INTRALAMINAR FRACTURE TOUGHNESS OF COMPOSITE LAMINATES – A NUMERICAL AND EXPERIMENTAL STUDY

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A numerical and experimental study of modo-I intralaminar fracture toughness of composite laminate using CT specimen configuration is presented in this paper. Four data reduction scheme was used to calculate the fracture behavior of material, namely; Energy Area Method, Compliance Calibration Method, J-Integral Method and ASTM E399 Standard test. The limitation of standard ASTM E399 for isotropic materials was presented and a new geometric correction function was proposed by numerical evaluation the strain energy release rate based on the J-Integral numerical method. A difference between the methods was presented and the main advantages and disadvantages were discussed.

***Keywords**: laminated composites, intralaminar, fracture toughness.*

1. INTRODUCTION

In laminated composites structures the mode-I intralaminar fracture toughness (K_{IC}), material resistance to unstable crack propagation way, plays a key role in determining the damage tolerance of the structure and its response during the propagation. The current numerical models for predicting this behavior are closely related to the value of fracture toughness, because in spite of representing a value of resistance, their determination is the basis for the identification of parameters used in simulations of fracture of these materials. Therefore, to characterize the damage tolerance of composites, there is a need for reliable experimental procedures in order to obtain their fracture toughness and the methodology applied should not have large variations in results, Laffan et al. (2010).

The first study reporting differences between the values of K_{IC} obtained by finite element analysis (numerical method) and experimental results was published by Jose et al. (2001). Using Compact Tension specimens (CT), the author obtained experimentally values of K_{IC} by ASTM E399 (1997) standard. Simultaneously, finite element models were performed by software MSC / NASTRAN and K_{IC} values were estimated using the numerical method MCCI (Modified Crack Closure Integral Method). The authors noticed that for orthotropic laminates a significant difference between values of K_{IC} was observed and this non-trivial difference showed that K_{IC} proposed by ASTM E399-90 for isotropic materials was not suitable for orthotropic materials such as laminated composites. This work represented an important milestone for future researchers, because their results showed the erroneous way that was being conducted for determination of intralaminar fracture toughness for composites. Based on previous work and attempts to overcome the problem of data reduction proposed by ASTM E399, Pinho et al. (2006) investigating the mode-I intralaminar fracture toughness associated with fiber-breaking performed several numerical models with different crack lengths, 1 mm thick subjected to 1 N load level. A normalized curve of the strain energy release rate (G_{IC}) obtained by J-integral method was created and a function of J-integral versus crack length, normalized, was proposed. Through this function and the critical load for each crack length the authors were able to estimate toughness values correctly on form of critical energy. Later, Donadon et al. (2007) investigated experimentally and numerically the mode-I intralaminar fracture toughness of a hybrid laminated. The numerical results obtained the J-integral method correlated well with the experimental results obtained by the compliance calibration method (CC). A good agreement was also obtained between the results of ASTM E399-90 and CC method for initial values of crack, but for propagation values was observed that the results of ASTM E399-90 exceeded both the numerical and experimental results. The author tried to overcome this problem proposing a method based on J-integral to estimate a new geometric correction function that takes into account the orthotropic effects. A new resistance curve was generated by ASTM E399-90 with the new polynomial and a good agreement between numerical and experimental results was found confirming the methodology used to estimate geometric correction function.

Recently, other authors have proposed methods to estimate the values of fracture toughness without the need to measure the crack length during the experiments, namely; Moura et al. (2009) proposed a method based on the equivalent crack length, Compliance Based Beam Method (CBBM), Laffan et al. (2010) used various numerical models with different crack lengths and set a polynomial representing the compliance of system, so it was created the Modified Compliance Calibration Method (CCM). Later, Catalanotto et al. (2010) used a system of Digital Image Correlation to identify the crack tip and subsequent post-processing of data to estimate its length. The authors mentioned that methodologies that do not require monitoring of crack length during testing eliminates errors during the data reduction and are more accurate when compared with one.

This paper presents a numerical and experimental study of the mode-I intralaminar fracture toughness of a composite laminate carbon/epoxy material system using the CT specimen configuration. The limitation of standard

ASTM E399 for isotropic materials is presented and a new geometric correction function is proposed by numerical evaluation the strain energy release rate based on the J-integral numerical method. Four methods of data reduction scheme were investigated for intralaminar toughness calculation; ASTM E399 with a new derived polynomial, J-integral based numerical method, Compliance Calibration and Area Method. A comparison between the methods was presented and the main advantages and disadvantages were discussed. A good agreement between the different methods was obtained. Based on this information, it was concluded that the methodologies used to estimate the mode-I intralaminar fracture toughness are valid for the material in question only.

2. MATERIALS AND MANUFACTURE

The raw material used to manufacture the laminated composite consisting of woven fabrics of carbon supplied by Torayca ® and epoxy based resin Araldite LY 5052 supplied by Huntsman ®. The fabrics under designation namely CO6151B is composed by carbon fibers T300B-1000 on the both direction weft and warp. Four unidirectional composites plates, lay- ups shown by Tab 1, were manufactured by hand lay-up method and subsequently cured in a vacuum bag with 1 atm pressure at room temperature during six hours.

Table 1: Lay-ups

Lay-up	Teste caracterization
$[0]_{12}$	Tension – Mechanics
$[0]_{10}$	Compression – Mechanics
$[0]_{12}$	Shear - Mechanics
$[0]_{40}$	Compact Tension – Fracture Mechanics

All plates were C-scanned in order to assess the final quality of the composites. According to the C-Scan images the plates shown few regions with manufacturing defects such as voids. After the composite manufacturing quality assessment the specimens were cut using a diamond disc-saw in appropriate sizes to form the samples as shown by Fig 1. The black arrows indicate the load line.

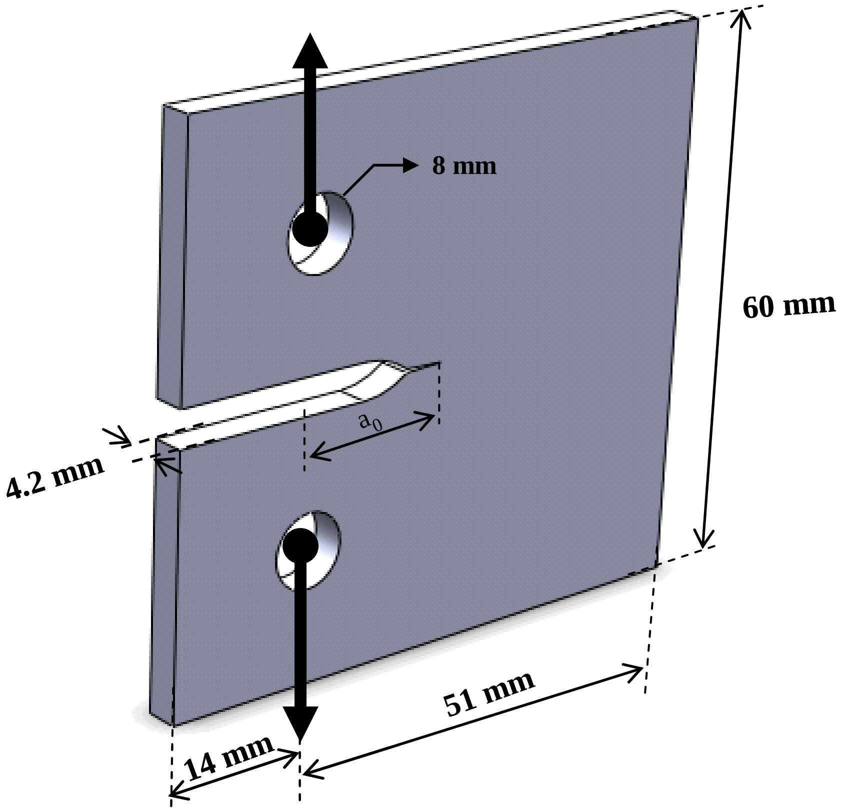


Figure 1. Dimensions of CT specimen

The material properties used for the data reduction were obtained using standard tests, ASTM 3039 (2008), ASTM 3410 (2008), ASTM 3548 (2008) and are presented in Tab.2 and Tab.3 in the principal material axes.

Table 2: Experimental moduli

Property	E_1^t [MPa]	E_2^t [MPa]	G_{12} [MPa]	E_1^c [MPa]	E_2^c [MPa]
Valor	48700	48700	2800	48700	48700
C.V (%)	3.96	3.96	9.73	3.96	3.96

Table 3: Experimental strengths

Property	F_1^{tu} [MPa]	F_2^{tu} [MPa]	F_{12}^u [MPa]	F_1^{cu} [MPa]	F_2^{cu} [MPa]
Valor	552.55	552.55	47	271.35	271.35
C.V (%)	3.12	3.12	5.21	6.99	6.99

Where E and G are the elasticity and shear module, respectively. F_{ij}^k are the stress strengths and the subscripts 1 and 2 indicate the 1 and 2 directions of the laminated. The subscript 12 indicates the shear direction, the superscripts k=t and k=c indicate the tension and compression strengths, respectively. The superscript u indicates ultimate strength. For this material, the Poisson's coefficient is about 0.0275.

A three step procedure was used to produce the sharp crack tip in the CT specimens. First a ~4 mm notch thick of approximately 30mm length was machined using a diamond disc-saw, second the notch was then extended to 35mm using a 1.5mm thick steel saw blade and finally a 0.2 mm thick razor blade shaving was used to further sharpen the notch-tip in a sawing motion. The quality of the crack tip was evaluated with the aid of the Stereoscope and a typical micrograph illustrating this quality is shown in the Fig 2.

Figure 2. Crack tip quality.

3. TEST METHOD AND EXPERIMENTAL SETUP

The CT specimens were tested using a Instron Machine Test, model 5500R, equipped with a 30kN load cell. All specimens were loaded under displacement control at a rate of 0.2mm/min. The measurements of load and cross-head displacement ware recorded by using an Instron built in data acquisition system. A square region in front of the crack tip was white painted. Then, stripes patterns were streaked perpendicularly to the crack tip with 1mm spacing to form a 20mm scale rule for the crack length monitoring. A camera connected with a monitor was used to view a magnified image of the area of the specimen containing the crack length monitoring. An event marker connected to the data logger was used to recording the crack growth during the test. The experimental setup for measuring the intralaminar fracture toughness using CT specimen is shown in Fig. 3.

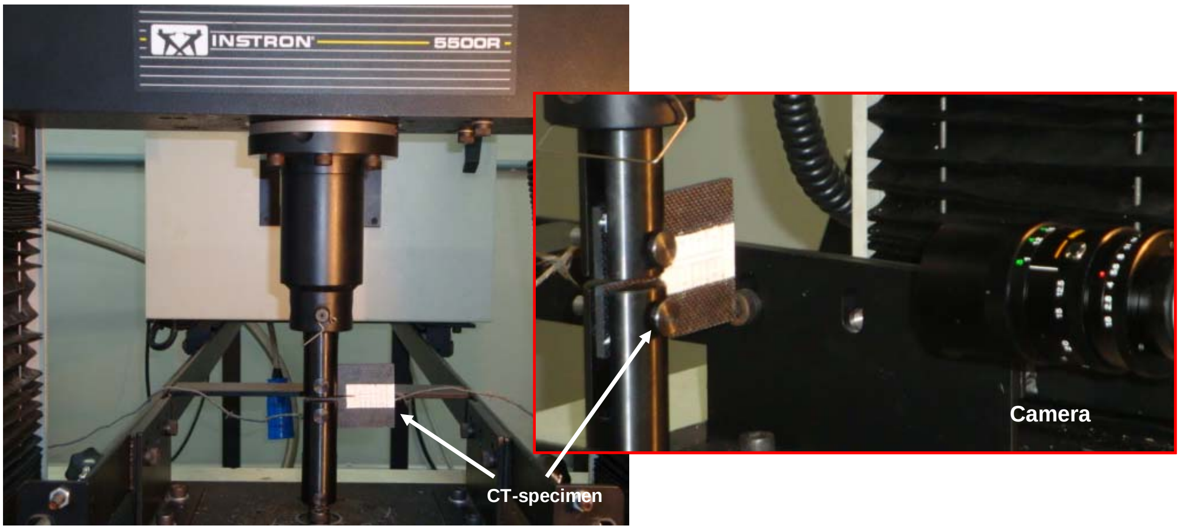


Figure 3. Experimental setup for CT specimen.

At the same time, numerical simulations were carried out in order to calculate G_{IC}, numerically, according methodology described in the next 4.3 section for different cracks lengths. Only half of the specimen was modeled due to the symmetry of the CT specimen. The model was meshed with uniform square 8-node quadratic shell elements (S8R5) available in ABAQUS software (ABAQUS, 2010). To avoid contact modeling between the loading pins and the CT body the load was uniformly distributed along the loading line of CT specimen. A finer mesh was assigned to the crack tip region (element size with 0.25mm) in order to obtain an accurate behavior in this region. The material used in the model and lay-up were given by Tab1, Tab2 and Tab3. The crack feature was assigned on the end point of the symmetric boundary and its direction was assumed to be normal to the loading line indicated by q vector. The simulations were performed to all crack lengths and respective critical loads experimentally obtained. Eight integral contours for each crack length were used. The finite element model setup is showed by Fig 4.

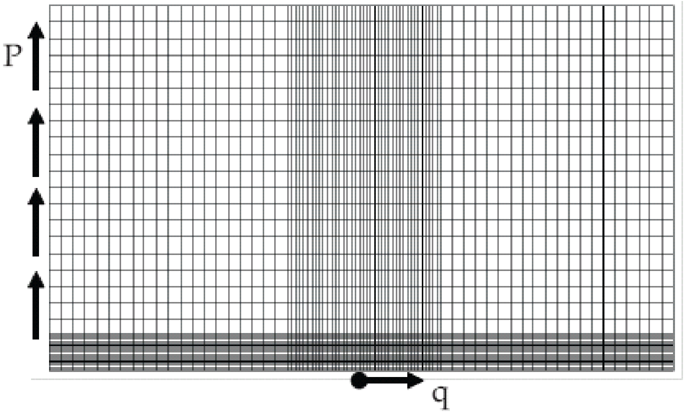


Figure 4. Finite element model setup.

4. DATA REDUCTION

No data reduction scheme for modo-I intralaminar fracture toughness characterization of laminated composites is currently available. Some researchers have used tests standards from ASTM E399 of the isotropic materials to calculate stress intensity factor to characterize the toughness of the laminated using CT specimen.

Usually the fracture behavior of materials is expressed in terms of critical strain energy release rate which represents the energy required for crack growth.

The G_{IC} of the orthotropic laminated plate with the pre-crack under mode-I loading can then be calculated from K_{IC} according to Paris et al. (1960) by Eq.(1);

$$G_{IC} = \frac{K^{2}{}_{IC}}{E^{*}} \tag{1}$$

Where E^* is the equivalent module of laminated given by Eq.(2);

$$E^* = \frac{\sqrt{2E_1E_2}}{\sqrt{\sqrt{\frac{E_1}{E_2}} - \nu_{12} + \frac{E_1}{2G_{12}}}} \tag{2}$$

Four data reduction scheme are used in this work. The limitation on the applicability of the standard dada reduction scheme from ASTM E399 for laminated composites is presented and a new geometric correction function to calculate K_{IC} is derived by J-integral method.

4.1 Area method

For the energy area method, the change of strain energy in the material can be calculated using the area under the load-displacement curve from the loading point 1 to 2 as shown in Fig. 5.The crack length that changes by a value Δa represents the dissipated energy during the crack propagation and is indicated by shaded region.

This method is among the simplest method of data reduction. The critical strain energy released can be calculated by Eq. (3);

$$G_{IC} = \frac{1}{2.t.\Delta a}(P_1 d_2 - P_2 d_1) \tag{3}$$

Where P_1, P_2 are loads and d_1, d_2 are displacements at the points 1 and 2, respectively.

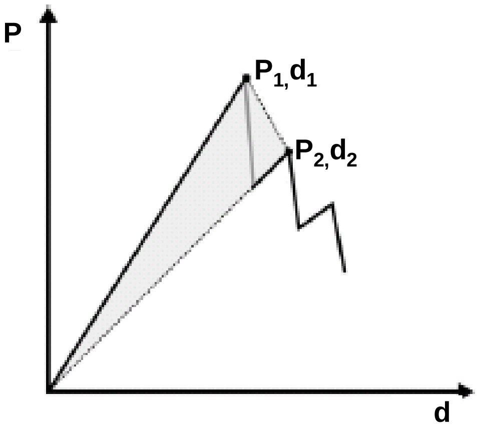


Figure 5. Load x displacement curve of area method.

4.2 Compliance calibration method

The critical strain energy release rate can be calculated using the change in compliance, C, with crack length, a, by Eq. (4), as Anderson (2005);

$$G_{IC} = \frac{P_c^{\,2}}{2h}\frac{\partial C}{\partial a} \tag{4}$$

Where P_c is the critical load associated with a given crack length and h is the thickness of the specimen. This method requires the elastic compliance of the specimen at each optically measured crack length that can be determined from the load displacement curve. The experimental C vs. a data need to be plotted and the best fit function should be found.

4.3 J-Integral melhod

For a linear orthotropic material under mode-I loading the G_{IC} can be equated with the J-integral proposed by Rice (1968). Some commercial finite element packages have numerical solution for prediction of this parameter. In this work, ABAQUS Standard version 6.10, ABAQUS (2010) was used to calculate the J-integral associated with intralaminar fracture toughness for composites. The software provides a calculation procedure for J-integral based on the virtual crack extension/domain (J-integral based method). The method requires two input parameters: Load and Crack tip assignment. In this case, the critical load and its respective crack length were obtained by tests results performed on the Instron Machine.

4.4 ASTM E399

The ASTM E399 testing standard valid for isotropic materials gives the critical stress intensity factor for CT specimen by Eq. (5);

$$K_{IC} = \frac{P_c}{h\sqrt{w}} f(a/w) \tag{5}$$

Where f (a/w) is the geometric correction function given by Eq. (6);

$$f(a/w) = \frac{2 + a/w}{(1 - a/w)^{1.5}} [0.886 + 6.64(a/w) - 13.32(a/w)^2 + 14.72(a/w)^3 - 5.6(a/w)^4] \tag{6}$$

The methodology proposed by Donadon et al. (2007) for derivation of a new geometrical correction function consists of the following steps;

- Calculation of J-integral for each different critical load, P_c, and respective crack length, a_i.
- Calculation of K_{IC} for each J previously calculated by inverse relation of Eq. (1) given by Eq. (7);

$$K_{IC} = \sqrt{E^*.J} \tag{7}$$

- Calculation of the new geometric correction function, f(a), by inverse relation of Eq. (5) given by Eq. (8);

$$f(a) = \frac{K_{IC} h\sqrt{w}}{P_c} \tag{8}$$

5. RESULTS

All the CT specimens were tested and the load, displacement and crack length were recorded during tests. A typical load-displacement curve and compliance curve are shown in the Fig. 6. All specimens exhibited stick-slip crack growth during testing. The cracks jumps from 3 to the 5mm each time and the specimens were loaded until the crack reached the final edge of the CT specimen.

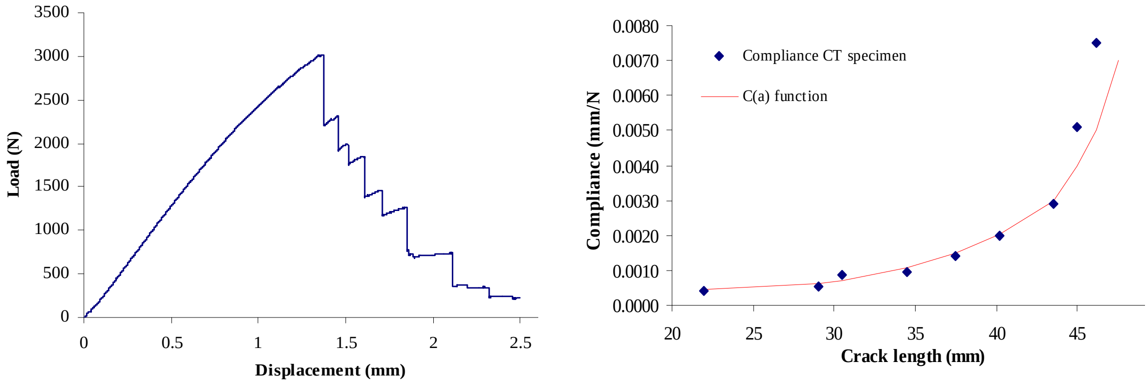


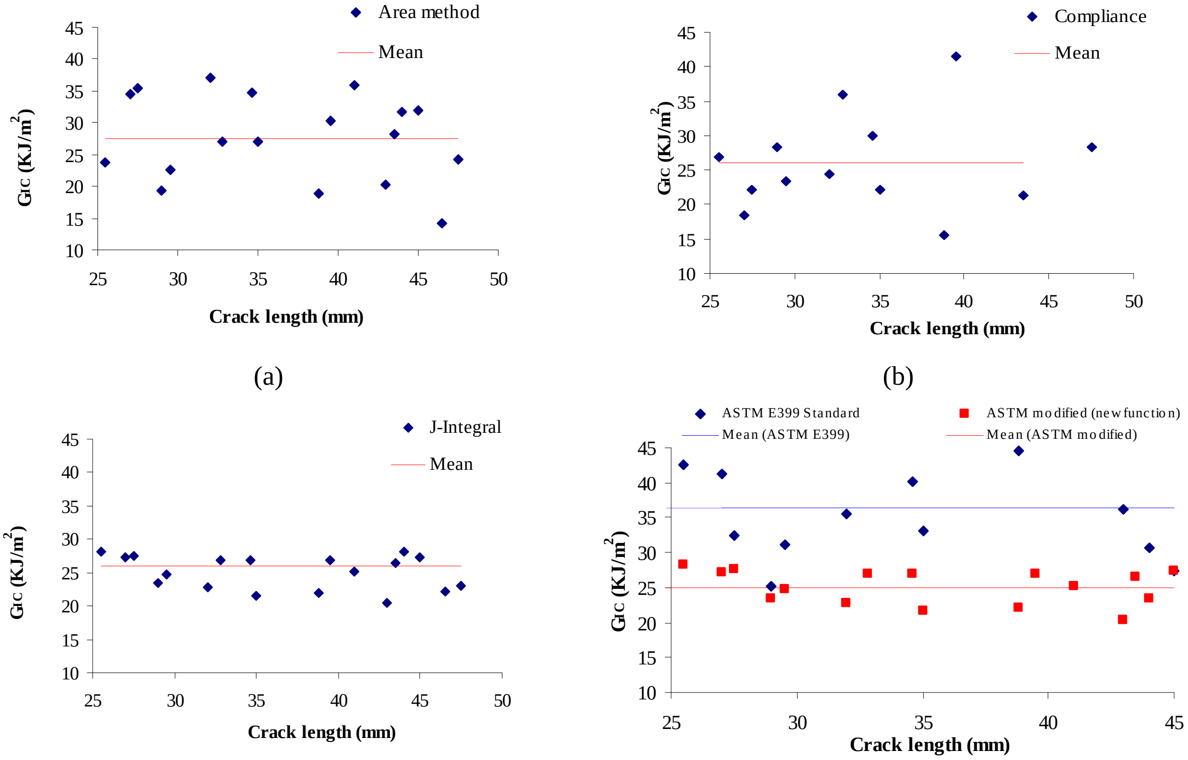
Figure 6. Typical load vs. displacement curve and Compliance curve for CT specimen

The best fit for the discrete points of the compliance versus crack length curves was represented by a polynomial cubic relationship as Eq. (9);

$$C(a) = c_1.x^3 + c_2x^2 + c_3x + c_4 \tag{9}$$

Where the best fit coefficients were $c_1 = 2{,}497\text{x}10^{-7}$, $c_2 = -1{,}736\text{x}10^{-5}$, $c_3 = 4{,}244\text{x}10^{-4}$ and $c_4 = -3{,}143\text{x}10^{-3}$, respectively. For this fit, the least square method was used.

The critical strain energy release rates of the CT specimen were computed through the four data reduction scheme previously described in section 4. The results are shown in Fig. 7.



(a) (b)

(c) (d)

Figure 7. G_{IC} vs. crack length by: (a) Area Method. (b) Compliance Calibration Method. (c) J-Integral Numerical Method. (d) ASTME399 Standard with typical and new geometric correction function.

Based on the methodology provided by Donadon et al. (2007) a new geometric correction function was derived and the Fig. 8 shows the difference between the ASTM geometric correction and the geometric correction function obtained using the procedure described in section 4.4. The higher values of G_{IC} obtained using the standard ASTM method are mainly due to the geometric correction employed. This result shows that finite geometric correction function provided by ASTM E399 isn't suitable for orthotropic materials and its use overestimates the fracture toughness values of these materials which can significantly overestimate the damage tolerance behavior of composites structures.

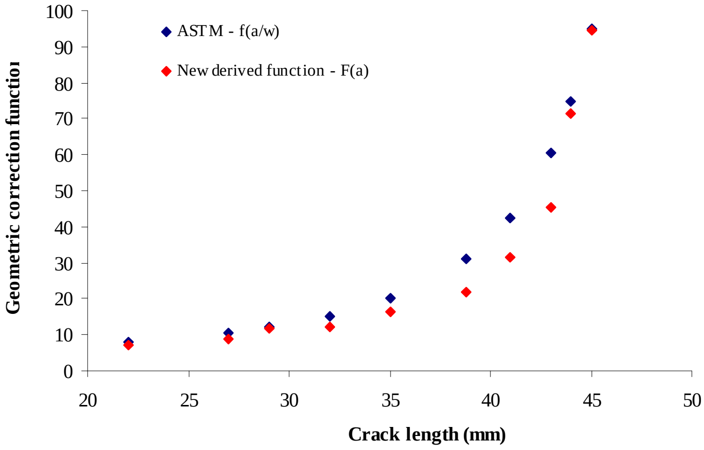


Figure 8. Geometric correction function vs.crack length

The difference between the mean values of critical energy release rate computed using the four data reduction schemes previously presented in section 4 is shown in Fig. 9;

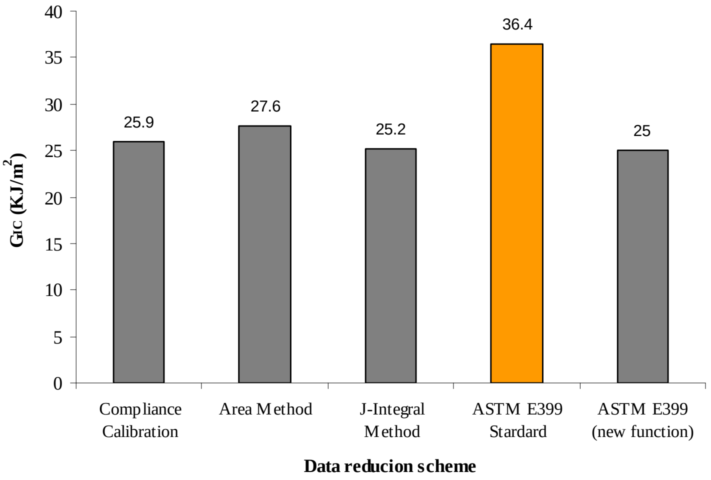


Figure 9. Mean modo-I intralaminar fracture toughness values by different methods.

6. CONCLUSIONS

This paper presented a detailed description on test methods and data reduction schemes to characterize the mode I intralaminar fracture toughness for composite materials. The main conclusions of the present paper are:

- The ASTM E399 significantly overestimates the intralaminar fracture toughness of composite laminates, as shown in Fig. 9 in orange color. Thus, the method in its original form is not suitable for orthotropic materials;
- The orthotropic effects play an important role in the fracture toughness evaluation of composite laminates;
- The methodology described in section 4.4 used to derive the new geometric function leads to a more realistic prediction of the intralaminar fracture toughness of composites. The method also accounts for orthotropic effects and can be extended to different specimen geometries;
- The energy area method is the simplest method to evaluate G_{IC} for composites and this represents an advantage over other methods;
- The fitting process used together with the compliance method may lead to a significant scatter in results. There is a significant difficulty on the fitting the best polynomial and this represents a disadvantage for this method;
- The values of G_{IC} obtained using the J-integral method showed a lower scatter when compared to compliance, area method and modified ASTM data reduction schemes. ;
- A very good correlation between compliance, area method, J-integral and modified ASTM data reduction scheme was found. A small scatter between the average values of G_{IC} from these methods was found.

7. REFERENCES

Abaqus 6.10.3 software e Manual teórico, 2010.

ANDERSON, T.L, Ph.D. Fracture Mechanics: Fundamentals and applications. 3.ed. London: Taylor & Francis, 2005. 611p.

AMERICAN SOCIETY FOR TESTING AND MATERIALS. ASTM E399-90: Standard test method for plain-strain fracture toughness of metallic materials. Annual Book of ASTM Standards 1997, 03.01: 407-528.

AMERICAN SOCIETY FOR TESTING AND MATERIALS. ASTM D3039/D 3039M-08. Standard test method for Tensile Properties of Polymer Matrix Composite Materials. Annual Book of ASTM Standards 2008.

AMERICAN SOCIETY FOR TESTING AND MATERIALS. ASTM D3410/D 3410M-08. Standard test method for Compressive Properties of Polymer Matrix Composite Materials with Unsupported Gage Section by Shear Loading. Annual Book of ASTM Standards 2008.

AMERICAN SOCIETY FOR TESTING AND MATERIALS. ASTM D3518/D 3518-94. Standard test method for In-Plane Shear Response of Polymer Matrix Composite Materials by Tensile Test or a +/- 45º Laminates. Annual Book of ASTM Standards 2008.

AMERICAN SOCIETY FOR TESTING AND MATERIALS. ASTM E1922-04. Standard test method for Translaminar Fracture Toughness of Laminated and Pultruded Polymer Matrix Composite Materials. Annual Book of ASTM Standards 2004.

Camanho, P.P., Catalanotti, G., Xavier, J., Dávila, G.G., Marques, A.T., Measurement of resistance curves in the longitudinal failure of composites using digital image correlation. Composites Science and Technology 2010(70)1986:1993

Donadon, M.V., Falzon, B.G., Hodgkinson, J.M., Iannucci, L., Intralaminar toughness characterization of unbalanced hybrid plain weave laminates. Composites Part A 2008(38):1597-1611.

Iwamoto, M., Ni, QQ., Fujiwara, T., Kurashiki, K., Intralaminar fracture mechanism in unidirecional CFRP composites. Part I: Intralaminar toughness and AE characteristics. Engineering Fracture Mechanics 1999(64):721-745.

Jose, S., Kumar, R.R., Jana, M.K., Rao, G.V., Intralaminar Fractures Toughness of a cross-ply laminate and its constituent sub-laminates. Composites Science and Technology 2001(61):1115-22.

Laffan, M.J., Pinho, S.T., Robinson, P., Iannucci, L., Measurement of the in situ ply fracture toughness associated with mode I fibre tensile failure in FRP. Part I: Data reduction. Composites Science and Technology 2010(70):606-613

Moura, M.F.S.F., Campilho, R.D.S.G., Amaro, A.M., Reis, P.N.B., Interlaminar and intralaminar fracture characterization of composites under mode l loading. Composites Structure 2009.

Paris, P.C., Sih, C.G., Stress analysis of cracks, fracture toughness and applications. SPT-381. ASTM; 1960:30-83.

Pinho, S.T., Robinson, P., Iannucci, L., Fracture toughness of the tensile and compressive fibre failure modes in laminated composites. Composites Science and Technology 2006(66):2069-79.

Rice, J.R., A Path Independent Integral and the Approximate Analysis of Strain Concentration by Notches and Cracks. Jornal of Applied Mechanics, Vol. 35, 1968, pp. 379-386.

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