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Fracture Analysis in Glass Fiber- Epoxy Resin Woven Composite under Mode-I Statical Loading by Using Finite Element Method and Its Comparison to Experimental Results

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ABSTRACT

Recently, woven composites are of high acceptance and demand because of their high resistance against impact loads in comparison to unidirectional composites in many fields such as aerospace industry. Although woven composites lamination quality is very delicate toward shear, cracks and delamination mainly because of interlaminar stresses. Because of time consuming and expensiveness of woven composite sampling and experiments related to their breakage, in this study we try to model specimens in Ansys software and put under static loading in fracture mode I and finally compare results with the other experimental results. The results show that delamination is formed along warps and strain energy release rate changes are observable from warp to warp. In addition, singular elements utilization for crack tip modeling has better results in comparison to other elements.

KEY WORDS: Woven Composite, Finite Element Method, Fracture Analysis.

1. INTRODUCTION

Woven composite complexity has made mechanism of analysis and failure reasons of these composites problematic. Main reasons of these composites failure can be:
-fiber failure and crack diffusion in matrix
-linear crack in matrix
-fiber separation from matrix in fiber connection place to that
-heterogeneity of matrix material compound
-porosity in warp and woof joints

In delamination process, all mentioned positions can be occurred. The mechanical properties of the laminated composite depend very much on the properties of the each lamina. Delamination represents the weakest failure mode in laminated composites, and is considered to be the most prevalent life-limiting crack growth mode in most composite structures. In general, a delamination will be subjected to crack driving forces resulting from either or combination of mode I (opening or peeling), mode II (sliding or in-plane shear) and mode III (tearing or anti-plane shear). Because delamination is constrained to grow between individual plies, both interlaminar tension and shear stresses are commonly present at the delamination front. Delamination can happen in three different modes. In this paper, we are going to investigate mode I.

A number of test methods have been proposed by many researchers to determine fracture toughness of metals, composites and adhesive bonded joints. The Double Cantilever Beam (DCB) specimen produced nearly mode-I behavior, End Notched Flexure (ENF) for mode-II of fracture, or the End Load Split test (ELS), and in mixed-mode I/II, using the Mixed-Mode Bending (MMB) method by Crews and Reeder for first time in 1988 for mixed-mode fracture are used to estimate fracture toughness for different materials [1].

2. Investigating Failure Theory in Mode-I

Fig. 1 shows an element near the tip of a crack in an elastic material, under the plane stress condition. Each stress component is proportional to a single constant, *K*. That is mathematically analyzable, and it characterizes the stress and displacement distributions at the crack tip, so it also characterizes the behavior and the criticality of the crack. This constant, which is called the stress intensity factor, completely characterizes the crack tip conditions in a linear elastic material. In a specific zone near the crack tip, the

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stress field is completely described by the stress intensity factor, K_I (for mode-I), and the stresses are given by the following equations [2]:

$$\sigma_{xx} = \frac{K_I}{\sqrt{2\pi r}}\cos\left(\frac{\theta}{2}\right)\left[1-\sin\left(\frac{\theta}{2}\right)\sin\left(\frac{3\theta}{2}\right)\right]$$
$$\sigma_{yy} = \frac{K_I}{\sqrt{2\pi r}}\cos\left(\frac{\theta}{2}\right)\left[1+\sin\left(\frac{\theta}{2}\right)\sin\left(\frac{3\theta}{2}\right)\right] \quad (1)$$
$$\tau_{xy} = \frac{K_I}{\sqrt{2\pi r}}\cos\left(\frac{\theta}{2}\right)\sin\left(\frac{\theta}{2}\right)\cos\left(\frac{3\theta}{2}\right)$$

where, r and θ are polar coordinates shown in Fig.1.

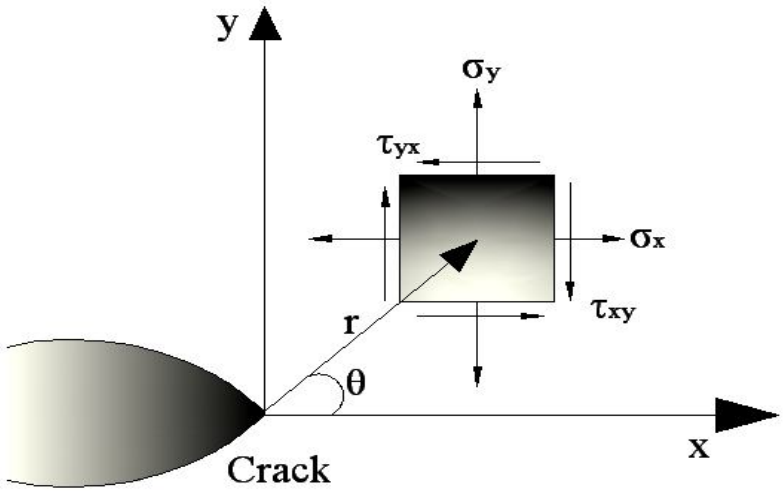


Fig. 1 Schematic of an element near the crack tip

In this attempt, the specimen is made of an orthotropic linear elastic material. The strain energy release rates for orthotropic material with the crack line parallel to the principal orthotropic direction which coincides with the fiber orientation can be calculated from the following relationship [2]:

$$G_I = \frac{K_I^{\,2}}{E_I} \quad (2)$$

where E_I is the effective module, K_I is mode-I stress intensity factor.

DCB specimen is used for interlaminar failure resistance experiment of woven composites in pure loading of mode-I. The modeling process of planned specimen in software has been shown in figures 2-6.

δ symbol is used for showing specimen's opening displacement. For detecting critical moment of crack growth point δ=0.1 mm and through adding 0.1 mm to this amount loading increases gradually and as crack growth starts, loading increase stops.

From among some criteria of failure mechanics, Tsai Hill theory is used for detecting criticalness of crack tip (crack diffusion) [3]. Some advantages of this theory are: utilization simplicity, detection speed and its accuracy. Among theories of failure mechanic, double cantilever beam and compliance theory theories are chosen in order to evaluating energy release rate in mode I. These theories are simple beam theory and compliance theory [4.5]:

I. Beam theory (BT)

$$G_1 = \frac{3P\delta}{2B\,a} \tag{3}$$

Where:
P= applied load (N)
δ=opening of specimen (mm)
B= width of specimen (mm)
a= crack length (mm)

II. Compliance theory (CT)

$$C = \frac{\delta}{P} \quad , \quad G_1 = \frac{P}{2B}\frac{dc}{da} \tag{4}$$

3. Specimen Characteristics

This specimen has 24 layers that 12 layers are placed above the crack level and another 12 layers are under crack level. Each layer is of 0.125 mm thickness and the whole layer is 3mm (2h) thick [6].

Table (1) Geometric Size of Specimen DCB

Size			
L = 50 mm	B = 25 mm	H = 1.5 mm	L_c = 120 mm

Table (2) Mechanical properties of utilized Woven Composite

E_{XX} = 20 GPa	υ_{vx} = 0.13	G_{xy} = 2.85 GPa
E_{yy} = 20 GPa	υ_{xy} = 0.13	G_{YZ} = 2.85 GPa
Ezz = 12 GPa	υ_{xy} = 0.3	G_{XZ} =1.9 GPa

4. Modeling of Woven Composite

The representative element of a woven composite could be modeled as described here. First the cross section of set of fibers modeled according to the geometrical characteristics of specimen (Fig.2). Then with extruding of the cross sections in Z direction we make wefts (Fig.3). Making of the cross section of the first woofs in X-Z plane and modeling of the directing line of the first woof then were done. By extruding of the cross section of the first woof along the made direction the first woof was made. Then other woofs with method mentioned in above was performed (Fig.4). In order to model composite matrix, we design a rectangular cube of unit cell size that contains fibers (Fig.5). Now, a number of unit cells are put on each other and glued in order to design specimen (Fig.6).

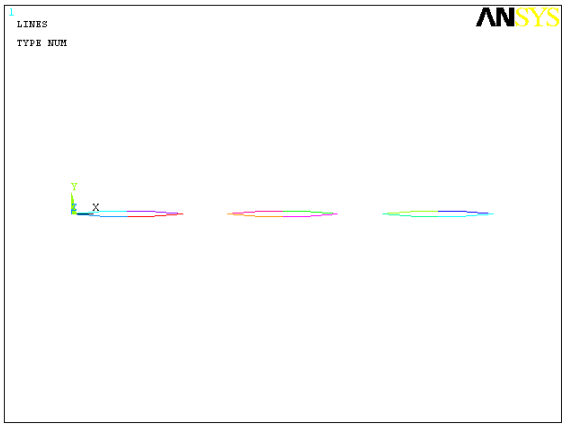


Fig. 2 Modeling of the periphery of the set of fibers in X-Y coordinates

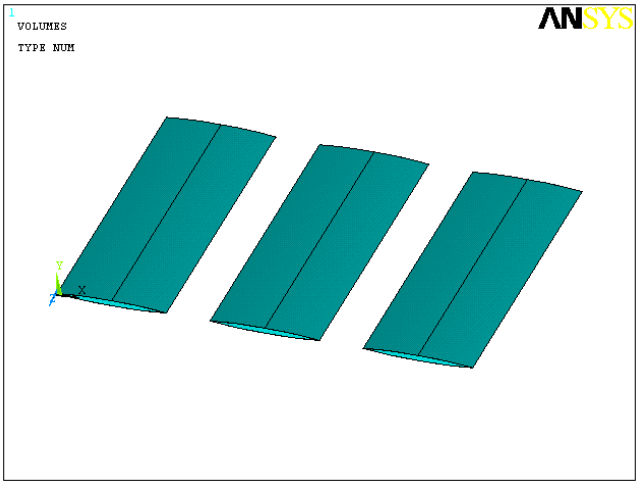


Fig. 3 Extruding of the cross sections

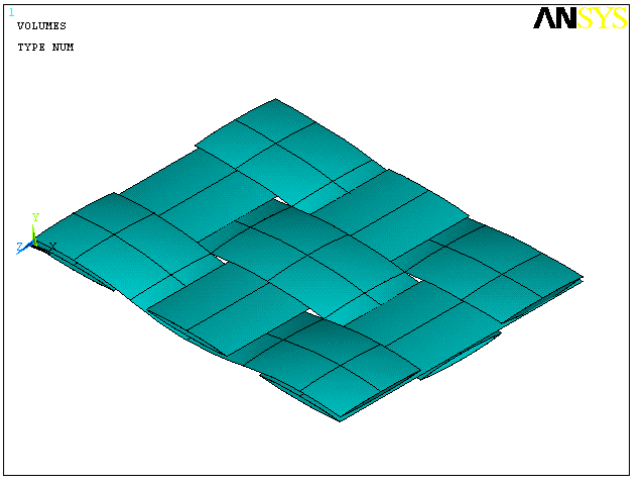


Fig. 4 Modeling a set of warps and woofs

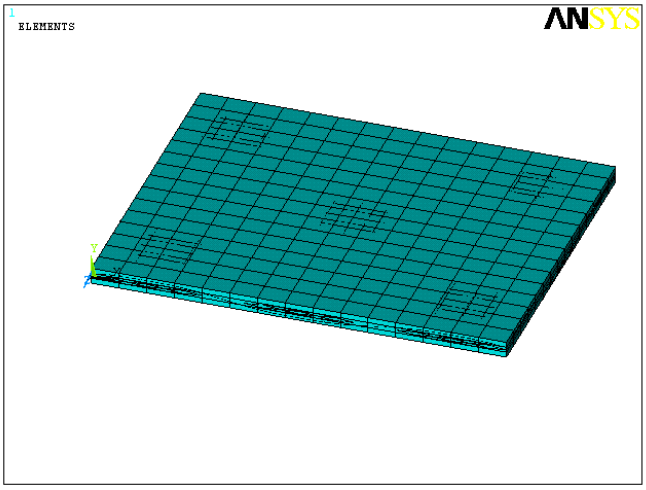


Fig. 5 A rectangular cube of unit cell size that contains fibers and matrix

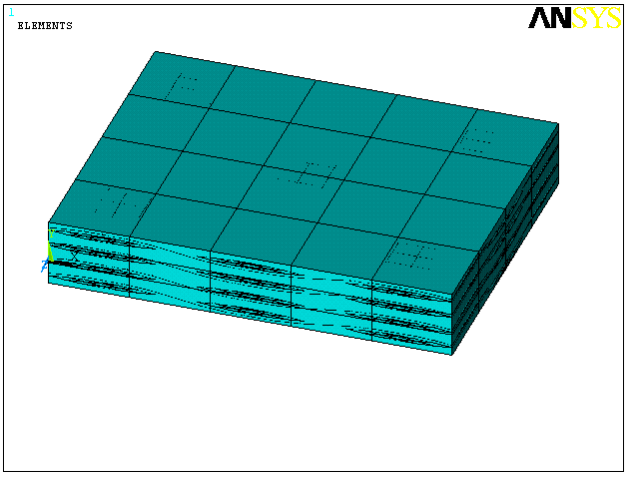


Fig. 6 The copy of layers on each other and performing glue process in order to thorough modeling of specimen

5. RESULTS

After end of modeling the specimen, we should apply boundary conditions and start to specimen analysis, and extract results of finite element method for comparison with experimental data [7-9].

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.

The curves plotted in figures (7), (8) show strain energy release rate versus crack length in mode-I by using beam and compliance theories, and their comparison to experimental results.

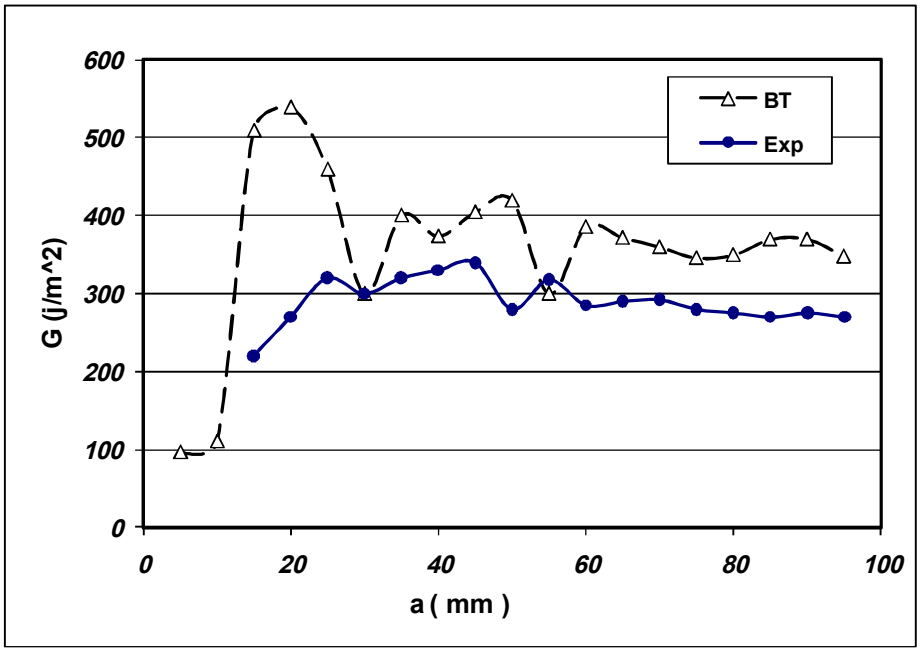


Fig. 7 strain energy release rate versus crack length in mode-I by using beam theory and experimental results

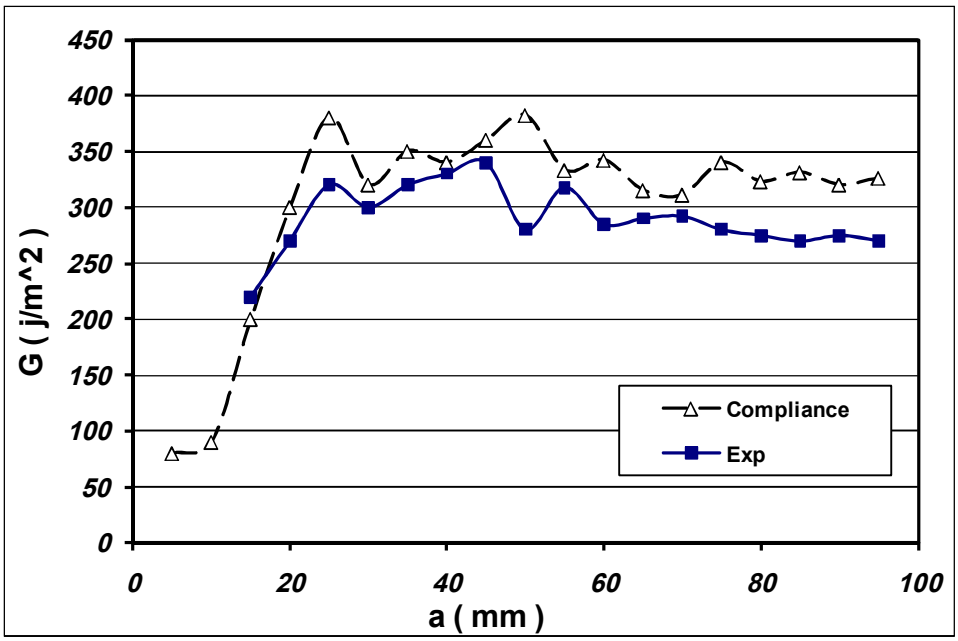


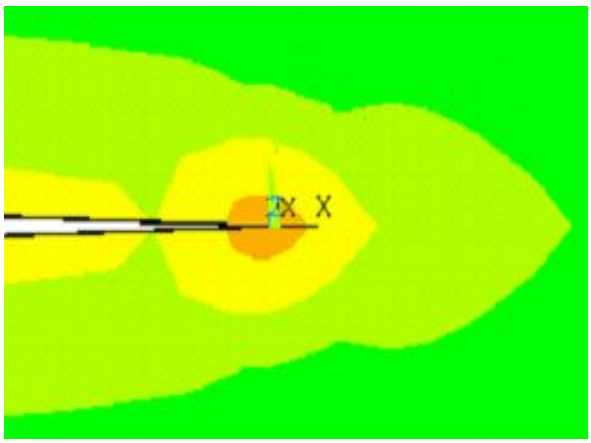
Fig. 8 strain energy release rate versus crack length in mode-I by using beam theory and experimental results

5.1. Stress Analyses in Mode-I

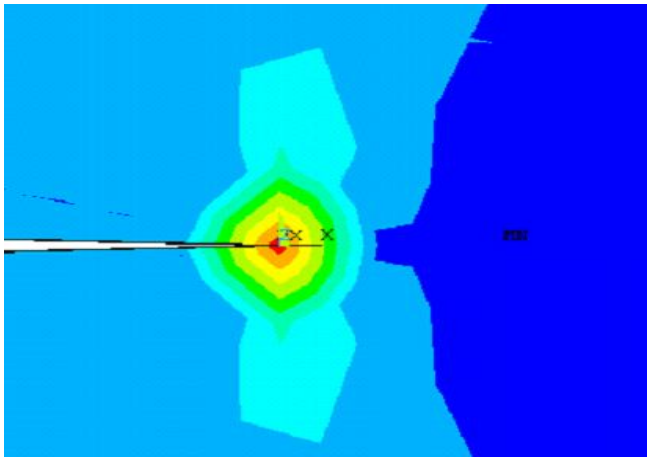
Comparing the results of finite element method with beam theory results shows that results of finite element method which plotted at Fig.7 in low crack length has too fault comparing to experimental results. Weakness of gluing in modeling of this types of composites because of pores in decussation of wefts and woofs is cause of this fault. With increasing crack length regard to enhancement of cohesion about resin and fibers, difference of results are increased,

Fig. 9 shows two-dimensional stress around crack in pure loading of mode I. Normal stress distribution of σ_y and σ_x toward delamination line is symmetric and shear stress distribution of τ_{xy} is of anti-symmetric form.

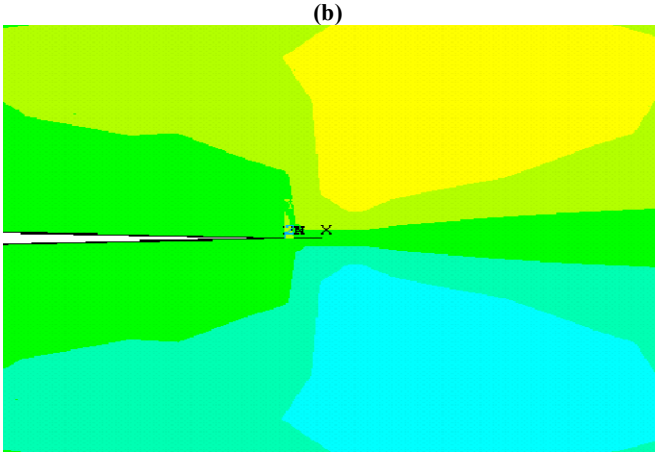
δ_y can be considered as the main reason of crack growth in pure loading of mode I. The maximum amount of σ_y is exactly on the tip of crack. σ_y along y has more tendency toward increase and along x has the least tendency. This habit of distribution caused the development of σ_y in the form of two joined circles (bean-shaped).This shape of stress distribution shows that magnitude of stress in above and bottom of crack tip is too high in comparison of the other parts of sample. Because of this phenomenon, the crack length is increased.



(a)



(b)



(c)

Figure (9) Stress distribution on the tip of crack with singular element in mode-I, (a) distribution of σ_x, (b) distribution of σ_y and (c) distribution of τ_{xy}

6. Conclusion

On the bases of represented data of this paper, it can be said that the only loading opening method in order to reach optimum results is loading opening via displacement method through which the crack growth will be stable.

According to displayed results in graphs (7) and (8), through two methods of beam theory and compliance theory and their comparison to experimental results it can be concluded that compliance method has better results in comparison to beam theory one. However using of compliance method because of plotting C-a diagram and approximated function of this diagram is semi-complicated the better results of this method is main cause of using this method. Furthermore with increasing degree of approximated function for C-a regardless of complexity of solution, precise of analyze is increased and deference of finite element method with experimental results decreased.

Acknowledgments

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