IJST, Transactions of Mechanical Engineering, Vol. 39, No. M1+, pp 261-271
Printed in The Islamic Republic of Iran, 2015

EFFECTS OF ELEMENT TYPES FOR CRACK TIPS IN WOVEN DCB MADE OF GLASS FIBRE-EPOXY RESIN*

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Abstract– Nowadays, textile and woven fabric composites are taken into consideration for applications in high mechanical properties and every in-plane direction. However, developments in modelling and characterisation of the fabric reinforced composite materials are considered more in the effects of element types used in the mesh generation of the crack tip. The type of element selected for the crack tip, a critical point for evaluation of crack growth in a double cantilever beam (DCB) sample, is extremely important. In this study, results of strain energy release rate (SERR) meshed with singular and or brick elements with the experimental data were compared to select better element type. The plotted results of the crack tips meshed with the brick elements and the diagrams revealing the SERR in contrast to the crack length was evaluated. In addition, the aforementioned operation has been repeated for singular elements. The theory of the failure mechanics has been used to calculate the amounts of SERR for several crack lengths. It is concluded that, numerical results from SERR of the crack tip when meshed with singular elements were closer to the experimental results compared with data of SERR when meshed with brick elements.

Keywords– Woven composite, finite element method, fracture analysis, brick elements, singular elements

1. INTRODUCTION

Textile composites and woven textile composites in particular have been increasingly under consideration for applications where high mechanical properties are desired in every in-plane direction. Two-dimensional woven fabrics consist of two types of interfaced yarns known as warp and fill and each yarn consists of a bundle of filaments. Woven textile plays a crucial role in composite technology providing glass fabrics that are widely used as reinforcing materials. The main advantages of woven composites are their cost efficiency and high process ability, particularly in the lay-up manufacturing of large-scale structures. Furthermore, the bending of fibres in the process of fabric weaving results in a substantial reduction in the material strength and stiffness**.** Numerical simulations are widely used in industries to optimise process and analyse the behaviour of materials under various conditions. However, in order to have a confidence in the results of such simulations, an accurate material model is required[1]**.** One of the best methods of evaluating the strength of these materials, considering the high cost and sensitivity of experiments is the Finite Element Method (FEM). This method involves the selection of an appropriate element for meshing different sections of sample. Since the crack tip is extremely important for meshing this section, the smallest elements need to be used.

There are different methods available such as Compliance [2], Berry[3], etc. to analyse the DCB (Double Cantilever Beam), which are loaded statically in mode I of failure.

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*Received by the editors January 16, 2014; Accepted November 10, 2014.
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Khaleed et al [4] used FEM simulation for ınvestıgatıon of producing Autonomous underwater vehicle (AUV) propeller blade.

Duong and Hung [5] used finite element models to solve the delamination problem in composite laminate structures. In this research singular elements have been used.

Baruffaldi [6] used the FEM (Finite Element Method) analysis of the unit cell providing the macroscopic shear stress-shear strain curve of basket-weave laminates in her research. She applied brick elements to the meshing of her designed unit cell. However, meshing of the crack tip due to the sensitivity of this point with brick elements is unable to produce exact results.

Denda and Marante [7] considered multiple curvilinear cracks in the two-dimensional general anisotropic solids and establish a computationally effective technique to determine the stress intensity factors accurately. They used singular element for meshing the crack tip too.

Khoshbakht et al [8] also studied the plane deformation of a composite specimen under combined tension – the bending loading using finite element method and mechanic failure rules. They used singular elements for meshing critical points of their specimen.

Khoshravan and Azimpour [9] applied singular elements for meshing the crack tip of their specimen using FEM. They predicted micro-buckling in composite laminate and emphasised the point that a singular element is the best type of element for meshing the crack tip.

Tao Zeng et al. [10] presented a simplified numerical model of 3D woven composites with discretization of a unit cell into a number of rectangular elements which is different from conventional FEM method and, by using this method have gained the mechanical properties and the local stress within 3D woven composites. In this method the simplified numerical model of 3D braided composites has been presented. But this method for modelling is not so exact.

In structurally inhomogeneous materials (adhesive compounds, composites and geo-materials), when there are domains with a disrupted structure close to a crack, and physical fields and aggressive media act on the fracture process, quite a large part of the crack becomes involved in the fracture process and different fracture mechanisms can occur when the size of the end zone of a crack changes [11]. Hence examination of crack tip is too important in analysing process.

In this research study, woven fabrics modelled with a new method in ANSYS software exactly [12] followed by numerical analysis has been carried out under static load. For estimation of the strain energy release rate for various crack lengths, the compliance theory is used. Using singular elements and brick elements**,** crack analysis has been carried out. When comparing the obtained results, the theoretical results are in agreement with the experiment results, especially for singular elements.

2. MATERIALS AND METHOD

Glass fibre reinforced composite with a fibre fraction volume of 60% was used. The thickness of each ply was 0.125mm. 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 plane of the weave and Z is the normal axe to the plane. The geometrical properties of the test bars are shown in Table 2 [13].

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	$G_{XY} = 2.85\ GPa$ $G_{YZ} = G_{XZ} = 1.9\ GPa$

Table 2. Dimensions of DCB sample

Length	150 mm
Width (B)	25 mm
Thickness (2h)	3 mm

3. MODELING OF WOVEN COMPOSITES

Modelling of the woven reinforced composite is extremely problematic due to the existence of the weft and woof filaments of fibres, the method of modelling is a significant part of this research. The Line and Key point command was used for making the section of the filaments which were then extruded to obtain a line of filaments due to the difference in structure of the woven composite compared to the unidirectional composite. The ANSYS software has no specific method for modeling the woven composite.

For modeling these types of composites we present a method that has 8 Steps.

1. For modeling cross sections of the warps, the periphery is simulated with four arcs, the radius of which is extracted from properties of the experimental sample. Cross sections of warps have been defined as an area confined to these arcs (Fig. 1).

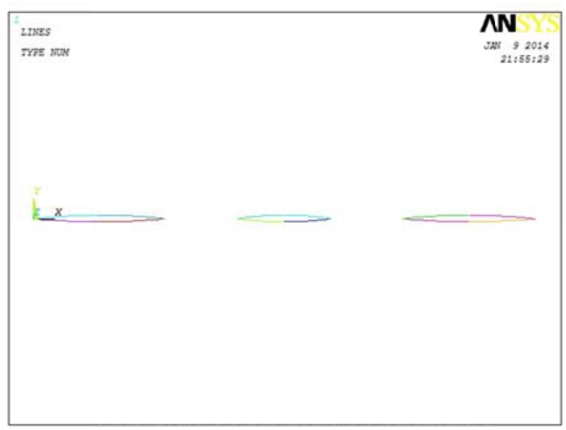


Fig. 1. Periphery of warps

2. For modeling of the warps, the cross sections defined in the X-Y plane have been extruded in the direction of Z (Fig. 2).

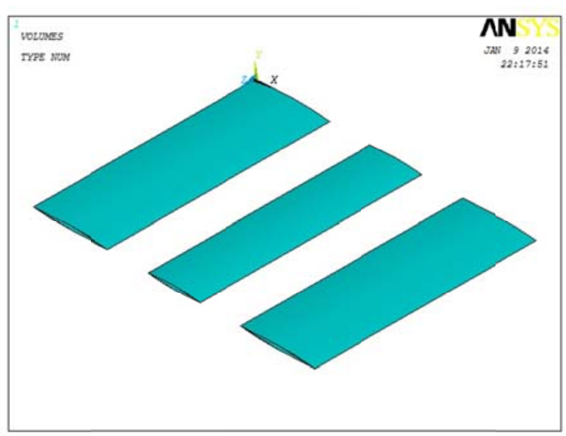


Fig. 2. Modeling of warps based on unit cell

3. In this section of the design, the cross sections of woofs have been generated according to steps one and two on the X-Z plane (Fig. 3).

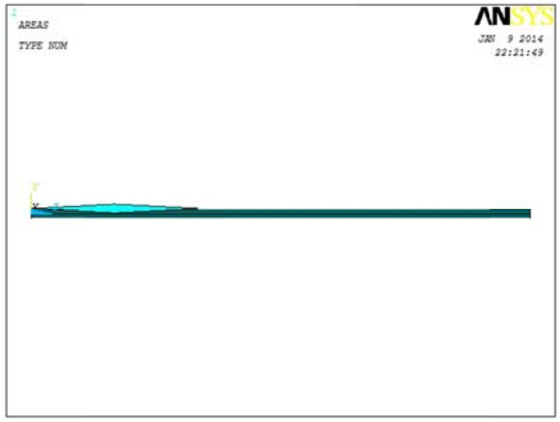


Fig. 3. Cross section of a woof

4. Generation of the woofs that are woven to warps is the most significant part of the design. To do this, key points are defined on the route of a guideline that is transmitted between the warps (Fig. 4).

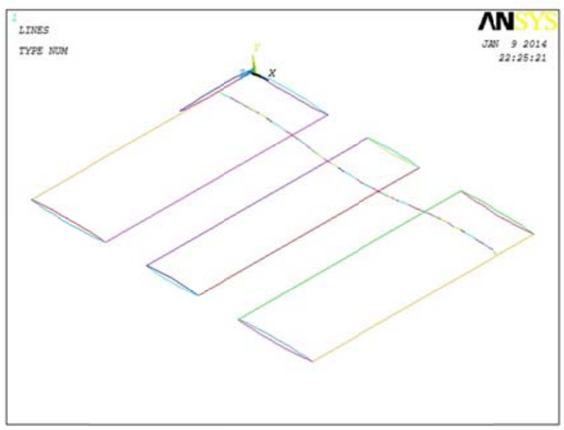


Fig. 4. Guideline of woof transmitting between warps

5. In order to generate the first woof, the cross section of step 5 has been extruded along the guidelines transmitted between warps (Fig. 5).

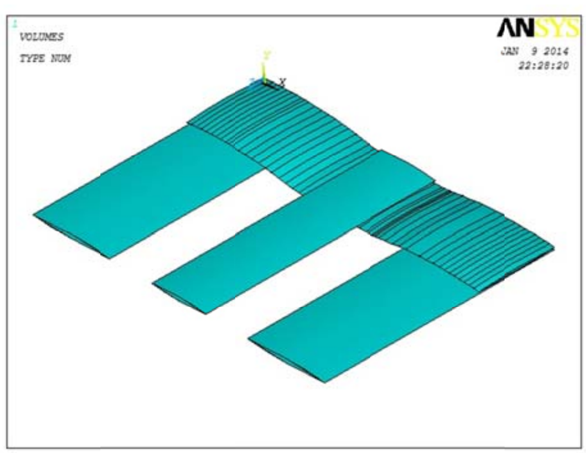


Fig. 5. First woof transmitting between warps

6. In this step, steps 4, 5, 6 are repeated to generate the second and third woofs. Now the unit cell of the fibres is presented.

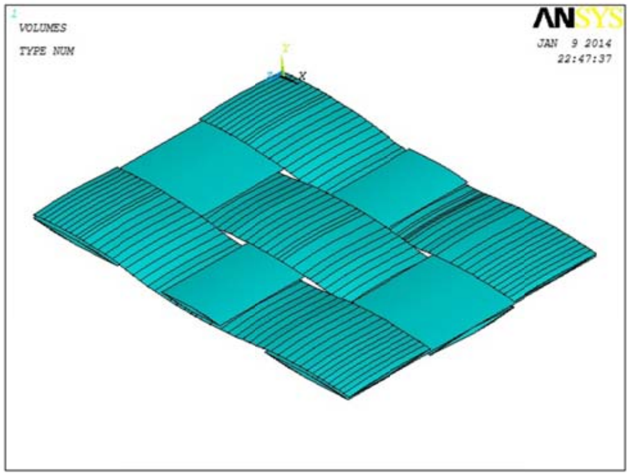


Fig. 6. Unit cell of fibres

7. In this step the matrix has been added to the fibre unit cell to fill out the woven composite unit cell (Fig. 7).

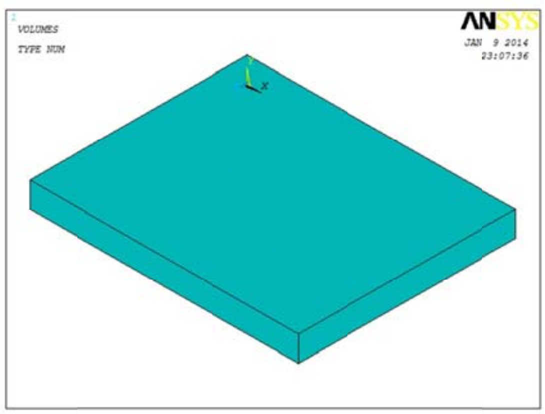


Fig. 7. Unit cell of woven composite

8. In order to generate the samples at several layers and dimensions, unit cells can be copied and merged in contact surfaces. In this research for modelling sample in ANSYS the layers should be copied and merged. A unit cell of fibre, whose dimensions are $9.5\times7.5mm^2$, is made of three warps and three woofs. Because of the symmetry half of the sample can be modeled, which is necessary for modeling virtual crack.

The multiple layers are copied symmetrically and the orientation angles of warps and woofs are chosen as 0° and 90° in whole layers. For the purpose of modeling virtual planar crack between two layers around mid-surface, the mid-surface that is equal to length of crack is not merged between two symmetric parts of modeled sample, while the remaining one is merged.

a) Equations of fracture mechanic

The theories of linear elastic fracture mechanics usually applied to homogeneous isotropic materials are also valid for composite materials. In this case, the Strain Energy Release Rate (SERR) presented by G_{crt} may be used to characterise the toughness of composite materials [14].

When the DCB sample is loaded in mode I for each load magnitude, δ (opening of sample) and a (crack length) are registered, and then the graph of compliance (C-a) versus crack length is plotted. This graph is used to obtain an approximate equation (Eq. (1)) for computing SERR (Figs. 11, 12).

From the Compliance theory [15], SERR has been found to be

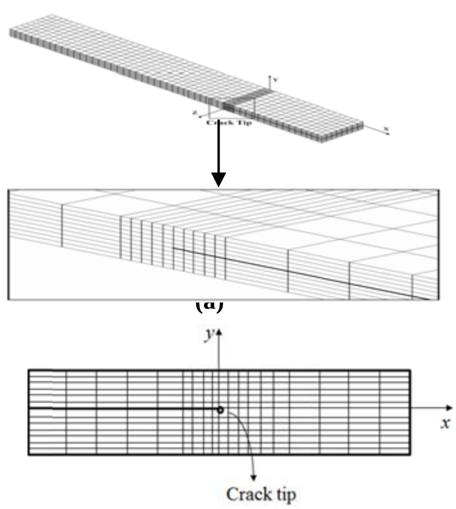
$$G_I = \frac{P^2}{2B}\frac{dC}{da} \tag{1}$$

Where C= δ/P and P is applied load, B is the width of the specimen, δ is opening of the specimen and C is compliance.

b) Elements used in the analyses

Because the sample is designed in three dimensions and woven composites are anisotropic materials, the mesh of the crack tip cannot be generated in two dimensions, so it must be meshed in three dimensions. In order to characterise the delamination, a three-dimensional model of woven glass fibre composites has been designed as the shape of a Double Cantilever Beam (DCB) on mode [16] [17]. Two types of elements are used to mesh the crack tip in woven reinforced composites:

1. **Brick elements[18]**: If the crack tip is meshed with brick elements because of the symmetry of loading and sample geometrical properties, the mesh of a quarter of the sample may be adequate. The element sizes of these types are the same. Certainly, because of the sensitivity of the crack region, the size of finite elements must be fine to achieve an accurate result. According to Fig. 8, the DCB sample meshed with a large amount of brick element is extremely high because of the sensibility of this crack region.



(b)

Fig. 8. Crack tip meshed with brick elements a) 3-D view [11] b) 2-D view in x-y plane

2. **Singular Elements** [19]: There is no way to mesh crack tips in three dimensional samples with singular elements except meshing in two-dimensions and extruding the generated meshes in a third direction. However, because of anisotropy in woven composites, utilising this process is impossible. The only way to do this is manual generation of singular elements in three dimensions. Defining key points around the crack line with their coordinates, the manual mesh has been generated using the KSCON command. The sample DCB with a crack tip meshed with singular elements has been illustrated in Fig. 9. Because of the symmetry of DCB, it will be

adequate to mesh half of the sample with singular elements[20]. Then, with use of the MIRROR command, the mesh of the symmetric side of the sample is generated.

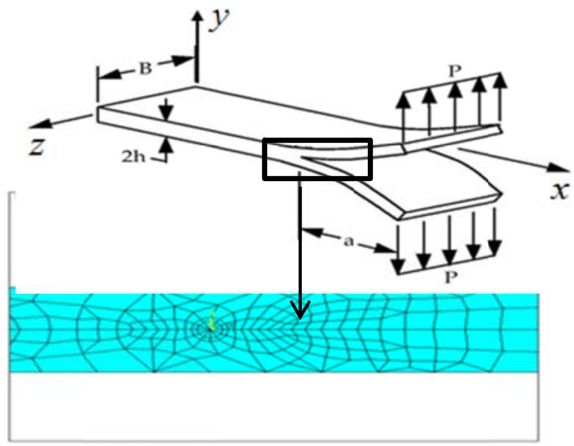


Fig. 9. Three dimensional mesh generation with singular elements on the crack tip [21]

3. RESULTS AND DISCUSSION

The numerical analysis of a DCB specimen has been carried out using the displacement control method in order to format stable delamination growth. Therefore, by checking the displacement of the two ends of the cantilevers, the load is applied to the specimen until it reaches the critical amount of force that is related to the material strength.

For delamination growth, the critical loads corresponding to the Von Misses stress of 35 *MPa*, based on iterating variation of displacement for various crack lengths, have been found out. Thus the critical load (F_{crt}) and critical displacement (δ_{crt}) corresponding to the crack length have been obtained. Then, by increasing the crack length, the same operation has been repeated. Therefore, for different values of crack lengths, the curve of load versus displacement has been drawn for brick and singular elements (Fig. 5). The experimental results in Fig. 10 were taken from [9].

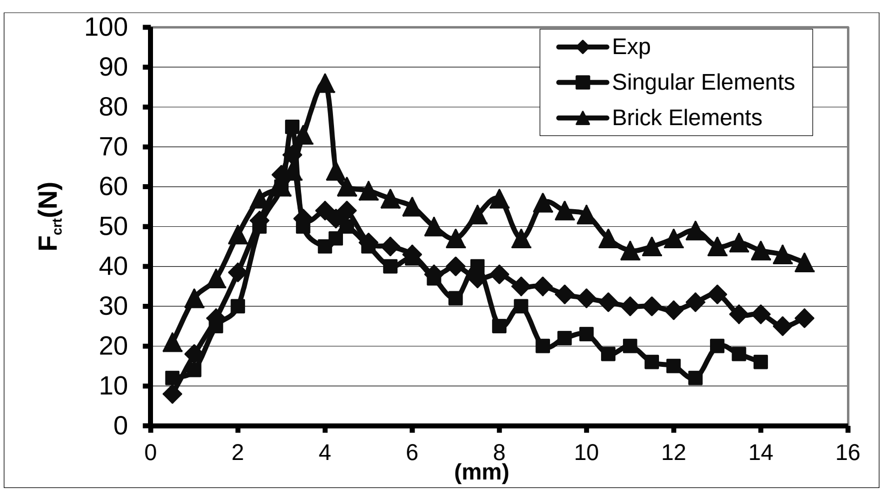


Fig. 10. Diagrams of load-displacement and comparison of numerical data with experimental data

The consequence of alternating FEM and experimental results is that the opening of the specimen increases the bending of the glass fibres. Because of the lower bending of the fibres, although this alternation is lower at the beginning of delamination, it becomes larger in the next stages. After studying the load-displacement diagram for the brick and the singular elements, it is found that singular elements produce better results than brick elements.

Using the obtained values of F_{crt} and δ_{crt} for different crack lengths, the values of C (compliance) have been computed. In Figs. 11 and 12, variation of the C versus crack length for brick and singular elements is shown. Then, the function *C* relative crack length *a* for both elements can be estimated.

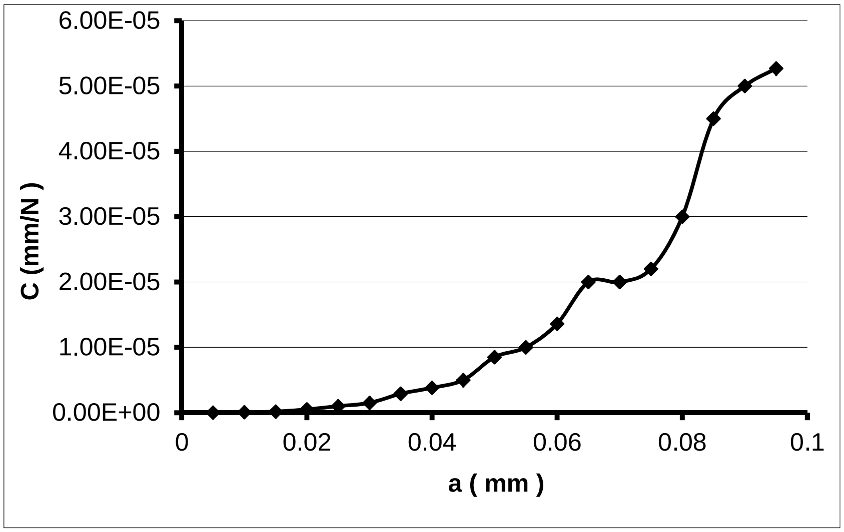


Fig. 11. Compliance versus crack length for brick elements

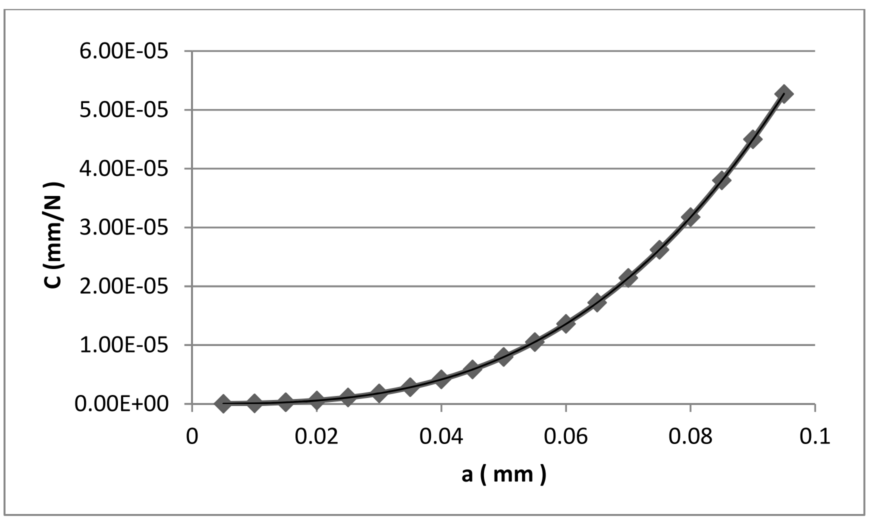


Fig. 12. Compliance versus crack length for singular elements

The obtained function for brick elements is

$$C = 0.482\, a^3 - 0.001\, a^2 - 5 \cdot 10^{-6} a + 2 \cdot 10^{-6} \tag{4}$$

If this function is derived with respect to a,

$$\frac{dC}{da} = 0.1446 a^2 - 0.002 a + 5 \cdot 10^{-6} \tag{5}$$

and using $\frac{dC}{da}$, SERR is determined. Then, the curve of the critical strain energy release rate (G_{Icrt}), which is the critical value of SERR, versus a is plotted for brick elements using the compliance theory (Fig. 13).

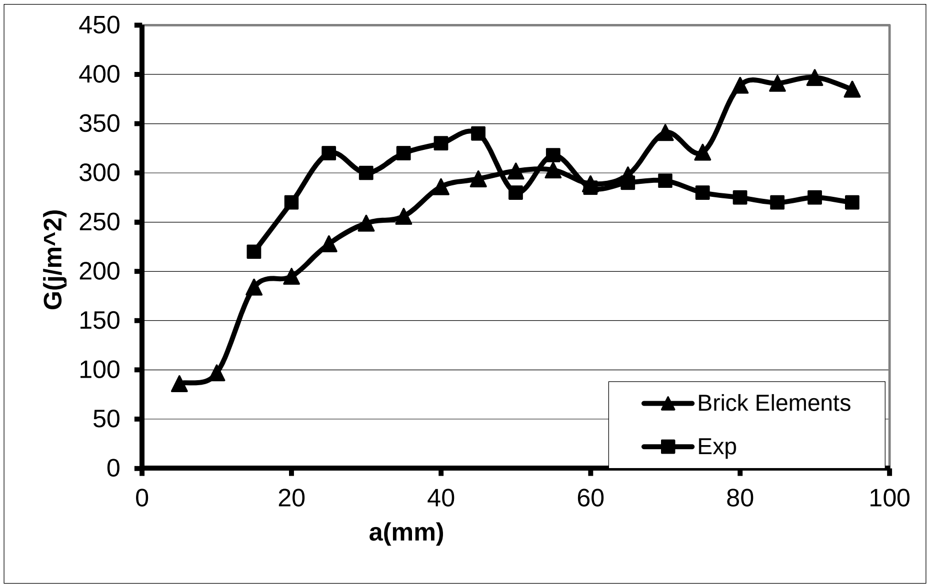


Fig. 13. Curves of strain energy release rate relative crack length for Brick elements

According to Fig. 13, which has been plotted for brick elements, while the brick elements present good results simply for the crack length between 40mm - 80mm, for the crack length before 40mm values of G_{Icrt} that are above experimental results and for crack length after 80–mm, these values drop out. Evaluation of the obtained results shows that there is a difference of 60% between the experimental and numerical results.

From the above evaluation, it can be seen that brick elements are not convenient to use. Therefore, singular elements for the solution of this problem must be used in spite of the difficulties.

The obtained function for the singular elements is:

$$C = 0.589a^3 + 0.003a^2 - 2.10^{-6}a + 2.10^{-8} \tag{6}$$

If this function is derived with respect to a, the following relation is found:

$$\frac{dC}{da} = 0.1767a^2 + 0.006a + 2.10^{-6} \tag{7}$$

and using $\frac{dC}{da}$, the Strain Energy Release Rate (SERR) is determined and the curve of G_{Icrt} versus a is plotted for singular elements using the compliance theory (Fig. 14).

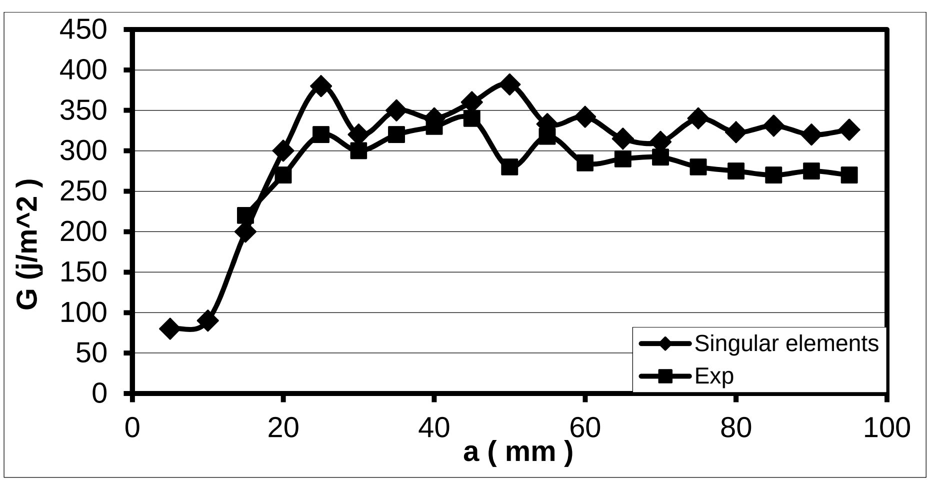


Fig. 14. Curves of strain energy release rate relative crack length for singular elements

Figure 14 indicates that the results of FEM using singular elements and experiment are comparable. We can clearly observe the growth of delamination along the weft filaments and a sudden change in the point of crossing the woof filaments. Numerical results show that there is a difference of less than 10% with the experimental results [9].

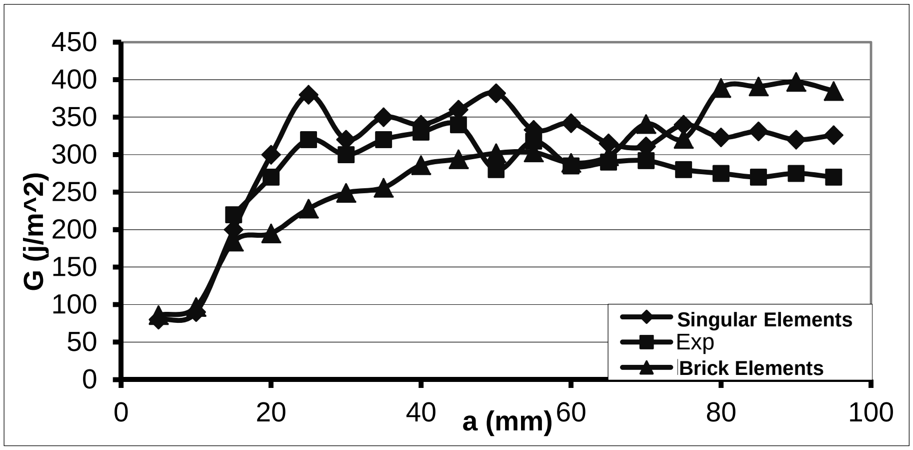


Fig. 15. Comparing the Curves of strain energy release rate relative crack length for types of elements

Finally, in comparison with the curves in Fig. 15, the difference between the results obtained for brick and singular elements shows that the results of the sample with the crack tip meshed with singular elements presents better results than those of the brick elements.

4. CONCLUSION

Because of the anisotropic constitution of the woven composites, modeling of this type of composite is too complicated; therefore a significant part of this paper is devoted to modeling. The effects of element types in the crack tip have been studied and it is concluded that using singular elements at the crack tip in a Double Cantilever Beam (DCB) presents better results than those of the brick elements.

Acknowledgments: The authors wish to thank the Research Offices of Islamic Azad University of Bonab and Ataturk University for supporting this work.

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