

Cryogenic Durability and Finite Element Analysis of Carbon Fiber Reinforced Composites

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Abstract

Carbon fibers were employed to reinforce the modified epoxy resins by flexibilizer to enhance the overall mechanical properties, the tensile strength, modulus, impact strength, fracture toughness test at both 77 K and at room temperature were examined for carbon fiber reinforced composites. At last section finite element simulation by ANSYS-13 was analyzed for crack propagation analysis of unidirectional laminates used for experimental by two methods-(a) Double cantilever beam (b) Single edge notch bending (J-Integral).

Keywords: Double cantilever beam; Single edge notch bending (J-Integral)

Introduction

Advanced organic matrix, fiber-reinforced composite materials are being increasingly used in the design of aerospace vehicles in order to reduce weight. The benefits of such reduction include increased payload capability, fuel capacity, and reliability through systems redundancy. In order to achieve enhancements in performance, these materials must have a lower density and higher stiffness and strength than conventional materials. They must also display stability over a range of temperatures as well as resistance to damage, moisture absorption, and fatigue. Advanced polymer matrix composites have already been used successfully in a variety of structural applications within the aircraft industry. However, as the use of composite materials expands into the realm of space transportation, these materials are subjected to more hostile environments, including exposure to cryogenic fuels. Carbon fiber reinforced epoxy composites (CFRPs) are one of the enabling materials to reduce the structural mass [1]. CFRPs are often used in the production of structural components for the aeronautics and aerospace industries, mainly because of their excellent specific mechanical properties and their high resistance to fatigue, and of the possibility of selecting the optimum laminate lay up for each application. Besides these properties, low thermal conductivity and high dimensional stability have made the CFRPs a good alternative for applications where very low temperatures are reached, such as in cryogenic tanks and their support elements. During their operational life in these applications, the CFRPs are subjected to low temperatures that could modify the mechanical properties of the material. These conditions affect the mechanical properties of the material by two reasons (a) the variation of the properties of the constituents of the material and (b) the appearance of residual stresses inside the material due to the mismatch between the thermal expansion coefficients of fibers and of the matrix. It is necessary, therefore, to carry out a mechanical characterization over the complete range of temperatures that can be reached during the operational life of components made of these materials.

The experimental characterization of materials at low temperatures calls for special test equipment and instrumentation, which increases the difficulty of obtaining valid results. Although the behavior of these materials at low temperatures has been analyzed by several authors few experimental results are available and no standardized test method has been fixed. Wilson and Bashford studied different types of CFRPs (different carbon fibers) for temperatures to 26°C for unidirectional laminates, analyzing the properties in both longitudinal and transverse

directions and for cross ply laminate (+ 45°). The measured Young modulus in the longitudinal direction and in tensile conditions remained practically constant [2].

Pintado analyzed the temperature effect on unidirectional laminates of carbon fiber in a cyanate thermoset resin. For the inter-laminar shear strength they also analyzed two different epoxy resins. Their aim was to select a material suitable for future launcher vehicles. They defined the methodology used for tests in compression, tensile, bending, in plane shear, inter-laminar shear and mode II fracture, at temperatures of about 20 K. They observed a slight drop of the compression and the TS in both the longitudinal and transverse laminate directions.

Delamination Techniques in Finite Element Analysis

Two techniques exist in ANSYS to simulate the behavior of delamination of layers in a composite material:

- Virtual crack closure technique (VCCT).
- Cohesive zone model (CZM).
- Both techniques use special elements (interface or contact) along a pre-defined interface to model the delamination of cracks
- The procedure selected by the analyst is based on considerations of the strengths and weaknesses of both methods [3-4].

CZM relates interfacial tractions to displacement discontinuities.

Strengths: Predicts initiation and growth of delamination without prior assumptions about the crack. Applicable to complex structures subjected to complex loading states.

Weaknesses: Characterization data can be difficult to obtain. Accurate assessments are strongly tied to element size.

VCCT calculates energy-release rate, with the assumption that the energy needed to separate a surface is the same as the energy needed to

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close the same surface.

Materials Selection

Raw materials

Table 1 shows various raw materials.

Mechanical testing

Tensile test: The tensile samples were prepared according to the recommendation of ASTM D 3039. The tensile properties of the cured specimen at 77 K were measured by WD-10 a mechanical tester using a 10 KN load cell with a crosshead speed of 5 mm/min [5]. The cryogenic temperature condition was achieved by dipping the clamps and the samples in a liquid nitrogen filled cryostat designed in our laboratory. The entire testing was conducted while the specimen and the loading fixture were submerged in liquid nitrogen. The fracture toughness (K_{IC}) test was carried out using three point bend specimens with dimension-150 × 20 × 5.68 mm. A pre-crack was made in the specimen by lightly tapping a sharp fresh razor blade into the bottom of the slot with 2.5 mm depth. The slot was sawed by HC-400 digital manual dicing cutter. Three point-bend specimens was accomplished. Similar to the cryogenic tensile testing, the specimens and the loading fixture were submerged in liquid nitrogen [6-8].

Calculation

The tentative value of fracture toughness, K_Q , is determined by:

$$K_Q = f\left(\frac{a}{w}\right) \frac{F_{max}}{BW^{1/2}}$$

F =load [N], S =span length [mm], B =specimen thickness [mm], W =specimen width [mm] and a =crack length [mm].

$$\text{with } f(x) = 6\sqrt{x} \frac{[(1.99 - x(1-x)(2.15 - 3.93x + 2.7x^2))]}{(1+2x)(1-x)^{3/2}}$$

The resulting K_Q is accepted as valid plane strain fracture toughness value if all characteristic lengths of the samples ($X=B$, W or a) comply with the condition:

$$X > L_{crit} = 2.5 \left(\frac{K_Q}{\sigma_f} \right)^2$$

following the STM recommendation to employ the fracture stress (σ_f) instead of yield stress as a conservative estimation of the conditions for plane strain dominance in crack propagation of brittle polymers [8-10].

Calculation of G_Q

For the bend specimens calculate G_Q in units of KJ/m² from the corrected energy, U , as follows (Table 2):

$$G_Q = \eta U / \{B (W - a)\}$$

For DCB fracture toughness: Generated least squares plot of log (di/Pi) versus log (ai) using the visually observed delamination onset values and all the propagation values. Draw a straight line through the data that results in the best least-squares fit [11-14]. Calculate the

1. Carbon fibre	T650-35
2. Epoxy	EPON 828
3. Flexibilizer	Jeffamine D 2000
4. Hardener/Curing agent	HY951

Table 1: Showing various raw-materials.

Sample	L	W	B
Epoxy RT	150	20	5.68
Thick CFRP RT	150	20	1.5
Thin CFRP RT	150	20	5.68
Epoxy 77 K	150	20	5.68
Thick CFRP 77 K	150	20	5.68
Thin CFRP 77 K	150	20	1.5

Table 2: Showing various sample.

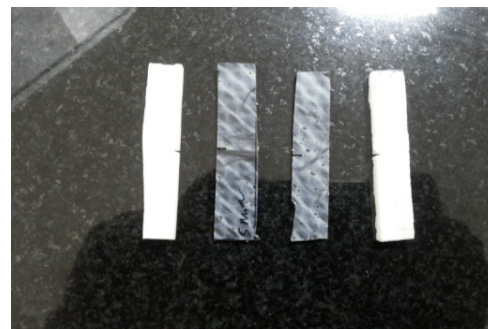


Figure 1: Impact samples.

exponent n from the slope of this line according to $n=Dy/Dx$, where Dy and Dx are defined. Calculate the mode I interlaminar fracture toughness as follows:

$$G_I = \frac{nP\delta}{2ba}$$

Impact test: Single-edge-notched bending specimens with dimensions of 63.5 mm × 12.7 mm × 5 mm used for this measurement were cut from the injection-molded plaques (Figure 1). The notches of different depths were made first by the formation of saw cut slots having rectangular shape with a width of 2.5 mm in the mid-section of specimens and then by sharpening with a fresh razor blade. Then the notch with a depth (a) was obtained. At least three specimens of every composition at each specified notch depth (were used to produce a good reproducibility. 6 specimens were used for each composition during the impact EWF measurements, 3 for room temperature and 3 for cryogenic temperature [15].

Surface morphology

Scanning Electron Microscopy (SEM): It shows relatively rough fracture surfaces and uneven at both RT and 77 K were clearly observed for the CFRP composites which correspond to the significantly improved fracture toughness. The rough fracture surfaces indicate the deflections of crack propagation, namely the crack paths deviate from their original planes. Once the fibers fracture, the interfacial shear stress decreases accordingly. In addition, the crack deflection can be found because of the rough fracture surface of composites, and it can enlarge the crack surface area. All of these toughening mechanisms can consume fracture energy and improve the fracture toughness of carbon fiber/epoxy composites, it can be found that when the carbon fiber content continues to increase, the fracture toughness decreases due to the increasing number of pores caused by the fiber bridging effect. The pores weaken the bond strength of fiber/matrix interface, and then weaken the energy-consumption ability of carbon fibers which consume fracture energy by fiber debond and pull-out [16-18].

Finite element analysis

Numerical study: DOFs at coincident nodes are coupled. The corresponding forces are computed. (b) DOFs of the nodes at the crack front are released. The corresponding displacements are computed (Figure 2).

The critical fracture energy value of core and reinforcement interface was calculated numerically. This method is based on determination of an energy, which expresses the change in potential energy when a crack extends.

For this reason, a finite element model with the same dimension as the experimental study has been constructed and the initial crack size chosen as 3 mm. The elements surrounding the crack lines were selected as quarter-point eight-noded rectangular elements in order to compute the exact singularity using the least numbered elements. The details of the finite element model near the crack line were illustrated.

The J-integral, proposed by Rice forms the basis of fracture beyond the linear elastic range. It is defined as a line integral in the two-dimensional strain field of a nonlinear elastic material.

$$J = \int_{\Gamma} W dx_2 - \eta_i \sigma_{ij} \frac{\partial u_i}{\partial x_j} \cdot ds$$

where Γ is any contour from the bottom crack surface around the tip to the top surface. In, n is the outward unit normal to the contour, W is the strain energy density, u is the displacements and ds is an infinitesimal element contour arc length [19].

The integral is path independent when the crack is straight, traction free, and any material interface parallel to the crack. is path independent when the crack is straight, traction free, and any material interface parallel to the crack. The energy release rate definition of J can be used to develop numerical methods for its evaluation

$$\frac{\partial U}{\partial a} \approx -\frac{1}{2} \{U\}_n^T \frac{\partial [K]}{\partial a} \{u_n\}$$

where U is the potential energy of the body, $\{u\}$ is the nodal point displacement vector, $[K]$ is the stiffness matrix, and a is crack length. The method $\{u_n\}$ is determined for crack length, a , and the stiffness matrix, $[K]$ is stored computer. The crack length is increased a small amount, on the order of 10^{-3} to 10^{-6} a typical element dimension, and a new stiffness matrix is determined. As seen in figure. there are changes in the stiffness only in the two elements surrounding the crack tip. The stiffness derivative is written approximately as:

$$\partial [K] / \partial a \approx \Delta [K] / \Delta a = \{ [K]_{a+\Delta a} - [K]_a \} / \Delta a$$

By employing this method, the J values were calculated. As mentioned above; the mechanical properties, which are used for the duration of finite element solution, material are given. A load of 100 N was applied as a uniform pressure on the upper surface of the material.

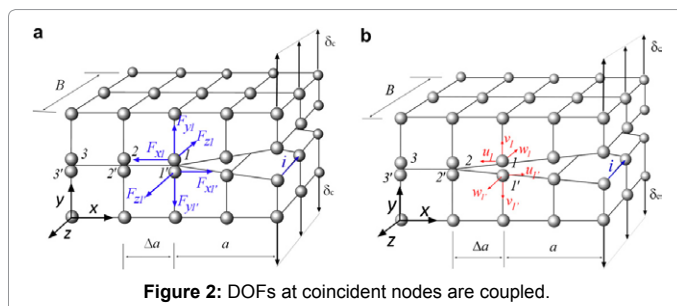


Figure 2: DOFs at coincident nodes are coupled.

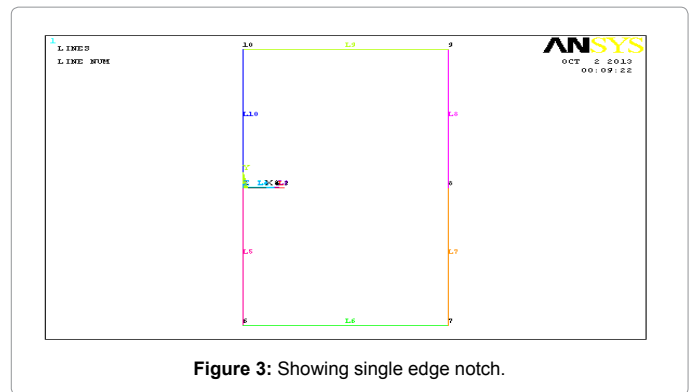


Figure 3: Showing single edge notch.

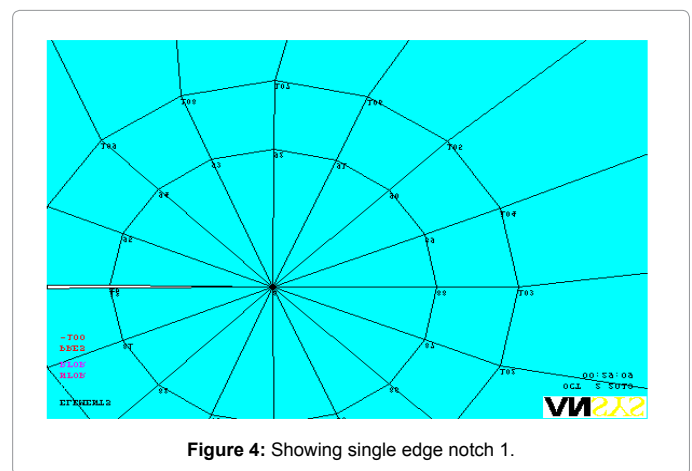


Figure 4: Showing single edge notch 1.

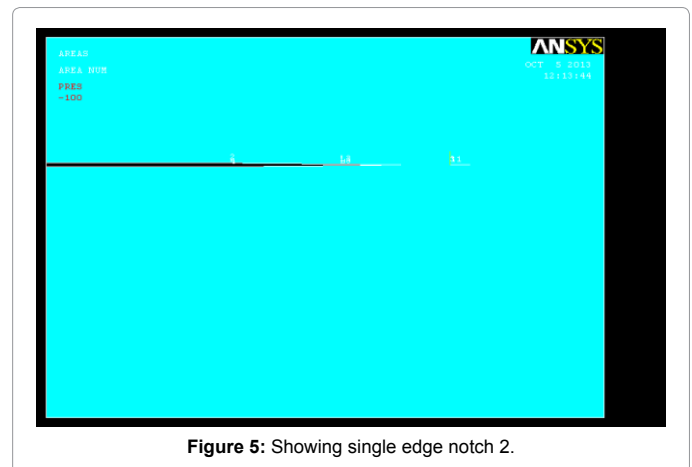


Figure 5: Showing single edge notch 2.

The results calculated by the use of experimental study were compared with the FEM results to show accuracy. Showing single edge notch (Figures 3-5).

Double cantilever beam modeling: Studies for mode I delamination have yielded a standard test method that uses Double Cantilever Beam (DCB) specimen with unidirectional fibers [1-3].

$$\text{Expressions for } G_I = 12 P^2 / E_1 B^2 H^3$$

Material properties of Carbon/Epoxy

$$E_1 = 115.1 \text{ GPa;}$$

$$E_3 = 9.7 \text{ GPa};$$

$\nu_{31} = 0.09$; $G_{13} = 4.478$, GPa For the middle layer of the interlaminar resin-rich region: $E = 3.1$ GPa; $\nu = 0.35$ (Figure 6).

Tensile properties: The stress strain curves of epoxy and carbon fiber/epoxy composites at 77 K and room temperature (Figure 7). It displays linear relationship between stress and strain, and thus exhibit brittle behaviors at liquid nitrogen temperature, addition of carbon fiber/softner at proper contents has lead to improvements in cryogenic tensile properties, average and standard deviation of tensile strength Young's modulus and ultimate failure strain at 77 K. A significant enhancement in the cryogenic tensile strength has been observed by the addition of carbon fiber at appropriate contents. It reaches 238.438 MPa at the RT corresponding improvement of 73.9% when compared with virgin epoxy modified by softner followed by decrease when the carbon fiber content was further decreased to 152.73 MPa at 77 K, when compare by virgin epoxy in room temperature by 36%. The Young's modulus at 77 K of the carbon Fiber epoxy composites were found to increase with increase content of carbon fiber. This can be owing to the introduction of carbon fiber with a high Young's modulus of carbon fiber/epoxy composites with 86.3% when compared with virgin epoxy modified by softner. Comparison of tensile strength in cryogenic and room temperature in Table 3 and Figure 8 [20].

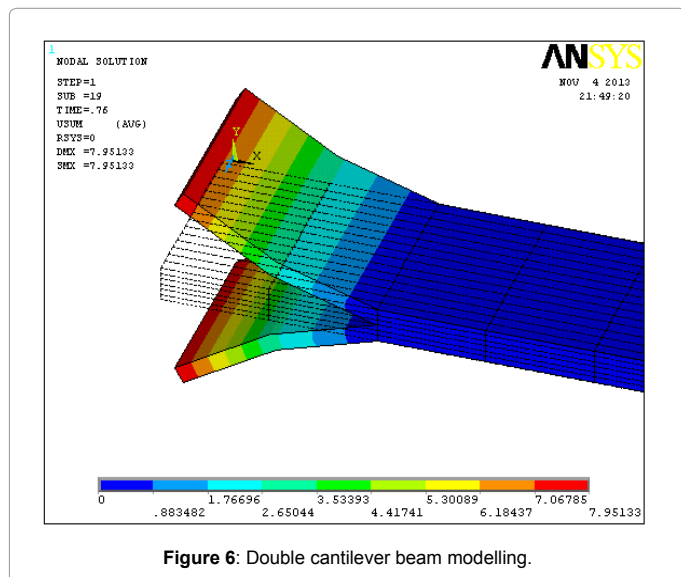


Figure 6: Double cantilever beam modelling.

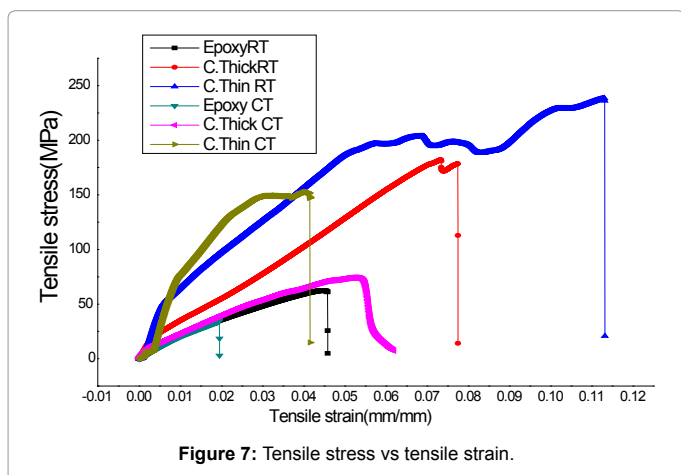


Figure 7: Tensile stress vs tensile strain.

Sl.no	Samples	Tensile strength (RT) (MPa)	Tensile strength(77 K)(CT) (MPa)
1	Epoxy	62.295	34.389
2	C.Thick	182.136	74.147
3	C.Thin	238.438	152.737

Table 3: Comparison of tensile strength in cryogenic and room temperature.

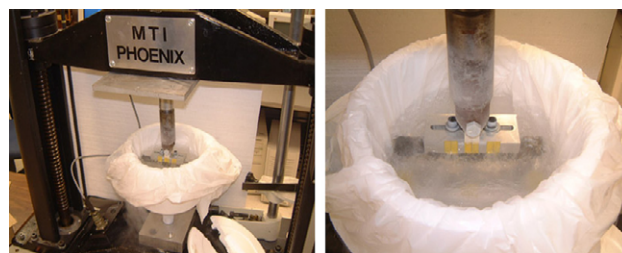


Figure 8: Cryogenic set up for samples.

Sample	Break (J)	Stress (J/m ²)	Strain(J/m)
Epoxy. thick (77 K)	0.17	5.66	50.97
Epoxy. thin(77 K)	0.2774	9.94549	89.5094
C. thin (77 K)	0.4713	138.65	261.846
C. thick (77 K)	0.0875	122.054	1098.48
Epoxy.thick (RT)	0.2458	7.68369	61.4695
Epoxy thin (RT)	0.1873	7.43521	66.9169
C.thin (RT)	0.0141	68.5212	685.212
C.thick (RT)	0.5196	41.3072	351.112

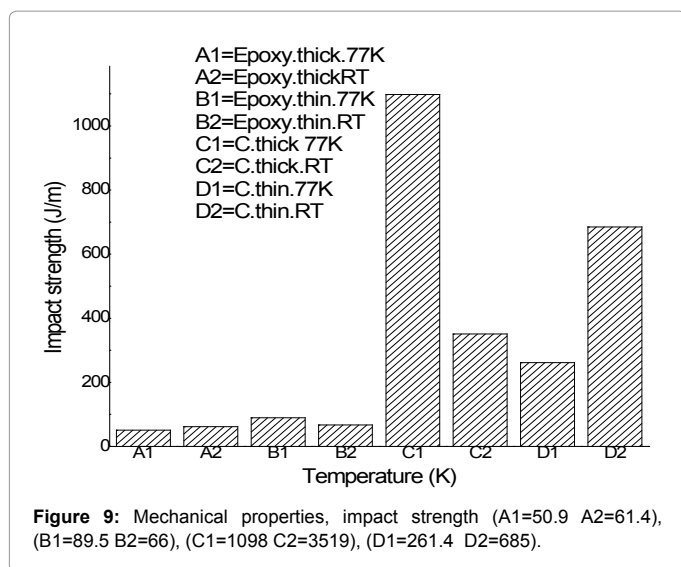
Table 4: Showing results for break, stress, strain.

Impact properties: The effect of epoxy and carbon fiber epoxy composites on notched izod impact strength at room and cryogenic temperature are studied. The presence of softner reasonably increases the impact strength upto 74.7%. This shows phenomenon transition from brittle to semi brittle, leading to more toughness. Declination of impact strength due to the absence of carbon fiber within the epoxy matrix both in RT and at 77 K was observed. The total fracture energy of unmodified epoxy composite slightly decreases compared to the virgin epoxy, while addition of the carbon Fiber to about 98% increase of the absorbed total energy. Carbon Fiber ensures better adhesion between the matrix and fibers leading to increased impact strength. The most pronounced enhancement of the total fracture energy and of J values, was observed in the softner-modified epoxy/carbon fiber composite-about 44%. This could be explained by the role of the softner in epoxy resin.

In addition to well-known toughening mechanisms such as multiple crazing and shear yielding [another possibility is that carbon fibers concentrate the stress at the crack tip and prevent a large region around the crack tip from undergoing either crazing or shear yielding. Thus, the energy dissipation (by crazing and shear yielding) [21].

Impact testing results: The below Table 4 shows data of izod impact testing (Figure 9).

SENB (Fracture toughness test): These results corroborated the finding of the mechanical testing. The pre-crack produced by slowly pressing the blade presented a distinct pattern close to the pre-crack, which suggests that the displacement fields at that region are affected by a stress state superimposed on the stress state characteristic of the loaded sample. This stress state, supposedly, corresponds to the



Samples	Load (N)	B(mm)	a(mm)	W(mm)	K_{IC} [MPa $m^{1/2}$]	G_c (KJ/mm 2)
Epoxy RT	20	5.68	9	20	1.59	0.006
Thick C.RT	210	5.68	9	20	34.41	0.20
Thin C.RT	310	1.5	9	20	89.78	1.5
Epoxy 77K	25	5.68	9	20	1.912	0.008
Thick C 77K	410	5.68	9	20	31.35	0.39
Thin C. 77K	338	1.5	9	20	97.39	1.63

Table 5: Showing results for samples.

“residual stresses” mentioned in the test standards. The larger K_{IC} values observed in case of carbon Fiber at 77 K by 97.3 MPa $mm^{1/2}$ when this pre-cracking method was used can be justified both as a consequence of these stresses (if they are compressive) and due to the perturbation of the unstable crack propagation, probably with both effects being interrelated. The relevant factor seems to be the state of the polymer during pre-cracking and not during testing. The difference between the carbon fiber/epoxy composites and epoxy composites at 77 K by 98% by the higher content of carbon Fiber. G_c for carbon fiber/epoxy composites for thin specimen at 77 K is 1.63 J/mm 2 as compare to thick CFRP at 77 K i.e 0.39 J/mm 2 . Finally although the plane-strain toughness is the ‘lower-bound’ (conservative) toughness. Different methods can be used to obtain the plane-stress toughness [22].

In the case in which the pre-crack was introduced by slowly pressing the blade a set of concentric lines emanating from a region close to the center of the pre-crack termination line was observed. This suggests that in this case the unstable crack origin was this region, which has the form of a penny shaped crack rather than the termination line of the precrack itself (straight-through pre-crack). This did not occur in the case of the pre-crack introduced by tapping on the blade in which the fracture surface presented features that resembled Hackle lines running perpendicular from the pre-crack termination line. This suggests that, in this case, the entire straight-through pre-crack worked as a nucleus for unstable propagation, as expected (Table 5).

Double cantilever beam method

Matrix-cracking or delamination may occur at cryogenic temperature even with a low-load level due to matrix embrittlement and thermally induced stresses in a structure. Therefore, relaxation of the crack propagation would be a more efficient means of applying composites for cryogenic use. In a point of this technical approach, in this study, mode-I interlaminar fracture toughness was compared in terms of strain energy release rate in the unstable crack propagation region. Table 6 shows the average strain energy release rates of each material system. The Carbon fiber-added composites generally show a higher strain energy release rate than that of the control. Therefore, it can be considered that employing carbon fiber as filler and utilizing carbon Fiber is effective strategies to obtain high fracture toughness at cryogenic temperature. G_c as 4.75 J/mm 2 as compared to room temperature that was 1 J/mm 2 [23].

Simulation

Results using ANSYS 13.0: ANSYS is an engineering tool which develops general purpose analysis. For the specimen under consideration we implemented 2-D crack analysis on rectangular sheet whose dimensions are already discussed under the topic of specimen configuration. Mesh concentration around crack tip is focused by using mesh tool in ANSYS 13.0. Here for LEFM, we solve the fracture mechanics problem for finding stress concentration factor (K).

Assumptions and approach:

- Linear elastic fracture mechanics (LEFM).
- Plane strain problem.
- As we have used LEFM assumption, the SIFs at a crack tip may be computed using the ANSYS KCALC command. The analysis used a fit of the nodal displacements in the vicinity of the crack tip.
- Due to the symmetry of the problem, only a quarter models were analyzed.
- The crack-tip region is meshed using quarter-point(singular) 8-node quadrilateral elements.
- (PLANE82). Since solution for central crack specimen is under consideration, so first on the path related to central crack. The corresponding Stress Intensity for 210 N load is K_{IC} =34.3 MPa $m^{1/2}$ (Table 7) (Figures 10a,10b and 11) [24-26].

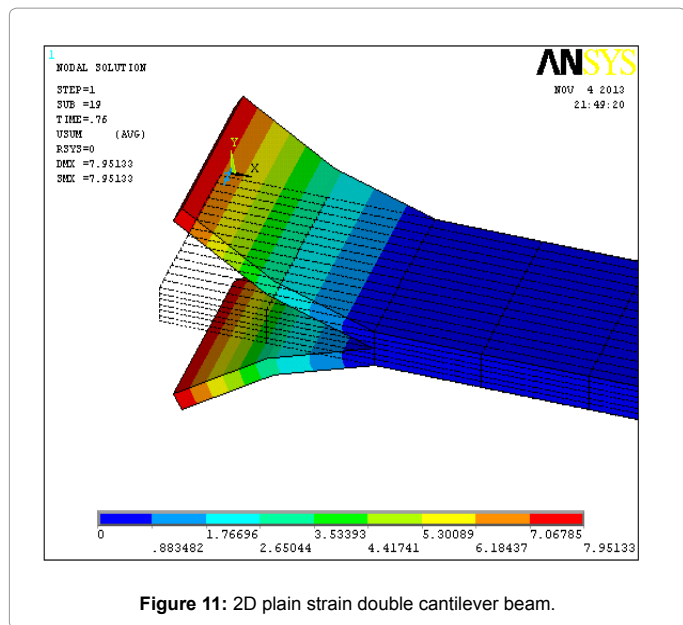
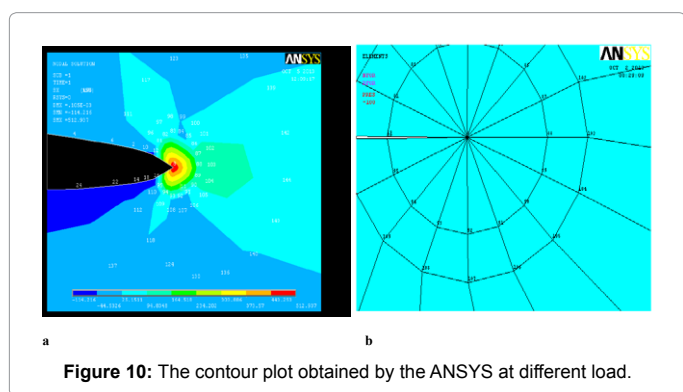
DCB FEM analysis: It was reported that the fracture toughness and the critical energy release rate G_I of the epoxy resin and 1.30 J/mm 2 . The macroscopic fracture toughness was dependent on the fiber orientations, although the same materials are used as matrix and reinforcement fibers with the same volume fraction. The fracture toughness was calculated from the elastic moduli, specimen size, crack length, and the critical load. Assuming that each multi-directional CFRP has constant fracture toughness regardless of the crack length and the specimen size, arbitrary values can be used for the crack length and the

Sample	Load(N)	Displacement	Log(δ/P)	Log(Δa)	n=1.599 slope	G_c (J/mm 2)
Epoxy 77K	300	1.2	-2.393	-0.4685		1.00
C.Thick (77K)	250	2.31	-2.034	-0.221		3.84
C.Thin(77K)	210	3.4	-1.795	-0.096		4.75
Epoxy RT	310	1.5	-2.31876	-0.19864	n=1.43	2.3
C.Thick (RT)	220	2.6	-1.94679	-0.95576		3.9
C.Thin (RT)	200	3.5				4.35

Table 6: Showing displacements for sample.

Samples	Load (N)	B(mm)	a(mm)	W(mm)	K_{Ic} [MPamm ^{1/2}]	G_c (KJ/mm ²)
Epoxy RT	20	5.68	9	20	1.59	0.005
Thick C.RT	210	5.68	9	20	34.31	0.1
Thin C.RT	310	1.5	9	20	89.18	1.1
Epoxy 77K	25	5.68	9	20	1.81	0.004
Thick C.77K	410	5.68	9	20	30.35	0.3
Thin C.77K	338	1.5	9	20	90.39	1.5

Table 7: Showing corresponding stress intensity.



specimen size. The macroscopic fracture toughness of multidirectional CFRP was investigated based on the mesoscopic fracture mechanics. The macroscopic fracture toughness of multi-directional CFRP was experimentally measured by MCC.

The macroscopic fracture toughness was also predicted with the macroscopic FEM model and the mesoscopic FEM sub-model. The tendency of the change of the macroscopic fracture toughness was the same between the experimental results and the prediction, although the difference between the experimental results and the prediction became

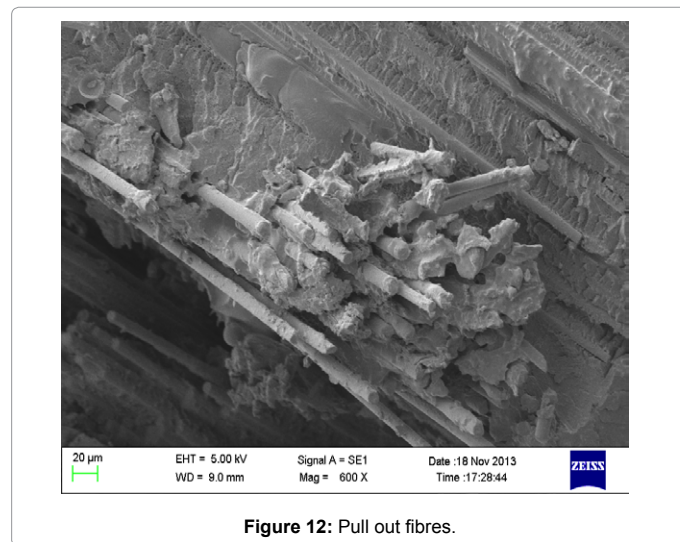
larger with increasing difference in adjacent ply fiber orientation. This may have been caused by the residual stress of the resin matrix phase due to large difference of fiber orientation between 2 layers and further studies are warranted to examine this. It was reported that the mesoscopic fracture toughness decreased when the sub-beam is asymmetric and this caused larger residual stress in the resin matrix DCB results (Table 8) [27].

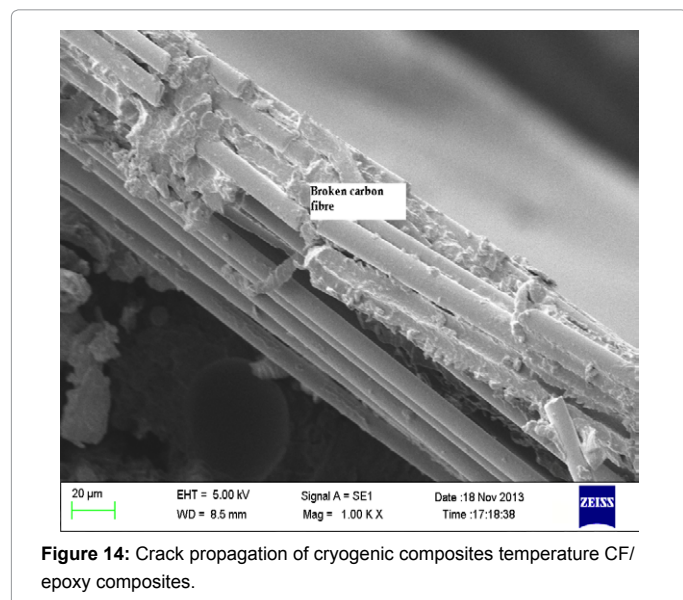
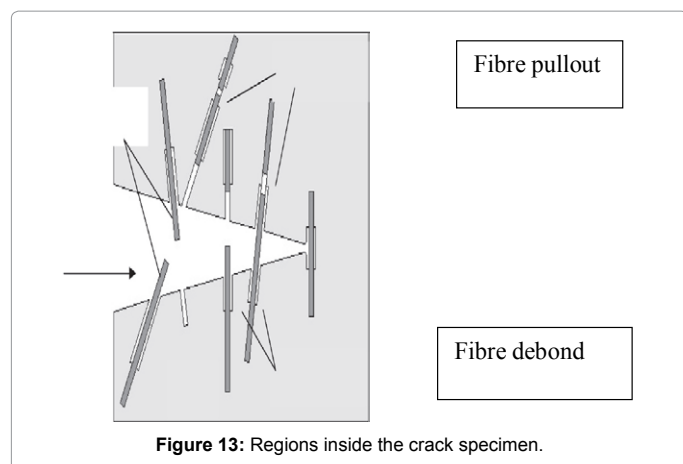
Surface morphology

Scanning electron microscope: The pullout length of carbon fiber is much less than the average length of the carbon fiber, it implies that the fibers fracture firstly and then are pulled out from the matrix during the fracture process. When crack spreads in composites, it need to overcome resistance to through grain boundaries in the matrix, and then crack extends along fiber/matrix interface and overcomes the interfacial shear resistance to make the fibers debond, fracture and pull-out. It can be thought that the interfacial shear stress increases with the increase of the crack opening displacement before fibers are pulled out. Once the fibers fracture, the interfacial shear stress decreases accordingly. In addition, the crack deflection can be found because of the rough fracture surface of composites from figure and it can enlarge the crack surface area. All of these toughening mechanisms can consume fracture energy and improve the fracture toughness of carbon fiber/epoxy composites. It can be found that when the carbon fiber content continues to increase, the fracture toughness decreases due to the increasing number of pores caused by the fiber bridging effect. The pores weaken the bond strength of fiber/matrix interface, and then weaken the energy-consumption ability of carbon fibers which consume fracture energy by fiber debond and pull-out. Figures 12 and 13 shows pullout, crack propagation.

Sample	Load(N)	Displacement	Log(δ/P)	Log(Δa)	n=1.599 slope	G_c (J/mm ²)
Epoxy 77K	300	1.2	-2.393	-0.4685		1.30
C.Thick (77K)	250	2.31	-2.034	-0.221		2.23
C.Thin(77K)	210	3.4	-1.795	-0.096		3.75
Epoxy RT	310	1.5	-2.31876	-0.19864	n=1.43	2.3
C.Thick (RT)	220	2.6	-1.94679	-0.95576		3.9
C.Thin (RT)	200	3.5	-1.73946	-1.16185		2.35

Table 8: Shows DBC results.

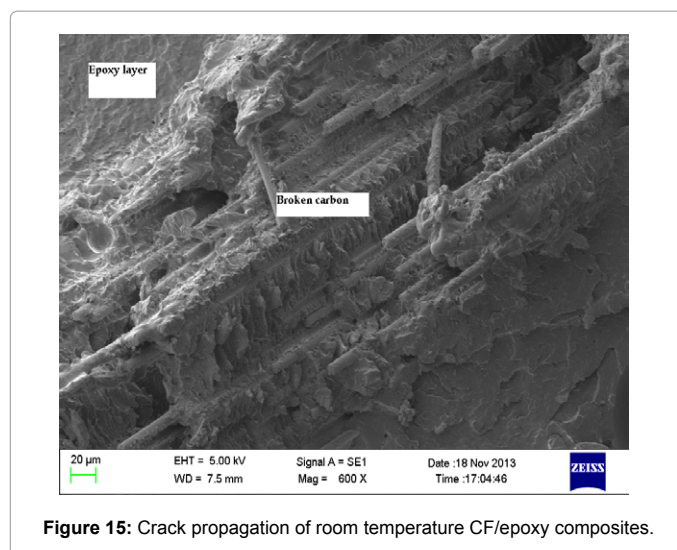




It shows relatively rough fracture surfaces and uneven at both RT and 77 K were clearly observed for the CFRP composites which correspond to the significantly improved fracture toughness. The rough fracture surfaces indicate the deflections of crack propagation, namely the crack paths deviate from their original planes. The porosity increases due to the addition of softener. The shear yielded deformation produces blunting of the crack tip, bringing about the reduction of stress concentration near the crack tip which consequently improves the fracture toughness in case of 77 K sample. As a result, the introduction of softener would effectively improve the fracture toughness of epoxy resins. In addition, the enhancement degree of the fracture toughness at 77 K was higher due to shrinkage, bonding becomes stronger than that at RT is shown in Figures 14 and 15 respectively [28,29].

Conclusion

Carbon Fiber have been employed to enhance the cryogenic mechanical properties of DGEBA/epoxy system modified by flexibilizer. The results showed that tensile strength, impact strength, fracture toughness, fracture energy at 77 K of composites have been simultaneously enhanced with a maximum value. Morphology observation (SEM) showed fracture surface both at 77 K and at



room temperature. Therefore, result shows that carbon fiber have great influence on these entire factor. The tendency of the change of the macroscopic fracture toughness in FEM was the same between the experimental results and the prediction, although the difference between the experimental results and the prediction became larger with increasing difference in adjacent ply fiber orientation.

References

1. Camanho PP (1999) Application of numerical methods to the strength prediction of mechanically fastened joints in composite laminates. University of London, UK.
2. Dávila CG, Johnson ER (1993) Analysis of delamination initiation in post buckled dropped-ply laminates. *AIAA Journal* 31: 721-727.
3. Camanho PP, Matthews FL (1999) Delamination onset prediction in mechanically fastened joints in composite laminates. *Journal of Composite Materials* 33: 906-927.
4. Davies P, Blackman BRK, Brunner AJ (1998) Towards standard fracture and fatigue test methods for composite materials. *Proceedings of the 6as Jornadas De Fractura, Sociedade Portuguesa de Materiais, Portugal* 151-167.
5. O'Brien TK (1998) Interlaminar fracture toughness: The long and winding road to standardisation. *Composites-Part B: Engineering* 29: 57-62.
6. O'Brien TK, Martin RH (1993) Round robin testing for mode I interlaminar fracture toughness of composite materials. *Journal of Composites Technology and Research* 15: 269-281.
7. Morais AB, Marques AT, Castro PT (2000) Estudo da aplicação de ensaios de fractura interlaminar de modo I a laminados compósitos multi direccionais. *Proceedings of the 7as Jornadas De Fractura, Sociedade Portuguesa de Materiais, Portugal*.
8. Choi NS, Kinloch AJ, Williams JG (1999) Delamination fracture of multidirectional carbon-fibre composites under mode I, mode II and mixed-Mode I/II loading. *Journal of Composite Materials* 33: 73-100.
9. Williams JG (1989) The fracture mechanics of delamination tests. *Journal of Strain Analysis* 24: 207-214.
10. Robinson P, Song DQ (1992) A modified DCB specimen for mode I testing of multidirectional laminates. *Journal of Composite Materials* 26: 1554-1577.
11. Kageyama K, Kikuchi M, Yanagisawa N (1991) ASTM STP 1110. American Society for Testing and Materials.
12. O'Brien TK (1998) Composite interlaminar shear fracture toughness, GIIC: Shear measurement of sheer myth? ASTM-STP 1330, American Society for Testing and Materials.
13. Corleto CR, Bradley WL (1993) Correspondence between stress fields and damage zones ahead of crack tip of composites under mode I and mode II

- melamination. Proceedings of the 6th International Conference on Composite Materials (ICCM-6) 3: 378-387.
14. Lee SM (1993) An edge crack torsion method for mode III delamination fracture testing. *Journal of Composites Technology and Research* 15: 193-201.
15. Li J, O'Brien TK (1996) Simplified data reduction methods for the ECT test for mode III interlaminar fracture toughness. *Journal of Composites Technology and Research* 18: 96-101.
16. Li J, Wang Y (1994) Analysis of a symmetric laminate with mid-plane free edge delamination under torsion: Theory and application to the Edge Crack Torsion (ECT) specimen for mode III toughness characterization. *Engineering Fracture Mechanics* 49: 179-194.
17. Crews JH, Reeder JR (1988) A mixed-mode bending apparatus for delamination testing. NASA TM 100662.
18. Reeder JR, Crews JH (1991) Nonlinear analysis and redesign of the mixed-mode bending delamination test. NASA TM 102777.
19. Rybicki EF, Kanninen MF (1977) A finite element calculation of stress intensity factors by a modified crack closure integral. *Engineering Fracture Mechanics* 9: 931-938.
20. König, M, Krueger R, Rinderknecht S (1995) Numerical simulation of delamination buckling and growth. Proceedings of the 10th International Conference on Composite Materials (ICCM-10), Whistler, Canada.
21. Krueger R, O'Brien TK (2001) Ashell/3D modeling technique for the analysis of delaminated composite laminates. *Composites Part A: Applied Science and Manufacturing* 32: 25-44.
22. Krueger R, Minguet PJ, O'Brien TK (1999) A method for calculating strain energy release rates in preliminary design of composite skin/stringer debonding under multi-axial loading. *Composite structures: Theory and practice*, ASTM STP 1383: 105-128.
23. Raju IS, Crews JH, Aminpour MA (1988) Convergence of strain energy release rate components for edge-delaminated composite laminates. *Engineering Fracture Mechanics* 30: 383-396.
24. Rinderknecht S, Kroplin B (1994) Calculation of delamination growth with fracture and damage mechanics. *Recent Developments in Finite Element Analysis*, CIMNE, Barcelona, Spain.
25. Dugdale DS (1960) Yielding of steel sheets containing slits. *Journal of Mechanics and Physics of Solids* 8: 100-104.
26. Barenblatt GI (1962) Mathematical theory of equilibrium cracks in brittle failure. *Advances in Applied Mechanics* 7: 55-129.
27. Hilleborg A, Modeer M, Petersson PE (1976) Analysis of crack formation and crack growth in concrete by fracture mechanics and finite elements. *Cement and Concrete Research* 6: 773-781.
28. Ye X, Liu T, Ye Y (2015) Enhanced grain refinement and micro hardness of Ti-Al-V alloy by electropulsing ultrasonic shock. *Journal of Alloys and Compounds* 621: 66-70.
29. Ye X, Yang Y, Tang G (2014) Microhardness and corrosion behavior of surface gradient oxide coating on the titanium alloy strips under high energy electropulsing treatment. *Surface and Coatings Technology* 258: 467-484.