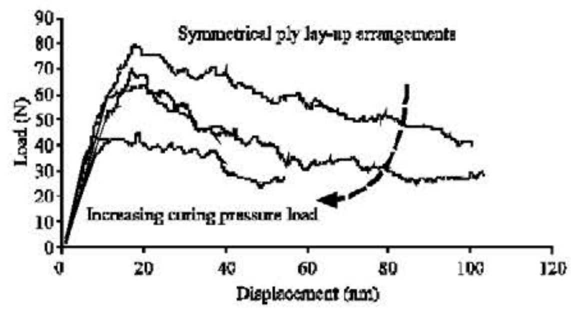

Fig. 7: Load-displacement characteristics for symmetrical ply arrangement

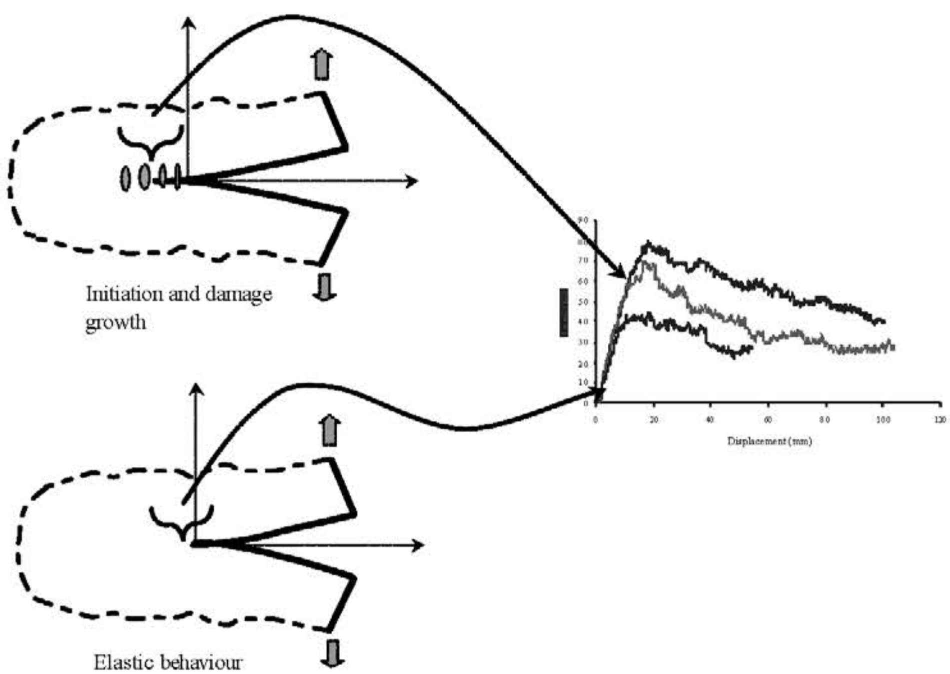

Fig. 8: Failure mechanism about the crack tip of woven GFRP/unsaturated poyester

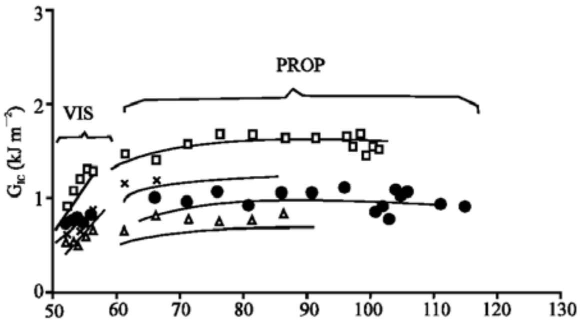

Fig. 9: Typical delamination-resistance curve (R-curve) for the Mode-I fracture

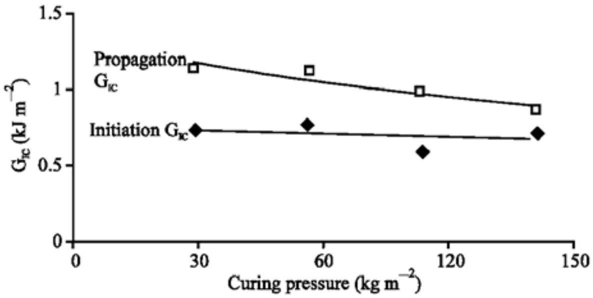

Fig. 10: Interlaminar fracture toughness versus curing pressure, using MBT

the crack propagation. Stable crack propagation was obtained when the crack propagated continuously under the external loading.

The delamination-resistance characteristic curves or the R-curves had been characterized as shown in the Fig. 9 for the different curing pressure in the symmetrical of lay-up arrangements. The visually observed initiation G_{IC} values were labeled VIS and the propagation values labeled as PROP on the graph. The characteristic R-curves for different curing pressures all indicated trends of approaching to a plateau. Fracture deformation at initiation values was very similar in all cases, while during propagation the separation of plies leads to formation of fiber bridging phenomenon. These mechanisms had contributed to the slow and stable crack propagation and extensive half-arm fibers bridged that were observed in specimens with lower curing pressure. As a result, higher G_{IC} propagation values had been obtained as compared to increasing curing pressure. This phenomenon was the main contributor to the rising R-curve shown in the Fig. 9. The increasing R-curves with small displacements are generally created from the testing on thicker specimens. While the stable propagation value of G_{IC} was a significance of fiber bridges breaking at roughly the same rate as they were created.

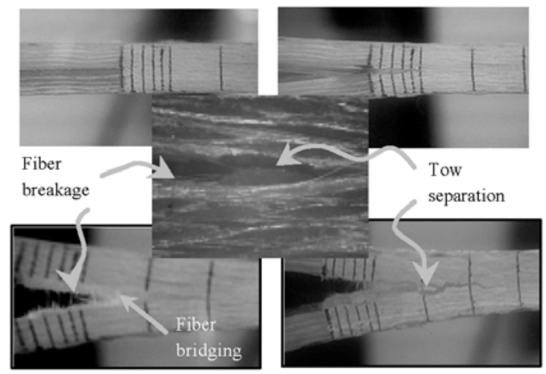

Fig. 11: Failure mode and mechanism of E-glass woven GFRP laminate

The resultant interlaminar toughness with respect to the curing pressure had been characterized with respect to the initiation and propagation toughness values as in Fig. 10. The fracture toughness values of woven GFRP were computed using the analysis of MBT method. Comparatively, the G_{IC} propagation values were significantly higher than the G_{IC} initiation values. Since the mechanism of initiation toughness involves only a layer of resin-rich and fiber-free crack-front, which depletes as the curing pressure increases. The depletion also means that the volume of localized plastic zone size had been reduced, leading to the characteristic decreasing toughness with increasing curing pressure.

Fractographic analysis: A fractographic investigation was undertaken during and after the fracture of DCB specimens for each of the curing pressure of 35.8, 70.1, 104 and 138.2 kg m^{-2}. Thickness cross-section fractured along crack propagation distance of 15 mm was systematically observed and captured as shown in Fig. 11. The failure by separation of the two double-cantilever arm illustrates the mode of fracture mechanisms involving tow cracking, splitting and separation, fiber bridging and fiber breakage. The fracture profile obtained from the test shows that fiber bridging occurred as early as in the first 5 mm of the crack propagation. The phenomenon then changed with fiber breakage as the crack propagated reaches up to 15 mm. This kind of behavior has also been reported by Shivakumar *et al.* (2006).

Under the Scanning Electron Microscopic analysis, Fig. 12, fiber bundle fracture and pullout on warp and weft direction of the fiber yarn can be clearly reviewed. However, fractured surfaces remain predominantly brittle matrix failure. Broken fiber ends indicating brittle failure mode and interfacial failure between the fibers and resin was common on the fracture surface. The brittle

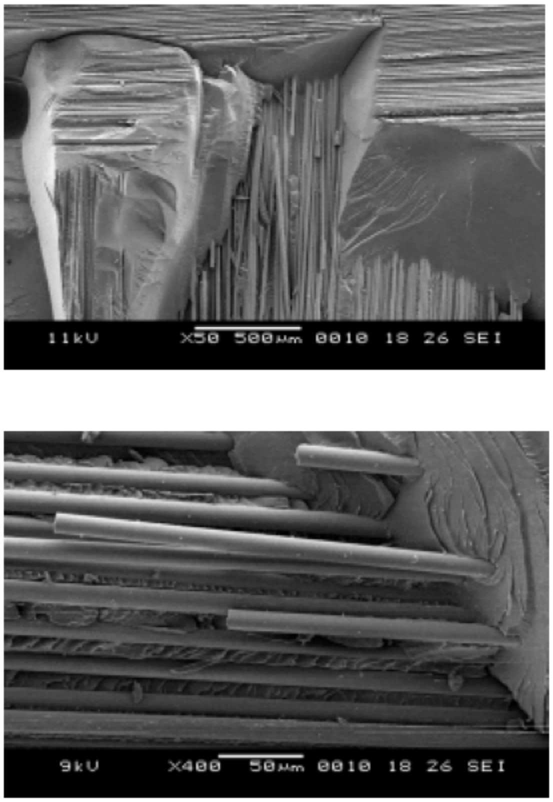

Fig. 12: Brittle failure and fiber bunch pullout of woven GFRP laminate

fragmentation of fibers by cleavage load is indicated by the flat broken fiber-ends. Similar evident characteristic is found with the resin-fractured regions. Fiber bundle pullout was also scarcely observed, which indicates fiber-matrix interfacial bond strength was exceeded before the tensile failure strength of the composite was attained.

CONCLUSIONS

Studies of influence of different curing pressure in mode-I interlaminar fracture toughness of symmetrical ply arrangement of woven GFRP composite was conducted. Quasi-static mode-I critical fracture toughness of advanced woven E-glass fiber reinforced composite material was an important controlling parameter to the interlaminar failure. The investigation found that both initiation and propagation G_{IC} values were consistently affected by the different curing pressure applied. Although the fiber weight fraction was not particularly significant. Fractured morphology has also indicated fiber bundle brittle fracture and pullout for the symmetrical ply arrangements. The study had provided a useful insight to different types of curing pressure as an important and useful controlling parameter to interlaminar failure of woven GFRP composites.

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REFERENCES

Ashcroft, I.A., D.J. Hughes and S.J. Shaw, 2001. Mode-I fracture of epoxy bonded composite joints: 1. Quasi-static loading. Int. J. Adhesion and Adhesives, 21: 87-99.

ASTM Standard E 1823, 1996. Standard Terminology Relating to Fatigue and Fracture Testing. Philadelphia: American Society for Testing and Materials.

ASTM Standard D5528-01, 2001. Standard test method for mode-I interlaminar fracture toughness of fiber-reinforced polymer matrix composite. Am. Soc. Testing Materials, West Conshohocken, PA.

Avila, A.F. and D.T.S. Morais, 2005. A multiscale investigation based on variance analysis for hand lay-up composite manufacturing. Composite Sci. Technol., 65: 827-838.

Bader, M.G., 2002. Selection of composite materials and manufacturing routes for cost-effective performance. Composites Part A. Applied Science and Manufacturing, 33: 913-934.

Berthelot, J.M. and J.M. Cole and F.F. Ling, 1999. Composite materials: Mechanical behavior and structural analysis. Spriger-Verlag Inc., New York.

Blackman, B., J.P. Dear, A.J. Kinloch and S. Osiyemi, 1991. The calculation of adhesive fracture energies from double-cantilever beam test specimens. J. Mater. Sci. Lett., 10: 253-256.

BS 3396-2, 1987. Woven glass fiber fabrics for plastics reinforcement-Part 2: Specification for desized fabrics. British Standard, United Kingdom.

BS 3396-3, 1987. Woven glass fiber fabrics for plastics reinforcement-Part 3: Specification for finished fabrics for use with polyester resin systems. British Standard, United Kingdom.

BS 3396-1, 1991. Woven glass fiber fabrics for plastics reinforcement-Part 1: Specification for loom-state fabrics. British Standard, United Kingdom.

BS ISO 15024, 2001. Fiber-reinforced plastic composites-Determination of mode-I interlaminar fracture toughness, G_{IC}, for unidirectionally reinforced materials. British: Standard, United Kingdom.

Davie, P. and M.L. Benzeggagh, 1989. Interlaminar Mode-I Fracture Testing. Application of Fracture Mechanics to Composite Materials. Friedrick, K. (Ed.), Elsevier Sci. Pub. B.V., pp: 81-112.

Faizal, M.A., K.B. Yeo and M.N. Dalimin, 2006. Mode-I interlaminar fracture toughness of hand lay-up plain-weave woven GFRP/unsaturated polyester laminates. Proceeding: The 1st Regional Postgraduate Conference on Engineering and Science, Johor, Malaysia, pp: 287-291.

Morais, A.B., M.F. Moura, A.T. Marques and P.T. Castro, 2002. Mode-I interlaminar fracture of carbon/epoxy cross-ply composite. Compos. Sci. Technol., 62: 679-686.

Perrin, F., M.N. Bureau, J. Denault and J.I. Dickson, 2003. Mode-I interlaminar crack propagation in continuous glass fiber/polypropylene composites: Temperature and molding condition dependence. Compos. Sci. Technol., 63: 597-607.

Pinho, S.T., P. Robinson and L. Iannucci, 2006. Fracture Toughness of the Tensile and Compressive Fibre Failure Modes in Laminated Composites. Compos. Sci. Technol., 66: 2069-2079.

Robinson, P., F. Javidrad and D. Hitchings, 1995. Finite element modelling of delamination growth in the DCB and edge delaminated DCB specimens. Composite Structures, 32: 275-285.

Robinson, P. and S. Das, 2004. Mode I testing of composite laminates reinforced with z-direction pins: A simple model for the investigation of data reduction strategies. Engineering Fracture Mechanics, 7: 345-364.

Schön, J., T. Nyman, A. Blom and H.A. Ansell, 2000. Numerical and experimental investigation of delamination behavior in the DCB specimen. Compos. Sci. Technol., 60: 173-184.

Shivakumar, K., H. Chen, F. Abali and C. Davis, 2006. A total fatigue model for mode I delaminated composite laminates. Int. J. Fatigue, 28: 33-42.

Stevanovic, D., P.Y.B. Jar, S. Kalyanasundaram and A. Lowe, 2000. On crack-initiation conditions for mode I and mode II delamination testing of composite materials. Compos. Sci. Technol., 60: 1879-1887.

Todo, M. and P.Y.B. Jar, 1997. Study of mode-I interlaminar crack growth in DCB specimens of fiber-reinforced composites. Compos. Sci. Technol., 58: 105-118.

Yeo, K.B. and M.N. Dalimin, 2001. Mode-I interlaminar fracture toughness of unidirectional carbon fiber epoxy composite. Borneo Science. J. Sci. Technol., 10: 1-9.