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Mode-I Fracture Toughness Investigation on Carbon/Glass Hybrid Composites

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ABSTRACT

Mode-I fracture toughness of carbon/glass reinforced polyester hybrid composites was experimentally and numerically investigated by using the COSMOS/M 2.6 finite element software after manufactured by utilizing the hand lay-up technique. The single edge notch-bending test was developed to evaluate the mode-I fracture toughness of the carbon composites, glass composites and hybrid composites at various fiber configurations. Scanning electron microscope was used to examine the fractured surfaces of hybrid composites under the effect of mode-I loading. The experimental results showed the stress intensity factor was reached to 882.34 MPa.mm$^{1/2}$ for the hybrid composites with stacking sequences [C/G/G/C] during the mode-I loading compared to the other stacking sequences. Glass fiber enhanced the stress intensity factors of the hybrid composite when the glass fibers are placed at the middle portion between the carbon layers. In addition, the experimental results are in good agreement with the finite element modeling.

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1. INTRODUCTION

Hybrid Composites are considered one of the most developed materials due to the light weight, high rigidity, low manufacturing costs and good corrosion resistance so they are used in automotive parts, aerospace, aircraft and wind turbines [1-3]. The hybrid composites consisting of polymer matrix such as polyester or epoxy and glass, carbon and Kevlar fiber which are used as a reinforcement in the matrix resin [4]. Fracture toughness is one of the most important tools of the material that can be used to measure the resistance to crack propagation. In addition, the enhancement in the fracture toughness and crack arresting of a composite material attributed to the hybridization. Number of the researchers investigated on the fracture behavior of the hybrid composites under the effect of mode-I loading conditions. Damage deformation mechanisms are instrumental in redistributing the overstresses around the notch; therefore, improving their fracture behavior [5-7]. In addition, various specimen types such as compact tension specimens (CTS), end notch flexure (ENF) specimens and single edge notch bending (SENB) were used to evaluate the mode-I fracture toughness [8-10]. Jung and Kim [11] investigated the fracture toughness of carbon-glass/epoxy hybrid composites after fabricate by using vacuum assisted resin transfer molding and found that the fracture toughness reduced with increasing in glass fiber content. In addition, Arasan et al. [12] studied the influences of the crack length and position on the fracture strength of the hybrid and non-hybrid composite plates. They concluded that the fracture toughness of hybrid and non-hybrid composites increased with the crack length increased. The CT specimen was used to evaluate the mode-I fracture behavior of glass-carbon/epoxy hybrid composites experimental and numerically. For mode I, the stress intensity factors of the tensile sample was larger along with fiber orientation [13]. The stress intensity factor (K_{IC}) was 24% error in results compared to the experimental work. The fracture strength of carbon-basalt/ epoxy hybrid composites was studied under the effect of Mode I fracture test by using CT specimen and found that the fracture toughness of hybrid composites decreased with an increase in the basalt fiber percent at the core between the carbon fabrics [14]. Santhanam et

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al. [15] performed the compact tension test to determine the Mode I fracture toughness for banana fiber and Glass fiber reinforced polyester matrix composites. The fracture toughness of banana fiber reinforced composite is in close agreement with glass fiber. In addition, Harikrishnan et al. [16] used jute/glass fibre hybrid composite to evaluate the fracture toughness experimental and numerically. The glass fiber composites exhibited maximum fracture toughness was 131.90 MPa.mm$^{1/2}$. Abdel Ghafaar et al. [17] established three different types of woven fibers in the epoxy resin and prepared by hand lay-up method to evaluate the mechanical properties under the effect of bending loads and observed that the maximum values of the flexural strength and modulus at CFRP compared to the hybrid composites and GFRP were 360 MPa, 17.11 MPa, respectively. In addition, Chinta et al. [18] carried out the single edge notch bending (SENB) to study the mode-I fracture toughness for non-hybrid woven carbon/epoxy (C20), and hybrid carbon core composite (G5C10G5), experimentally and finite element modeling (ANSYS). The non-hybrid carbon composite exhibited higher fracture toughness than that the other laminates. Kaleemulla et al. [19] reported the various notch configurations to evaluate the fracture behavior of glass- textile satin /epoxy hybrid composites and found that fracture toughness increase with an increasing in the glass fabric. The effect of displacement rates on the mode I of the carbon/epoxy composites fracture using double cantilever beam (DCB) test were experimentally and numerically investigated. For all displacement rates (1, 10, 100, 500 mm/min), it was found that there is no fibre bridging and the experimental work is in a good agreement with the numerical analysis with maximum error (15%) [20]. The maximum principle stress (MPS) theory was used to evaluate the crack propagation angle of CLS, MMF specimens of the epoxy/ glass composites and found that the fiber/ matrix interface plays an important role in determination of the crack propagation path direction [21].

The paper aimed to study the effect of the fiber configurations of the carbon/glass reinforced polyester hybrid composites on the fracture toughness after utilizing the single edge notch bending (SENB) test. The critical stress intensity factor K_{IC} for the various fiber configurations experimentally and by finite element modeling (COSMOS/M 2.6) for the GFRP, CFRP, and glass-carbon/polyester hybrid composites was investigated. Fracture analyses of the hybrid and non-hybrid specimens were examined by scanning electron microscope (SEM).

2. EXPERIMENTAL WORK

2. 1. Materials and Specimens Fabrication

In this paper, two types of fabrics are used as reinforcement for fabrication the hybrid composites, twill weaves (2x2) carbon fabric (C120-3K) and E-glass fabric (biaxial weave 300 g/sqmt). Beside, the unsaturated polyester resin was used as a matrix. The manual hand layup technique was developed for manufacturing the non-hybrid and hybrid composites as a form of four layers. The details about the used technique and properties of the reinforcement and polyester resin are reported in previous publications [22-24]. The designation and stacking configuration of hybrid and non-hybrid composites are listed in Table 1 and Figure 1.

2. 2. Mode-I Fracture Test

According to ASTM D5045-99, Mode-I fracture toughness test for non-hybrid and carbon/glass reinforced polyester hybrid composites with different fiber configurations was conducted on SENB specimens with a thickness of 4 mm, as shown in Figure 2 [25]. Fracture test were carried out on the universal testing machine (INSTRON 8801) at a cross speed of 0.05 mm/min. The pre-crack length was 1 ± 0.01mm and cut by disc saw along the mid-span of each specimen of hybrid and non-hybrid composites. Five samples were tested for each laminate.

Mode-I stress intensity factor can be determined by Equation (1):

TABLE 1. Designation of hybrid and non-hybrid composites

Laminates	*Stacking sequences*	**Carbon and glass contents (wt.%)**	**Volume fraction of carbon/glass (vt.%)**
C	[C/C/C/C]	60/0	50.15/0
G	[G/G/G/G]	0/60	0/40.37
L1	[C/G/G/C]	30/30	27.31/18.37
L2	[G/C/C/G]	30/30	27.31/18.37
L3	[C/G/C/G]	30/30	27.31/18.37
L4	[G/C/G/C]	30/30	27.31/18.37

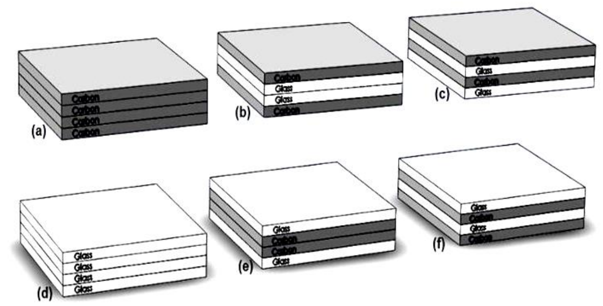

Figure 1. Stacking configuration of a) 4 C, b) C/2G/C, c) C/G/C/G, d) 4 G, e) G/2C/G, f) G/C/G/C structure of the hybrid and non-hybrid composites

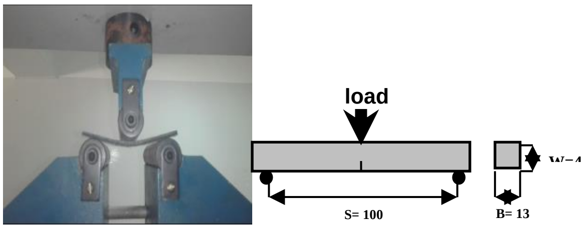

Figure 2. Universal testing machine showing the SENB during the fracture toughness test, (Dimensions in mm)

$$K_{IC} = \left(\frac{P}{BW^{\frac{1}{2}}}\right) f\left(\frac{a}{w}\right) \quad (1)$$

where B, w and a are the sample thickness (mm), width (mm) and crack length (mm), P and KIC are the fracture load and the mode-I stress intensity factors and F (a/w) is the correlation factors. The ratio between a and w was 0.25, where a is the pre-crack length, w is the thickness, and B is the width of the specimen. The applied load was vertically affected at the center of the specimen. The maximum load Pmax was experimentally estimated by using load displacement curve of each laminate .The crack geometry factors f (a/w) can be estimated as follows by Equation (2) [26, 27].

$$f\left(\frac{a}{w}\right) = 6x^{\frac{1}{2}}\left(\frac{[1.99-x(1-x)(2.15-3.93+2.7x^2]}{(1+2x)(1-x)^{3/2}}\right) \quad (2)$$

3. FINITE ELEMENT MODELING

Finite element modelling was employed to investigated the fracture parameters such as the stress intensity factor (KIC) and the crack propagation angle specially aroud the crack edge region under the plain strain condition. COSMOS/M 2.6 finite element package was used to perform the linear elastic stress analysis of the SENB specimen [28]. The non-hybrid and hybrid composites at variuos stacking sequenes were anlyzed by using the SENB sample under the effect of mode-I loading. COSMOS/M 2.6 mesh is the element type which used in the present numerical anlysis. The conditions for the front and real edges were (Uy = 0), where the meshing of the SENB specimen is consist of 28823 element and 45486 nodes, as shown in Figure 3.

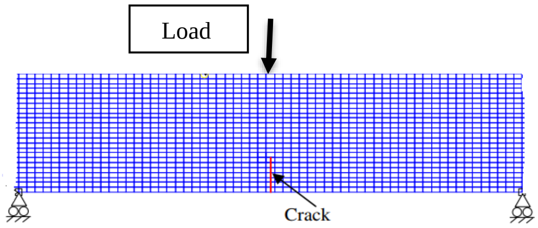

Figure 3. Load and boundry conditions of SENB specimen

4. RESULTS AND DISCUSSIONS

4. 1. Mode-I Fracture Behavior

The SENB test was used to predict the critical stress intensity factor and the crack path at the tip of crack of hybrid and non-hybrid composites at varuos configuations under the effect of Mode-I loading. However, the critical stress intensity factor (K_I) was determined by using the analytical formulas Equations (1) and (2). Figures 4a and 4b show the load displacement curves after the fracture test of the carbon/ glass reinforced polyester hybrid composites with variuos stacking sequences [C/G/G/C] and [C/C/C/C]. In addition, the load dispacement curves have an initially linear behaviuor (stable crack) then the load drops until reached to the maximum value (un stable crack). As shown in Figure 3a. It was observed that the maximum load was 5.77 KN ocured at the hybrid composite with stacking sequence [C/G/G/C]. While, for the glass composites (non-hybrid), Figure 4b, reached to 4.40 KN.

Figure 5 shows the principle stress contours of hybrid composites with stacking sequences [C/G/G/C] under the effect of Mode-I loading to MPS criteria around the crack tip. The stress field at the crack tip varies with $1/\sqrt{r}$, where r is the radial distance. For carbon-glass/polyester hybrid composite, it can be observed that the stresses are high theoretically tending to infinite at the tip of crack. Therefore, this region called stress singularity due to the reduction of radial distance to its minimum value. As shown in this figure, the maximum stresses are noticed at the region of crack tip and on this basis, the internal stresses developed here often exceed the yield stress of the used hybrid material, which makes it soften, and then crack easily propagated.

Expermental and numerical results of the critical stress intensity factor (K_{IC}) of the hybrid and non-hybrid composites at various stacking sequences under the mode I loading are sumerized in Table 2.

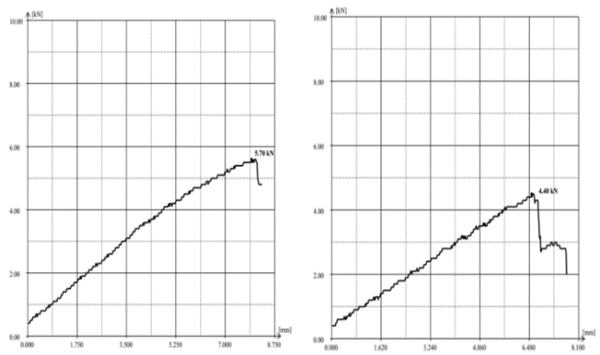

Figure 4. Load displacement curves of hybrid and non- hybrid composites with stacking sequence a) Laminate [C/G/G/C], b) Laminate [G/G/G/G]

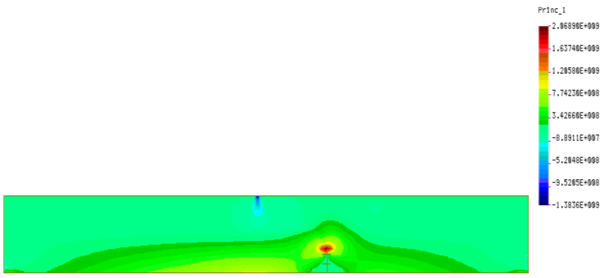

Figure 5. Principle stress concentration of SENB specimen under mode I loading of laminate L1 with stacking sequences [C/G/G/C], numerically

It can be evidented that, the hybrid composites with outer carbon layers [C/2G/C] has highest stress intensity factor value (881.34 MPa. mm$^{1/2}$) compared to the stress intensity factor (686.60 MPa. mm$^{1/2}$) with outer glass layers (G/2C/G). However, the critical stress intensity factor was affected by the different fiber arrangement and the equal number of carbon and glass layers of the all hybrid composites. The maximum value of the stress intensity factor of laminate L3 with stacking sequence [C/2G/C] due to the high stiffness of carbon fiber at the core (center). This is leads to the highest resistance of crack propagation at the tipe of crack. In addition, the glass composites (G) with stacking sequence [G/G/G/G] exhibited minimum value of the stress intemsity factor (672.84 MPa. mm$^{1/2}$). The reduction in stress intensity factor of this composite was attributed to a lower resistance to crack initiation and propagation among to the other laminates. The difference in stress intensity factor between fiber configurations [C/G/G/C], [C/G/C/G is not large. This is due to the reinforcing position of glass fiber may affect the fracture resistance of the hybrid composites. The numerical modeling results have a good agreement with experimental results. The maximum error in the numerical and experimental results of the stress intensity factor was 5.16% in the hybrid and non-hybrid composites specimen. The crack propagation was determined according to the maximum principle stress criterion. In this criterion, the crack was propagated in normal direction to the maximum principle stress criterion (MPSC). The stress distribution around the crack tip of the laminate L1 with stacking sequences [C/G/G/C] is shown in Figure 6. As the seen in this figure, it was noted that the value of the principle stress is high, theoretically tending to infinite (stress singularity) at the crack tip and decreases as the redial distance is increased. From the stress distributions at the crack tip, it can be seen that the point of the maximum principle was tangent to the crack tip.

TABLE 2. Experimental and numerical results of the stress intensity factor

Laminates	*Stacking sequences*	**Max force (KN)**	**$K_{IC\ Exp}$ (MPa. mm$^{1/2}$)**	**$K_{IC\ Nn}$ (MPa. mm$^{1/2}$)**	**Error (%)**
C	[C/C/C/C]	4.98	761.52	765.34	3.82
G	[G/G/G/G]	4.40	672.84	677.65	4.81
L1	[C/G/G/C]	5.77	882.34	885.21	2.87
L2	[G/C/C/G]	4.49	686.60	691.76	5.16
L3	[C/G/C/G]	5.70	871.63	874.69	3.06
L4	[G/C/G/C]	5.72	874.69	879.27	4.58

4. 2. Fracture Surface Figures 7 and 8 show the fractographs of mode-I fractured surface of the hybrid composites with laminates L1 and L2, sequentially. For hybrid composite with laminate L1 as shown in Figure 7, it was clearly that there is good bonding between carbon and glass fibers and matrix phase. In addition, minimum fiber pull-out may be observed. In this case, stable and homogenous by distributes voids are created upon fiber-matrix debonding under state loading.

As shown in Figure 8, there are, some fibers were peeled out. In addition to, the traces of fibers in the polyester resin regions mixed with the pores, voids and debonded fibers. This is leads to the reduction in stress intensity factors of laminate L1 with stacking sequences [G/C/C/G].

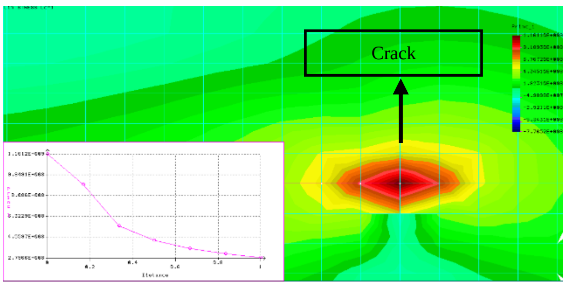

Figure 6. Crack propagation direction for mode I loading with stacking sequences [C/G/G/C], numerically

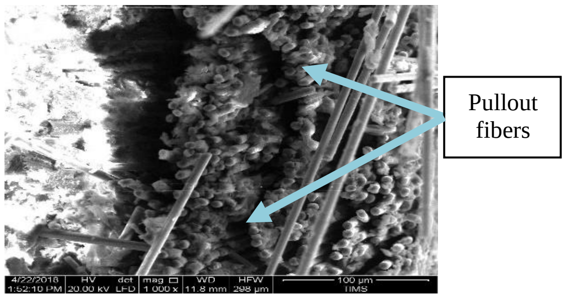

Figure 7. Fracture surface of the hybrid composites with combinations L1 [C-G-G-C]

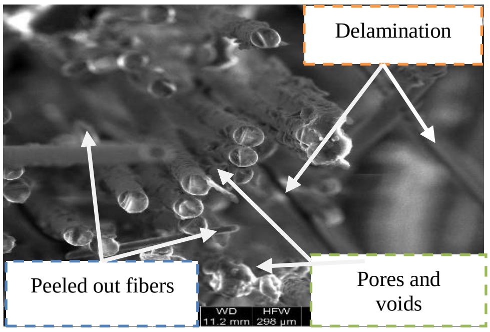

Figure 8. SEM image of the hybrid composite with L2 with stacking sequence [G/C/C/G]

5. CONCLUSIONS

The influences of fiber configurations of the glass/carbon reinforced polyester hybrid composites on the mode-I fracture toughness experimentally by using the SENB test and the finite element modeling were investigated. In the experimental results, it was observed that the hybrid composite with stacking sequence [C/G/G/C] exhibited maximum value of stress intensity factor (16.35 MPa. $mm^{1/2}$), while the minimum stress intensity factor was (12.18 MPa. $mm^{1/2}$), obtained in the glass composites [4G]. For hybrid composites with fiber configurations [C/G/G/C], The position of the glass fiber is affect the stress intensity factor. Glass fiber leads to an improving in the stress intensity factor of the hybrid composite when the glass fibers are placed at the middle portion. The maximum principle stress criterion (MPSC) was effective to predict the crack propagation path for the mode I fracture toughness. The finite element results of the stress intensity factors (KIC) are a good agreement with the experimental results.

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Persian Abstract

چکیده

چقرمگی شکست حالت کامپوزیت های ترکیبی پلی استر تقویت شده با کربن/شیشه به صورت تجربی و عددی با استفاده از نرم افزار اجزای محدود COSMOS/M ۲.۶ پس از ساخت با استفاده از تکنیک چیدمان دستی مورد بررسی قرار گرفت. آزمون پرتوی تک لبه برای ارزیابی چقرمگی شکست حالت کامپوزیت های کربن ، کامپوزیت های شیشه ای و کامپوزیت های ترکیبی در پیکربندی های مختلف الیاف توسعه داده شد. میکروسکوپ الکترونی روبشی برای بررسی سطوح شکسته کامپوزیت های ترکیبی تحت تأثیر بارگذاری حالت I استفاده شد. نتایج تجربی نشان داد حداکثر ضریب شدت تنش ۸۸۲.۳۴ MPa.mm۱/۲ بود که در کامپوزیت های ترکیبی با توالی انباشته [C/G/G/C] در طول بارگذاری حالت I در مقایسه با سایر توالی های انباشته به دست آمد. این به سطحی مناسب بین کربن و الیاف شیشه و فاز ماتریسی نسبت داده می شود. از نتایج بدست آمده، نشان داده است که نتایج تجربی با مدل سازی عناصر محدود مطابقت خوبی دارد.