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Modification of Determination Procedure of Numerical 3D Correction Factor (β) of Arcan Specimen

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Abstract. In this paper the mixed-mode interlaminar fracture behavior of Carbon-Epoxy composite specimens was investigated based on numerical analyses. Study of behavior of composite materials and determining their ultimate strength seems to be an essential issue in practical engineering. Hence, the behavior of Carbon-Epoxy laminated composite is studied numerically by modeling of Arcan specimen in ABAQUS finite element software. The modeling was fulfilled in the way that loading can be carry out in different loading angles and also analyses is repeated for wide range of crack length ratio between 0.1 to 0.9. The numerical analysis was performed with ABAQUS finite element software under a constant load of 1000 N. the entire test apparatus is modeled in both 2 dimensional and 3 dimensional. Results of numerical analyses are demonstrated is several diagrams. Also, a hypothesis about boundary conditions of 2 dimensional models is investigated and has been proved. The results show that some of conventional constraints must be modified to extract right correction factors from finite element models.

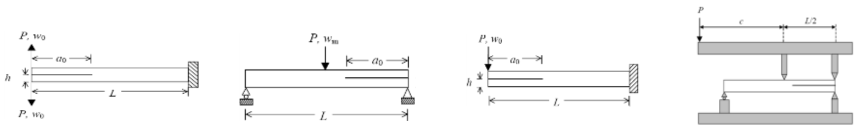
Keywords: Arcan specimen, Energy Release Rate

1 Introduction

Composite structures have been applied in many applications including the aerospace, marine, and civil industries. Preventing failure of composite material systems has been an important issue in engineering design [1]. The delamination phenomenon in a laminated composite structure may reduce the structural stiffness and strength, redistribute the load in a way that the structural failure is delayed, or may lead to structural collapse. Therefore, delamination is not necessarily the ultimate structural failure, but rather it is the part of the failure process which may ultimately lead to loss of structural integrity.

Much of numerical investigations presented in literatures lead to excellent results. In three separate studies were conducted by Krueger in NASA technical institute virtual crack closure method for calculation of j integral is investigated with different finite element software and also, crack initiation and propagation were probed with shell elements and cohesive element. This study showed that 20 node quadrilateral elements give the best results and also the results suggested that element types with similar formulation yield matching results independent of finite element software used [2-4].

There are many configuration presented for testing the delamination in mode I, mode II and mixed mode condition in literatures. Double cantilever beam (DCB) method in 1989 by Williams for mode I of fracture, End-Notch Flexure (ENF) method by Carlson in 1986 for mode II of fracture and Mixed Mode Bending (MMB) method by Crews and Reeder for first time in 1988 for mixed mode fracture are used to estimate fracture toughness of different materials (Figure 1). MMB method is modified and use for calculating the critical interlaminar fracture toughness of AS4/PEEK by Reeder in 1990 [5- 7]. Many other researchers such as Prashanat and Verma [8], Kim [9] and Dharmawan [1] calculated the critical fracture toughness of different material via DCB, ENF and MMB apparatus.



(a) (b) (c) (d)

Fig. 1. Most applicable configurations for delamination testing, (a) double cantilever beam (DCB) for mode I, (b) end-notch flexure (ENF) and (c) end load split (ELS) for mode II, (d) mixed mode bending (MMB) for mixed mode I&II testing

Arcan specimen for the first time in 1978 was presented for providing plane stress condition in fracture test of mode I, mode II and mixed mode conditions [10]. This apparatus latter was used for developing COD criterion [11]. The influence of finite geometry and type of material is studied by HalBack [12]. Yoon also evaluated the fracture toughness of Carbon-Epoxy unidirectional composite with the same specimen [13].

In this research correction factors of Arcan specimen for different loading angles is calculated via 2D and 3D finite element models separately and the results were compared. Furthermore, the influence crack length ratio is investigated in 2D condition.

2 Two Dimensional Finite Element Model

The purpose of fracture toughness testing is to determine the value of the critical stress intensity factor. This material property is used to characterize the resistance to fracture in the design of structural members. The stress intensity factors ahead of crack tip for a modified version of Arcan specimen were calculated by using the following equations:

$$K_I = \frac{P_C\sqrt{\pi a}}{wt} f_1\left(\frac{a}{w}\right) \quad (1)$$

$$K_{II} = \frac{P_C\sqrt{\pi a}}{wt} f_2\left(\frac{a}{w}\right) \quad (2)$$

where P_C in critical load at fracture, α is loading angle, *w* is specimen length, t is the specimen thickness and a is crack length. In turn K_I and K_{II} are obtained using geometrical factors $f_1(a/w)$ and $f_2(a/w)$, respectively which have to be determined through finite element models [14-15].

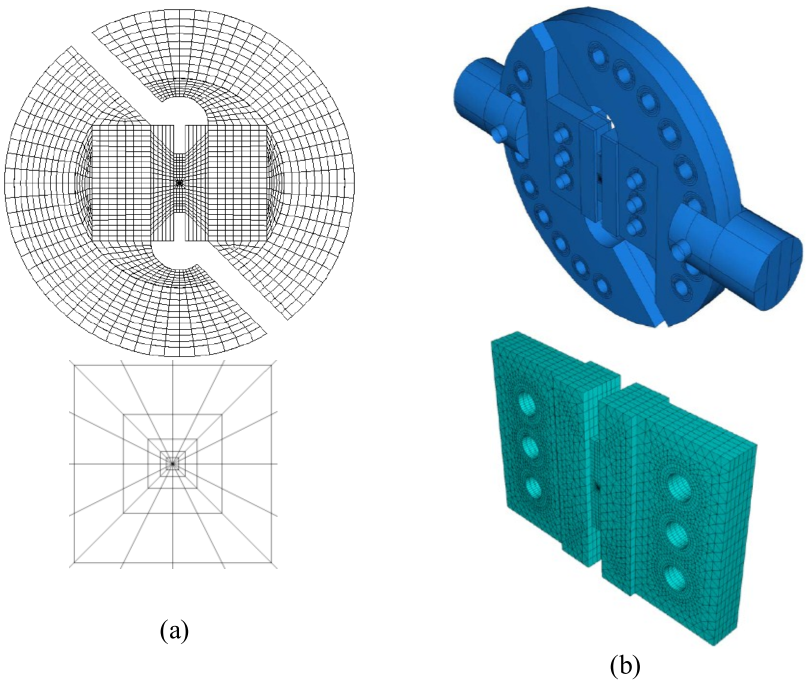


Fig. 2. Two dimensional mesh pattern (a) and mode-I three dimensional model (b)

For this purpose, the numerical analysis were performed with ABAQUS finite element software under a constant load of 1000 N. the entire apparatus was modeled using eight node collapsed quadrilateral elements and the mesh was refined around crack tip, so that the smallest element size found in the crack tip elements was approximately o.25 mm. Figure 2a demonstrates the mesh pattern of Arcan apparatus. Linear elastic finite element analysis was performed under a plain stress condition using $1/\sqrt{r}$ stress field singularity. To obtain a $1/\sqrt{r}$ singularity term of the crack tip stress field, the elements around the crack tip were focused on the crack tip and the mid-side nodes were moved to a quarter point of each element side.

3 Three Dimensional Finite Element Analysis

3D models almost always give more reliable results. For the purpose of calculation of correction factors in real conditions, 3D model of test apparatus is simulated in ABAQUS finite element software. First, 3D models as can be seen in Figure 2b were provided in SOLIDWORKS software and then were imported to the finite element software. After assigning an appropriate property to each part, the calculation domains were meshed by three types of elements, suitable for each part. The type of elements for each part was chosen in a way to achieve an accurate results for the specific purpose for which the elements were used. Quadrilateral twenty node elements were used for main specimen and mesh is refined at the crack tip. Also In 3D condition, to obtain the $1/\sqrt{r}$ singularity term of the crack tip stress field, elements around the crack tip must focus on the crack tip and the mid-side nodes have to move to a quarter point of each element side so wedge 15-node element would fulfill this purpose [16].

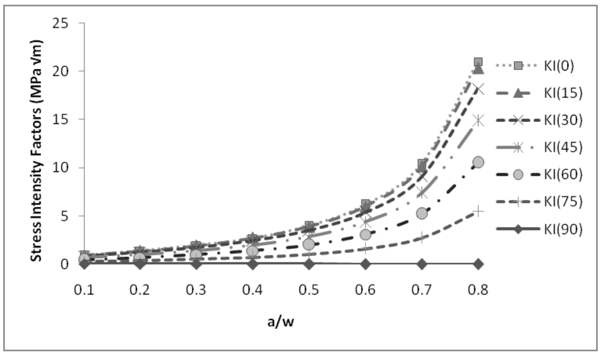


Fig. 3. change of mode-I stress intensity factor versus crack length ratio

4 Results and discussion

4.1 effects of crack length ratio on fracture parameters

Figure 3 shows the effect of increase of loading angle and crack length ratio on stress intensity factors of mode-I. Increase of loading angle decreases the stress intensity factors of mode-I, also, increase of crack length according to Equation 3 and 4, increases the normal stress acting at crack tip and as a result, the stress intensity factors. [17, 18]

$$\sigma_{yy} = \sigma_a \left\{ 1 + \sqrt{\frac{a}{r}} \left[2\left(\sqrt{\frac{E_{yy}}{E_{xx}}} - \nu_{yx} \right) + \frac{E_{yy}}{G_{xy}} \right]^{\frac{1}{2}} \right\} \quad (3)$$

$$K_I = \lim_{r \to 0} \sigma_{yy} \sqrt{2\pi . r} \quad (4)$$

Variation of mixed-mode ratio due to change of crack length ratio for different loading angles were presented in Figure 4. In this figure increase of crack length causes a light reduction in mixed mode ratio, this means that increasing of crack length leads to increase of influence of mode-I in fracture process by increasing the energy released rate of GI, in other words, growth of crack length, reduce the resistance of mode-I material more than resistance of mode-II and as a result, the tendency to mode-I fracture increases.

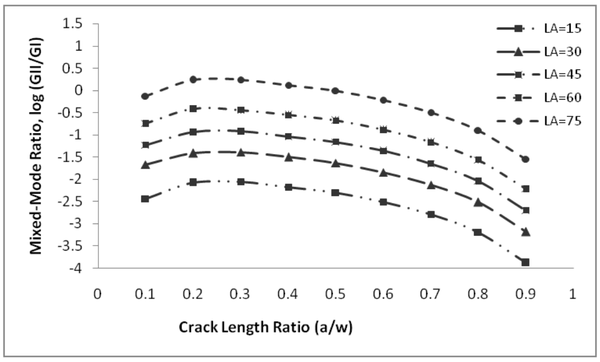


Fig. 4. change of mixed-mode ratio, $\log(G_{II}/G_I)$, versus crack length ratio

4.2 Correction factors

In order to determine fracture toughness from Equation 1 and 2 the correction factor of $f_1(a/w)$ and $f_2(a/w)$ must be calculated through finite element modeling of specimen. The geometrical factor or non-dimensional stress intensity factor for

Carbon-Epoxy composite is shown in Figure (5). In these diagrams, which were obtained via 2D and 3D finite element models, the change of non-dimensional stress intensity factor $f_1(a/w)$ and $f_2(a/w)$ for different loading angles was presented.

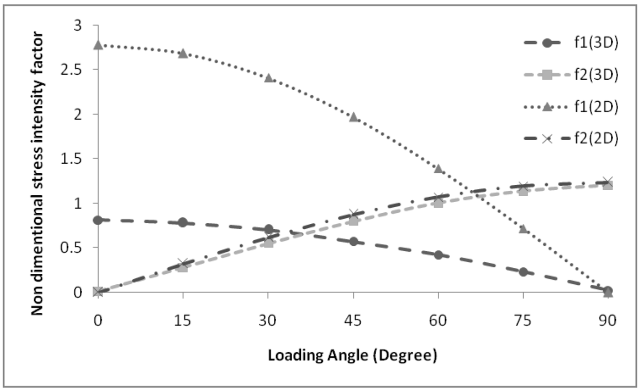


Fig. 5. Non dimensional stress intensity factor vs. loading angle for Carbon-Epoxy composite material

As can be observed in the Figure 5, 2D results for correction factors are very different from 3D results although mode-II geometrical factors of two models are close to each other relative to mode-I factors but still the results have significant disparity.

There are some evidences with which this difference can be explained. The first reason is the nature of two kind of simulation. In other words, several parameters exist which do not involved in two dimensional simulations. The place where the specimen is installed, imperfection of specimen and deformation of different parts of testing device are some of these factors which may lead to some differences between simulations. But, in fact, any of these parameters cannot make such disparity between results. The most important reason is the way in which the boundary condition of two-dimensional model is assigned. However, these test never simulated three dimensionally so far, to check which of the boundary conditions are necessary and how they must be applied to model in order to achieve the right correction factors. In other words, the different boundary condition may dramatically change the results, so a three dimensional model which can exhibit the whole process of the test can help us excessively to choose appropriate boundary conditions. Deformed shape of crack tip of 2D and 3D models for pure mode-I are demonstrated in Figure 6. As can be seen, the deformation of crack tips is not similar in two figures, which attest to an existence of a rotation in 2D model which is a result of incompatibility of boundary conditions.

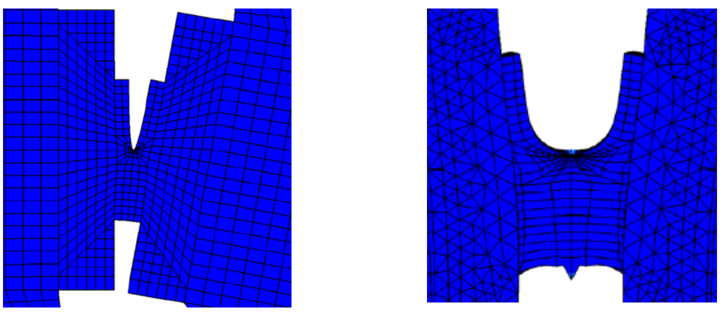
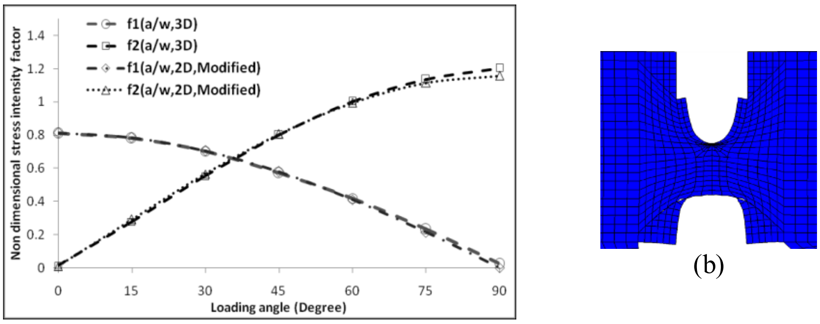


Fig. 6. deformed shape of mode-I for 2D and 3D models



(a) (b)

Fig. 7. Modified correction factors (a) and deformed shape of crack tip of modified

To obtain an accurate 2D model it is essential to modify conventional boundary conditions. For this purpose, a new boundary condition is proposed for 2D model and also these constraints are applied to check the hypothesis. Deformed shape of mode-I loading of modified 2D model is demonstrated in Figure 7b. An obvious improvement can be observed in model response which is in good accordance with 3D response. Furthermore, the effect of this change on correction factors is investigated in Figure 7a. Improvement in results is ostensible and in many cases correction factors determined via 2D models are almost as same as 3D results.

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