Investigation of interlaminar mode-I fracture toughness of corrugated composite plates

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ABSTRACT

In this study, delamination of the corrugated composite plates made of unidirectional glass fibers and polyester resin has been investigated. The samples are fabricated by hand lay-up process based on ASTM-D5528 standard. Using experimental tests, the strain energy release rate in mode *I* has been calculated for composite corrugated specimens by the prevalent method of interlaminar failure. Also, the samples were simulated as a double cantilever beam by Abaqus software and the mechanical properties of unidirectional glass/polyester composite and the results of numerical solution are also obtained. Fracture surfaces of experimental samples were analyzed by scanning electron microscope. Force-displacement curves obtained from experimental and numerical methods have been campred to find the material behavior and calculate the strain energy release rate for different samples with three pre-crack lengths. The results show that the corrugated composite plates have a higher interlaminar fracture toughness rather than flat samples and the four-wave sample with a crack length of 60 and 65 mm has the highest values of the strain energy rate released, equal to 963.77 $\frac{j}{m^2}$ and 705.95 $\frac{j}{m^2}$, respectively.

KEYWORDS

Corrugated composite plates, delamination, fracture toughness, strain energy, failure mode *I*

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Introduction

Delamination is one of the failure mode in laminated composites. The growth of interlaminar cracks can occurs in three ways or a combination of them. The strain energy release rate is used as a measure of prediction of crack growth, and when its value is equal to a critical value, crack growth occurs. The Double Cantilever Beam method is the main procedure to find the strain energy release rate of the mode *I*, and to express the mode *I* of failure the composite interlaminar, this sample is made and tested [1]. An Asymmetric Double Cantilever Beam is also used to study the Delamination of Mixed Mode *I/II*. Tay [2] has reviewed studies on the Mixed Mode *I/II*. Shokrieh and Zeinedini [3] proposed a new method for predicting the Mixed Mode *I/II* failure of interlaminar fracture toughness. They presented the relationship between the fracture toughness of Double Cantilever Beam and Asymmetric Double Cantilever Beam. Dalli et al. [4] studied the Delamination of mode *I* in carbon fiber reinforced composites.

A review of previous studies shows that the effect of corrugation on interlaminar fracture toughness in composite plates has not been investigated so far. Also, by increasing applications of corrugated plates, it is necessary to study the delamination and failure modes of this structures. Therefore, in this study, the interlaminar delamination of corrugated composite plates with different wave geometries has been investigated. For this purpose, different geometries have been considered and the modeling has been done using Abaqus software. Experimental studies have been done to validate the results.

Modeling and experiments

2.1. Modified beam theory

According to the energy method, crack growth occurs when the amount of energy available for crack growth is such that it is able to overcome the resistance of the material at the crack tip. In linear elastic materials, the rate of energy release *G* is presented as the rate of change in potential energy relative to the change in crack levels in the material. When $G = G_c$, failure is occurred. G_c is the critical strain rate. In the modified beam theory method, the strain energy release rate is obtained from the following equation [1].

$$GIc = \frac{3 p_c \delta_c}{2b\left(a + |\Delta|\right)}$$

In this equation, a, b, P and $|\Delta|$ are initial crack length, sample width, applied load, displacement and crack correction factor for opening and rotating of the crack tip, respectively Figure 1. The modified beam theory method is the most efficient method to calculate the mode *I* interlaminar fracture toughness.

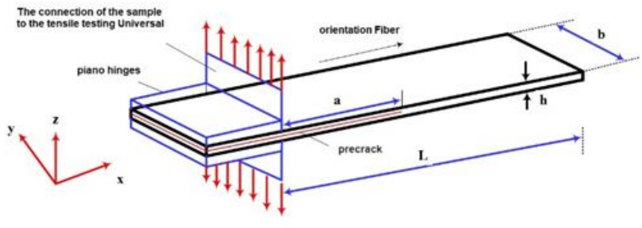

FIG. 1 Double Cantilever Beam Specimen

To correct and eliminate the rotation of the Cantilever Beam, the correction value $|\Delta|$ is added to equation (1) as if it has a slightly longer delamination ($a + |\Delta|$). This correction value $|\Delta|$ is obtained experimentally from the plot of the cube root of compliance $c = (\delta / p)$.

2.2. Fabrication of test specimens

Composite specimens of Double Cantilever Beam *(DCB)* are prepared according to ASTM-D5528 standard. The *DCB* sample has length L = 195mm, width b = 23mm, and thickness h = 3.5mm Figure 2. The specimens are fixed in the test set-up and the load is applied to the upper edge of the sample. Applied load and displacements are continuously recorded by the SANTAM Universal Testing Machine (*STM-120*).

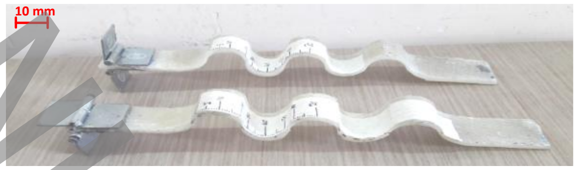

FIG. 2 specimens made according to the standard

2.3. Finite element modeling

In this research, finite element modeling of mode *I* failure has been done using Abaqus software. Three-wave, four-wave, and flat, Double Cantilever Beam specimens are modeled in two dimensions. It should be noted that the mechanical properties of composite layers are required to perform the required simulations. Therefore, for this purpose, tensile test specimens are made according to ASTM D3039 standard and are subjected to tensile testing.

Results and Discussion

Load–displacement curves for specimens are obtained using FE simulations and experiments. Also, the values of strain energy release rate are obtained and compared with experimental results.

3.1. Experimental results

The Double Cantilever Beam test is done at speed 2.5 mm/min. Results in figure 3 show that the four-wave specimens with crack length of 60 mm and 65 mm have the highest G_I values 963.77 $\frac{j}{m^2}$ and 705.95 $\frac{j}{m^2}$, respectively. It is seen that for crack length 70 mm, the three-wave specimen has a strain energy release rate 421.05 $\frac{j}{m^2}$. If delamination in a composite specimen is considered as a damage, the strength and mechanical properties of the composite material should be reduced by increasing the delamination length. Almost in all specimens, the Load -displacement curves show this behavior.

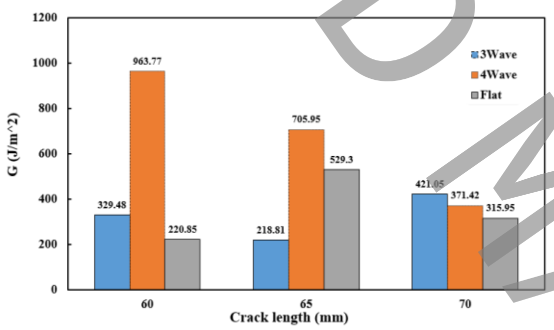

FIG. 3 G_I for specimens with different crack length

3.2. Numerical results

Specimens of three-wave, four-wave and flat, Double Cantilever Beam are modeled in two dimensions using Abaqus software. The initial crack simulation and the Shell-Planar model are used. It is seen that the four-wave specimen with a crack length 60 mm has the highest G_I with magnitude 702.16 $\frac{j}{m^2}$. The three-wave specimen with crack length 65mm gives the highest strain energy release rate 565.05 $\frac{j}{m^2}$ and at a crack length of 70 mm, the four-wave specimen has the highest G_I value 491.42 $\frac{j}{m^2}$.

Conclusions

In this paper, the delamination of the mode I in corrugated composite plates with different number of waves as well as flat plates is evaluated experimentally and numerically. Specimens are fabricated with unidirectional glass fibers and polyester resin. The values of the strain energy release rate are calculated by analytical relations. Comparison of numerical and experimental results is done by considering different number of waves and crack length. The results showed that:

•The magnitude of critical force decreases as the delamination length increases, but the corresponding displacement increases.

•The Load–displacement curves tends to be more stable as the delamination length increases.

•The results showed that in all specimens there is a stable delamination growth and crack only grow near the pre-crack location.

•By analyzing the curves of the strain energy release rate in both experimental and numerical methods, it is obtained that a specimen with four waves has a highest value of strain energy release rate.

•By comparing the results it is found that corrugated plates have a high resistance to crack growth compared with flat plates and the strain energy rate released in corrugated plates is higher than flat plates.

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