NUMERICAL MODELING OF DELAMINATION IN WOVEN COMPOSITES

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Abstract

The aim of this paper was to provide modeling and numerical analysis of delamination for increasingly complex woven reinforced composites. Modeling of the woven reinforced composite due to the existence of the weft and warp filaments of fibers was a significant part of this research. The FEM model of the unit-cell provided the required results of strain energy release rate with a low volume of computation. The computed loads by FEM were put in derived equations of the fracture toughness (G_c). The obtained numerical results showed the growth of delamination along the weft filaments and a sudden change in the point of crossing the weft filament. The curves drawn with the answers of finite element method showed that, usage of singular elements for modeling of crack tips will give us the best answer comparing with brick elements.

1 Introduction

Woven reinforced composites are becoming increasingly popular for a variety of applications in among many other fields, civil engineering, architecture and aerospace engineering. Typical examples include membrane roofs and covers, sails, inflatable buildings and pavilions, airships, inflatable furniture, airspace structures etc [1]. The higher coefficient of thermal expansion of this composite comparing to others is its specific physical property which advantages it in applications [2]. The utility of woven composites in industrial application has been shown by too many authors [3-5].

However, woven reinforced laminates due to the interlaminar stresses are quite susceptible to transverse cracking and delamination [6]. The characterization and modeling of fracture behavior is thus highly relevant for the design of composite parts.

There is different methods to weave the fibers in woven reinforced composites from which, due to the variation of the radius of curvature, the properties of the composite is resulted [7], either the influent role of adhesion between fibers and matrix in the stiffness of the woven composites is underlined [8].

Lee et al [9] had analyzed the fracture in woven composites by modeling and comparing with the unidirectional composite. They had proposed a non-linear model with an inelastic fracture, even though the behavior of woven layers in weft and woof directions was considered elastic.

Kim et al [7] had examined the pressure strength of the woven composites. They concluded that the critical stress which leads to delamination was lower than the stress leading to micro buckling of fibers. Thus so the pressure strength of woven composites is based on delamination.

Abot et al [10] had shown that the pressure strength in weft direction and woof direction were the same and they were equal to the half of the pressure strength of the unidirectional composite in fibers direction. Either the Poisson ratio in this composite is neglected because the nature of this material is so that tensile in both weft and woof directions are the same.

Pandita et al [11] had studied the influence of the loading direction, stress concentration at the crack tip and ductility of the matrix on fatigue behavior of woven composites. They underlined that the fatigue characteristics are highly influenced by loading direction. They observed that for a loading in the weft or woof direction, the fracture of fibers was predominant and for a loading out of those directions the fracture of matrix occurred in first.

Iannucci et al [12] had modeled each woven layer by two unidirectional layers situated in perpendicular of each other and the thickness of each was the half of the woven layer.

The influence of the kind of woven layers on the critical strain energy release rate (G_{IC}) using the compliance method has been studied by Kim et al [13], which corresponds to the shape of the created crack in woven composites. In the Plain woven composites, the crack follows a very winding way, even though in Satin woven composites this way is quite linear. Also for the Plain woven composite the roughness of the crack tip is higher comparing to Satin or Twill woven composites.

2 Material

The glass fiber reinforced composite with a fiber fraction volume of 60% was used. The thickness of each ply was 0.125 *mm*. Each test bar had 24 plies. The mechanical characteristics of this composite for its unidirectional ply are presented in Table 1 in which XY is the plan of the woven and Z is the normal axle to the plan.

Table1: Mechanical properties of the composite

Young modulus	$E_{XX} = E_{YY} = 20\ GPa$ $E_{ZZ} = 12\ GPa$
Poisson ratio	$\nu_{XY} = \nu_{YZ} = 0.13$ $\nu_{XZ} = 0.3$
Shear modulus	$G_{XY} = 2.85\ GPa$ $G_{YZ} = G_{XZ} = 1.9\ GPa$

Dimensions of test bars were: 150 *mm* × 25 *mm* and height of 3 *mm*. A Teflon film was included at the mid-plane thickness to initiate the delimitation.

3 Governing equations

The concepts of linear elastic fracture mechanic (LEFM) normally applied to homogeneous isotropic materials are also valid for composite materials. In this case, the strain energy release rate (SERR) presented by G_c may be used to characterize the toughness of composites materials [14].

$$G_I = \frac{P^2}{2B}\frac{dC}{da} \quad (1)$$

Where:

$$C = \frac{\delta}{P} \quad (2)$$

Following relations are obtained from relation (1).

• Berry relationship [15]

$$G_I = \frac{nP\delta}{2Ba} \quad (3)$$

By computing n using beam theory:

• Beam theory (BT)

$$G_I = \frac{3P\delta}{2Ba} \quad (4)$$

• Corrected beam theory (CBT) [16]

$$G_I = \frac{3P\delta}{2B(a+|\Delta|)} \quad (5)$$

By computing C using beam theory and introducing in relation (1):

• Compliance beam theory (CBT1)

$$G_I = \frac{12P^2a^2}{EB^2h^3} \quad (6)$$

In above relations different parameters are:

a	Crack length
B	Width of specimen
C	Compliance of specimen
E	Young's modulus
G_I	Strain energy release rate in Mode I
G_{IC}	Critical SERR (fracture toughness)
h	Specimen height
I	Moment of inertia of one half beam
n	Exponent of "a" in the empirical relation "$C=\beta a^n$"
P	Applied load
δ	Opening of specimen
Δ	Correction applied in the crack length

4 Modeling of woven sheet

The modeling of the woven reinforced composite caused many difficulties because of the existence of the weft and woof filaments of fibers and the method of modeling is a significant part of this research. The Line and Key point command was used for making of the section of the filaments which were then extruded to obtain a line of filament.

Due to the difference of structure of woven composite comparing to unidirectional one, the Ansys software [17] has not a specific method to modeling of woven composite. Hence, for modeling of this kind of composite we have suggested to do following steps.

1. Modeling of the periphery of the set of fibers in X-Y coordinates using four arcs with radius

of 0.9 mm conform to the geometrical characteristics of specimen.

2. Making of the cross section of set of fibers using above mentioned arcs.
3. Extruding of the cross sections in Z direction to make wefts.
4. Making of the cross section of the first woofs in X-Z plane in above of weft fiber.
5. Modeling of the directing line of the first woof, in order to extrude the made cross section in this direction.
6. Extruding of the cross section of the first woof along the made direction. Thus the first woof is made.
7. Making of the cross section of the second woof in the symmetrical site of the first woof relative to wefts.
8. Making of the directing line of the second woof which is symmetrical of the directing line of the first woof relative to wefts.
9. Extruding of cross section of the second woof along its directing line to made the second woof.
10. Repeating of the steps of making of the first woof, in order to make the third woof.

Different above mentioned steps have been shown on the Fig.1.
Thus a Unit Cell as shown in Fig. 2 is made.

Then, we had to make the matrix in the cubic shape which could contain the entire unit cell. This matrix is an isotropic material.
In order to bond by adhesion the fibers to the matrix, we should use the Glue operator of the software. This not possible due to the weakness of the software in the Glue operation of interfered volumes. To resolve this mater we should subtract the existing fibers in unit cell from the matrix. Hence we would have a matrix in which the volume of fibers is empty. Then we model each of the fibers of the unit cell in the empty space of the matrix. Whereas, instead of interference of volumes we have interfaces of fibers and matrix for which we can do Glue operation to bond fiber and matrix and make a modeled layer of a woven composite.
In the studied specimen we had 24 layers with a layer thickness of 0.125 *mm*. Because of the symmetry of DCB specimen only 12 layers are copied each on other and bonded by Glue operation.

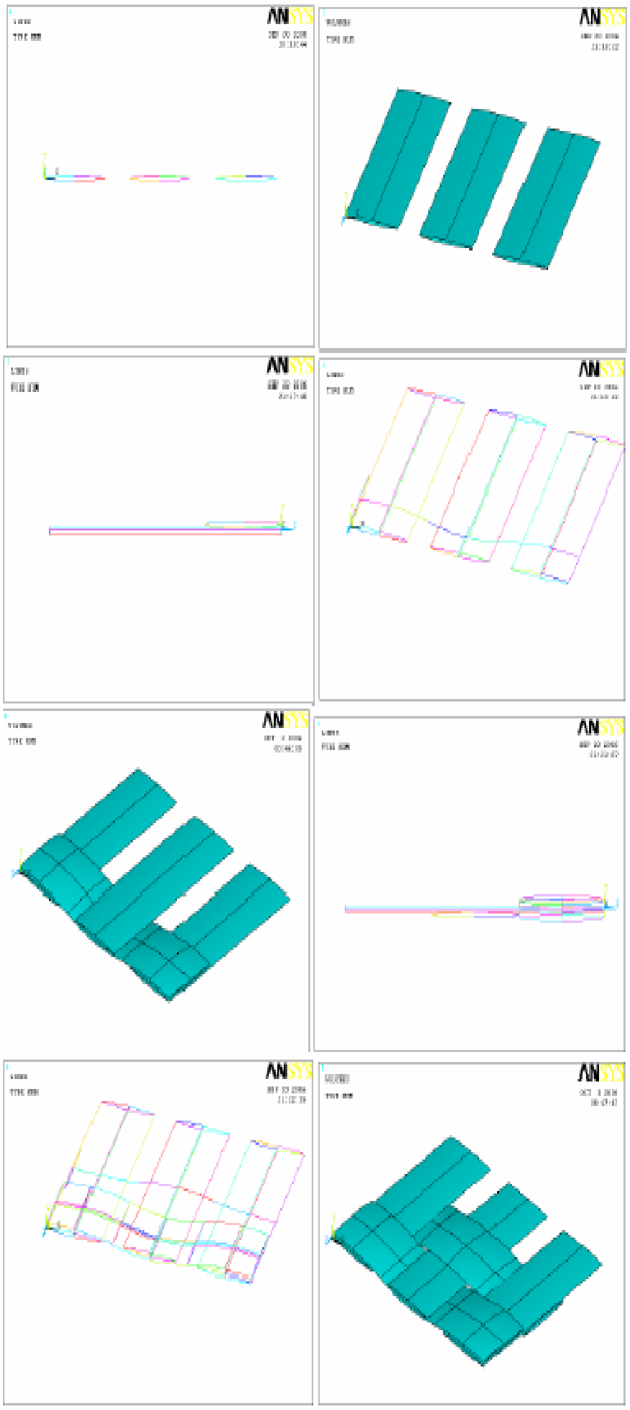

Fig. 1. Different steps of modeling
(Left to right-above to below)

5 Computational

In order to characterize the delamination, a three-dimensional model of woven glass fiber composites with the shape of double cantilever beam (DCB) designed for crack experiments on Mode I was made. Two kinds of mesh generating in crack tip in woven reinforced composite were used.

• By using singular elements in crack tip.
We made several keypoints on the crack and meshed each of them (Fig. 2).

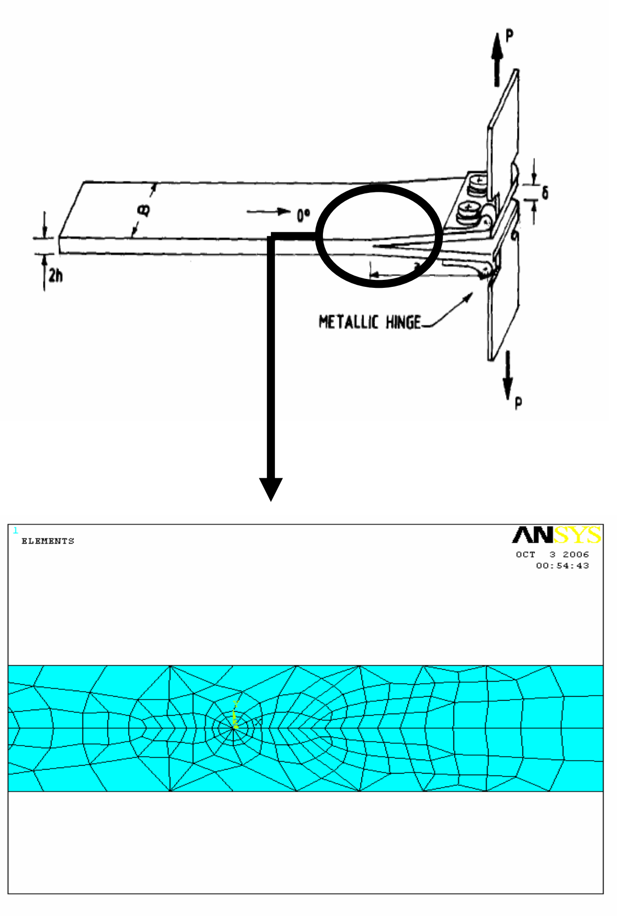

Fig. 2. Mesh generation in 3D state using singular elements in crack tip

• By using brick elements [18].
In this case due to the symmetry of the specimen and loading, only its quarter was mesh generated. In the two planes of symmetry the relative boundary conditions were applied. To obtain a reasonable precision in the computation, refined brick elements were chosen in the vicinity of crack tip (Fig.3).

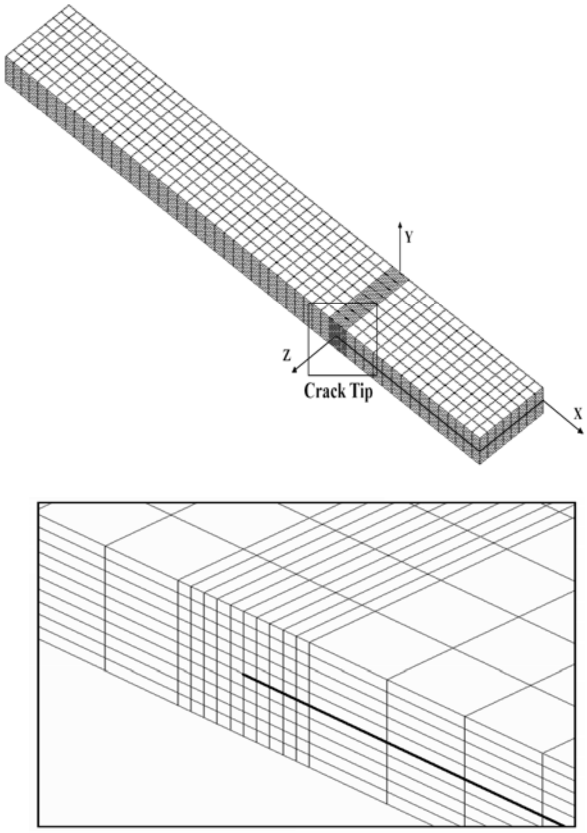

Fig. 3. Mesh generation in 3D state using brick elements in crack tip

In order to reduce the volume of computation a unit cell was taken from that model on which the modeling of delamination was carried out [19].

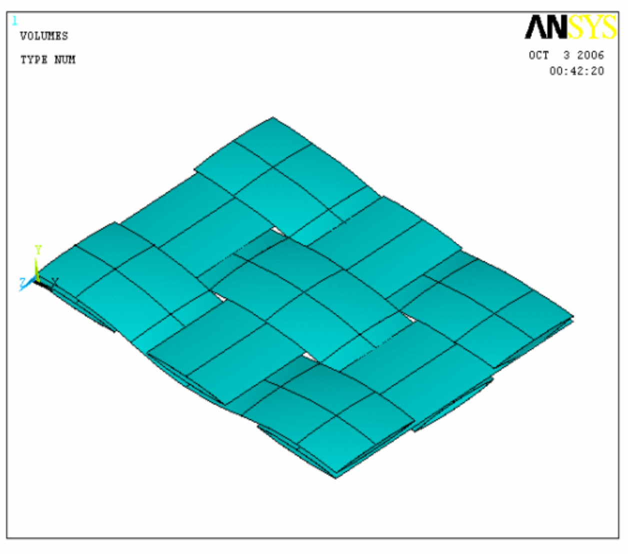

Fig. 4. Model of the woven reinforcement showing weft and warp filaments

Then using the criterion of Irwin-Kies based on the compliance of the specimen with an initial crack (Equations 1&2) and its derived equations (3) to (6), the curves of SERR versus the crack length were computed. Finite element method (FEM) using Ansys package was used.

6 Results and discussion

The numerical analysis of DCB specimen was carried by displacement control in order to have a stable delamination growth. Hence, by displacement of the two ends of the cantilevers, the load is applied to the specimen and to reach to the critical load of delamination growth which corresponds to the Von Mises stress of 35 *MPa*, the iteration by variation of displacement value is carried. Thus the critical load (F_C) and critical displacement (δ_C) for its corresponding crack length were obtained. Then by increasing the crack length the same operation was repeated. Thus for different values of crack lengths, the curve of load versus displacement was drawn (Fig. 5).
In the following curves experimental results were taken from reference [20].

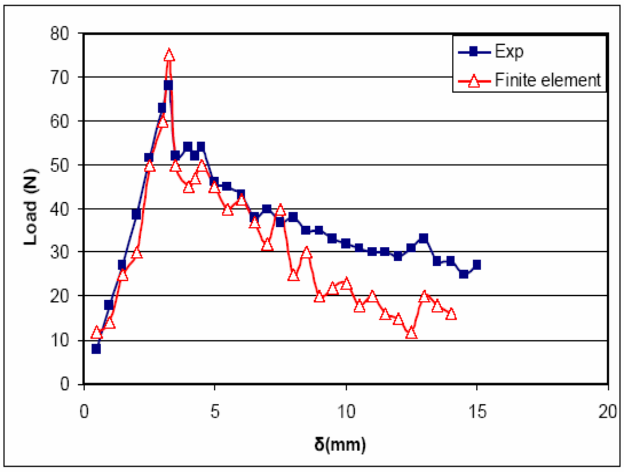

Fig. 5. Load –Displacement curve

The higher bending of glass fibers by increasing of the opening of specimen is the cause of increasing of scatter of F.E. results and experimental ones. This scatter is lower in the beginning of delamination growth because of lower bending of fibers.
Using the obtained values of F_C and δ_C for different crack lengths, the values of G_{IC} have been computed.

Result using the beam theory (Equation 4) was shown on the Fig.6.

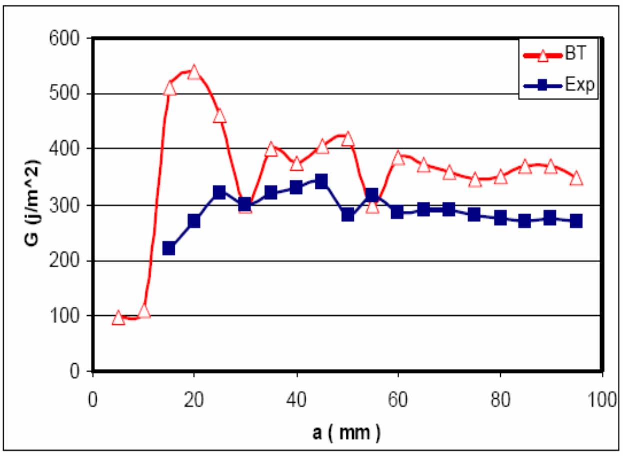

Fig.6. Curves of strain energy release rate using beam theory (BT)

As shown on the Fig. 7, the curve obtained by the corrected beam theory (CBT) has less variations comparing to the beam theory. In this method either introducing the correcting factor the |Δ|, some modifications in mesh generating in crack tip comparing to the specimen analyzed by BT have been introduced. Thus, the kind of mesh generating in crack tip influences the result.

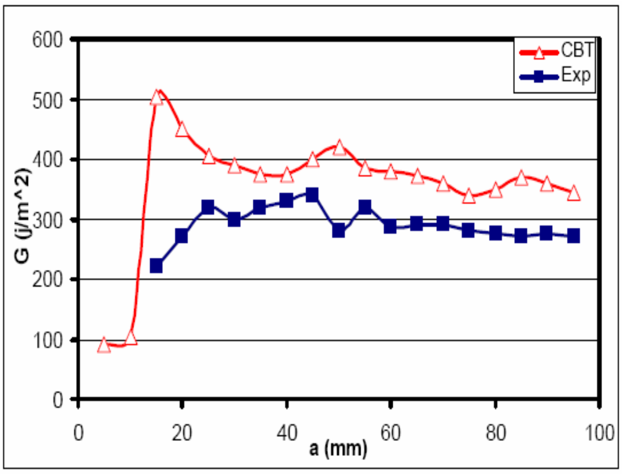

Fig.7. Curves of strain energy release rate versus crack length by CBT

As per relation (4) the values of dC/da versus crack length (a) should be computed to obtain G_{IC} versus (a.) Hence, the slope of compliance C versus (a) was computed drawing the curve of C versus in Excel software. Then the approximate function of versus a using this software was obtained (Fig.8).

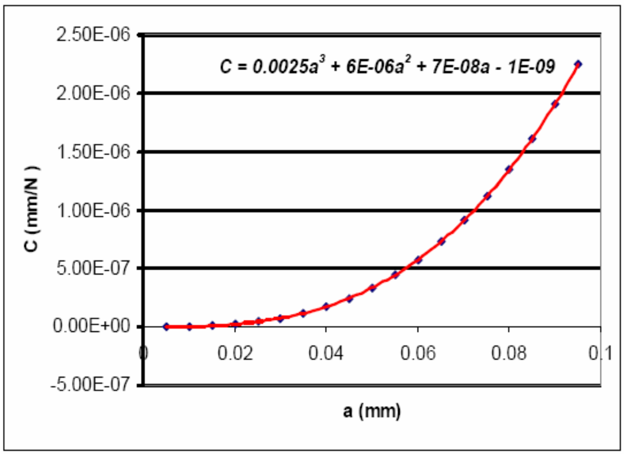

Fig. 8. Approximation of C-a as a function of degree

The obtained function was as relation (7).

$$C=0.0025a^3+6E\text{-}06a^2+7E\text{-}08a\text{-}1E\text{-}09 \qquad (7)$$

Deriving the above relation relative to (a), we obtained dC/da.

$$dC/da= 0.0075a^2+6E\text{-}06a +7E\text{-}08 \qquad (8)$$

Then by using the above relation values of dC/da versus (a) were computed from which the curve of G_{IC} versus (a) was obtained (Fig.9).

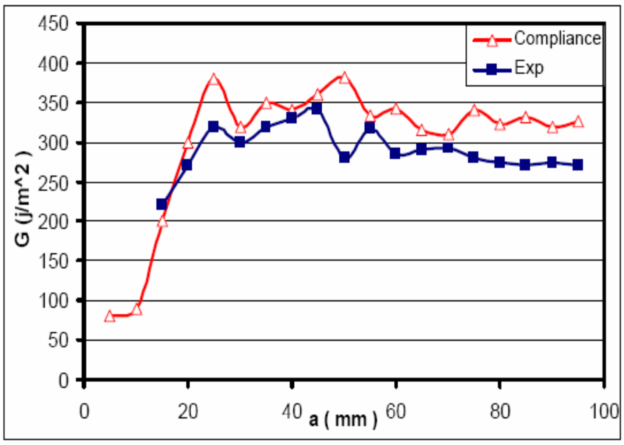

Fig. 9. Curves of strain energy release rate versus crack length using compliance method

Results of the G_{IC} versus crack length (Fig.10), show a net difference with experimental ones. The variations of the curve using this theory are higher comparing to other theories. Theses variations are clear for crack lengths lower than 60 *mm*.

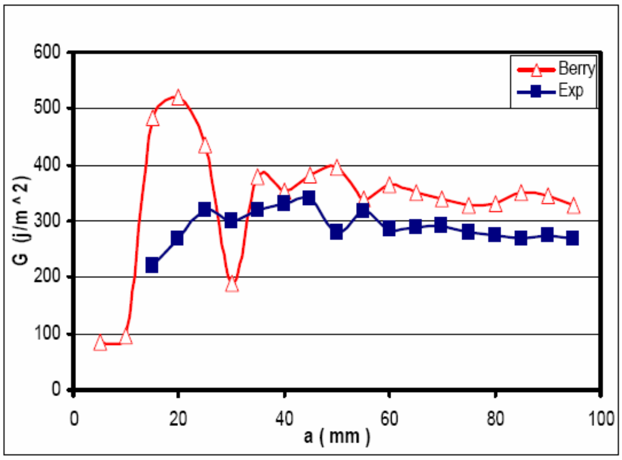

Fig. 10. Curves of strain energy release rate versus crack length

Fig. 9 shows that the curve obtained by compliance method has the lowest scatter with the experimental results.

The curves of the Fig.11 show results obtained by relations (3) to (6) and the experiments [20]. Theses results are obtained by using singular elements in mesh generating of crack tip. We observe clearly the growth of delamination along the weft filaments and a sudden change in the point of crossing the woof filaments. Numerical results show a scatter of less than 10% with the experimental existing result in the biography [20]. Thus a modeling of woven reinforced composite and evaluation of delamination by finite element is proposed.

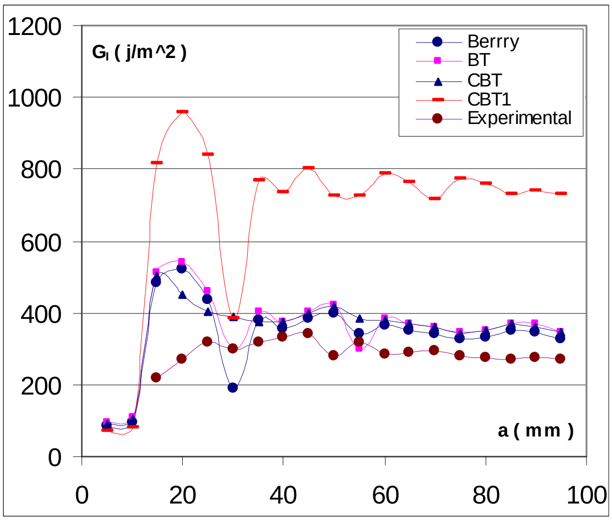

Fig. 11. Curves of strain energy release rate versus crack length

Conclusion

Modeling of the woven reinforced composite due to the existence of the weft and warp filaments of fibers is a significant part of this research. The FEM model of the unit-cell provided the required results of strain energy release rate with a low volume of computation.

The computed loads by FEM are put in derived equations of the fracture toughness (G_c). The obtained numerical results show the growth of delamination along the weft filaments and a sudden change in the point of crossing the weft filaments. Except one case, they are in good correlation with experimental results and the scatter is less than 10%.

References

[1] Jones R.M. "*Mechanics of composite materials*". 2nd edition, Taylor & Francis, Inc. USA, 1999.

[2] Korab J., Stefanik J., Kavecky S., Sebo P. and Korb G "Thermal expansion of cross-ply and woven carbon fiber-copper matrix composites". *Composites*, Part A, Vol. 33, pp 133-136, 2002.

[3] Alkateb M., Mahdi E. Hamouda A.M.S. and Hamdan M.M. "On the energy absorption capability of axially crushed composite elliptical cones". *Composite Structures*, Vol. 66, pp 495-501, 2004.

[4] Lin B.K., Krueger R. and O'Brien T.K. "A shell/3D modeling technique for the analysis of delaminated composite laminates". *Composites,* Part A: Applied Science and Technology, Vol. 32, pp 25-44, 2001.

[5] Park V.C., Lee D.G. "Through-thickness compressive strength of carbon-phenolicwoven composites". *Composite Structures*, Vol. 70, pp 403-412, 2005.

[6] Khoshravan M.R. and Jami A. "Interlaminar stresses in CFRP composites", *Proceedings of the International Conference on Advanced Fibers and Polymer Materials (ICAFPM)*, Shanghai, China, Vol. 1, pp 338-342, 2005.

[7] Kim J., Shioya M., Kobayashi H., Kaneko J. and Kido M., K. "Mechanical properties of woven laminates and felt composites using carbon fibers. Part 1: In plane properties". *Composite Science and Technology*, Vol. 64, pp 2221-2229, 2004.

[8] Moore D.R. and Cervenka A. K., "Future requirements in the characterization of continuous fiber-reinforced polymeric composites". *Journal of Pure Appl. Chem* , Vol. 74, No. 4, pp 601-628, 2002.

[9] Lee J.H., Wang H., Korjakin A. and Richard H.A. "Investigation of mixed Mode I/II interlaminar fracture toughness of laminated composites by using a CTS type specimen". *Engineering Fracture Mechanics*, Vol. 61, pp 325-342, 1998.

[10] Abot J.L., Yasmin A., Jacobsen A.J. and Daniel I.M. "In-plane mechanical, thermal and viscoelastic properties of a satin fiber carbon/epoxy composite". *Composite Science and Technology*, Vol. 64, pp 263-268, 2004.

[11] Pandita S.D., and Verpoest I. "Tension-tension fatigue behavior of knitted fabric composites". *Composite Structures*, Vol. 64, pp 199-209, 2004.

[12] Iannucci L., Dechaene R., Willows M. and Degrieck J. "A failure model for the analysis of thin woven glass composite structures under impact loadings". *Computers and Structures*, Vol. 79, pp 785-799, 2001.

[13] Kim J., Shioya M., Kobayashi H., Kaneko J. and Kido M. "Mechanical properties of woven laminates and felt composites using carbon fibers. Part 2: interlaminar properties". *Composite Science and Technology*, Vol. 64, pp 2231-2238, 2004.

[14] Shido Y., Horigushi K., Wang R. and Kudo H. "Double cantilever beam measurement and finite element analysis of cryogenic Mode I interlaminar fracture toughness of glass-cloth/epoxy laminates". *Engineering Materials and Technology*, Vol. 123, pp 191-197, 2001.

[15] Lee L., Rudov-Clarck S., Mouritz A.P. Bannister M.K. and Herzberg I. "Effect of weaving damage on the tensile properties of three-dimensional woven composites". *Composite Structures and Technology*, Vol. 60, pp 21-37, 2002.

[16] Morais A., Moura M., Marques A. and Castro P. "Mode I interlaminar fracture of carbon/epoxy cross-ply composites". *Composite Science and Technology*, Vol. 62, pp 679-686, 2002.

[17] Anon. ANSYS 8.0 Documentation, ANSYS, Inc, Canonsbudg, Pennsylvania, 2003.

[18] Khoshravan M.R.and Monir Vaghefi M., "Numerical evaluation of delamination on Mode II in glass fiber reinforced composites". *Engineering Transactions, Polish Academy of Sciences*, Vol. 53, pp 55-68, 2005.

[19] Baruffaldi G., Riva E. and Nicoletto G., "3D Finite element damage analysis of a twill-weave lamina subjected to in-plane shear". *Proceedings of the 2nd international conference on composite materials and model identification (COMPTEST)*, Bristol, 2004.

[20] Money, M.W., NPL, *Report DMA (A) 178*, ISSN 0143-7313, National Physical Laboratory, UK, 1989.