Effect of Interlaminated Carbon and Basalt Fiber Reinforced Hybrid Composites on Mode I Fracture Toughness

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Abstract. The fracture toughness and failure behavior of interlaminated hybrid composites were investigated. Hybrid interlaminated carbon and basalt fibers have been manufactured by fluid injection molding. The compact tension (CT) from hybrid composite panel has been used for Mode-I tension tests based on ASTM-D5045 standards. The experiment was aimed at investigating the stress intensity factor ($K_{IC}$) of interlaminated hybrid composites having different stacking of carbon and basalt fibers. The experimental results showed that hybrid composites with configuration CBCBC (B2 code) have maximum average values about 5.8% and 2.0% higher than the C₁ and B₁ configurations, respectively. Replacing 20%, 30%, and 40% carbon by basalt fibers led to decrease in stress intensity factors ($K_{IC}$) by 8.87%, 7.56%, and 5.46%, respectively. Additionally, SEM measurements showed that the dominant failures that occurred include delamination, pull-out fiber to epoxy and fiber splitting. Thus, the fracture toughness of composites is significantly influenced by interlaminated hybrid composite epoxies.

Keywords: Intensity factor, Fracture toughness; Failure, Hybrid composites; Interlaminated

1. Introduction

Hybrid composites are a combination of reinforcements in single matrices that were developed due to the challenges involved in obtaining new materials [1, 2]. They offer numerous advantages such as superior stiffness and strength, ease of fabrication, corrosion resistance, light weight and low costs [2]. Therefore they have been widely employed in automobile components, boats, sport equipment, etc. [3]. However, composite materials have the disadvantages of brittleness and low toughness; thus, they have been widely investigated in recent years. During the last two decades, natural fibers have been commonly used for the strengthening of composites. Basalt fibers are a new type of fibers in composite reinforcement, and they are a natural resource from volcanic rock. Most combinations of carbon and basalt fibers have resulted in improved mechanical, thermal, and environmental properties. Basalt fiber is analogous to glass fiber produced by the melting of volcanic rock at a temperature of 1700 °C [4-6]. Basalt fibers have mechanical properties similar to glass fibers. Moreover, they are non-toxic, eco-friendly and easy to recycle. There have been several studies focused on the mechanical properties of
basalt fibers as a reinforcement on composites [4-13].

As described above, fracture toughness is an important structural property of composite materials. Fracture toughness is the ability of composites containing a crack to resist propagation fracture. Cracks on a material cause a decrease in its strength [14]. In many cases, increasing the crack length on materials significantly decreases their static strength. This is usually the case in brittle materials, hence they have low fracture toughness. Laffan, et.al [15] reviewed the fracture toughness associated with translaminar failure modes of continuously reinforced laminated composites. They presented measurements on the toughness linked with failure modes, and showed that several steps need to be taken before a resistance curve can be fully characterized. Evaluation and standardization in terms of the linear elastic fracture mechanics as well as the elastic-plastic fracture mechanics parameters have been previously studied [16]. Chamhho et.al [17] studied the fracture toughness based on the analytical model with an aim to calculate the mode I fracture toughness of a multidirectional laminate material. Additionally, the fracture toughness of hybrid composites have also been studied [18-21].

In this work, the interlamination of carbon and basalt fibers has been performed with the purpose of improving the toughness behavior of carbon fiber reinforced polymers (CFRP). This has not been studied previously for mode I fracture toughness of hybrid composites. Additionally, our aim is to also investigate the resistance of an interlamination of basalt fibers on carbon fibers to loads capable of causing brittle or ductile crack extension.

In order to realize this, CT specimens were prepared according to the ASTM D 5045 standards. The critical stress intensity factor (KIC) has been calculated by the compliance method to predict the fracture toughness of hybrid composites. The failures of hybrid composites after the tests have been analyzed using a scanning electron microscope (SEM).

2. Experimental method

2.1 Materials

In this work, two different phases of woven fibers have been employed for the strengthening of composites. Carbon plain weave fabrics (C120-3K), produced by Hyundai Fiber Co. Ltd. (Korea), have been used as the main filler, and basalt plain weave fabrics (EcoB4-F210), fabricated by Seco-Tech (Korea), have been used as the complementary filler. A thermosetting polymer, like an epoxy resin (HTC-667C), modified with an aliphatic amine hardener, produced by Jet Korea Industrial Corporation, was used as the matrix [10]. Table 1 shows the interlaminated variation hybrid composites where C and B represent carbon fibers and basalt fibers respectively. Additionally, alcohol and wax were used as supporter materials for the injection molding processes.

2.2 Fabrication of hybrid composites

In this experiment, laminated hybrid composites, containing woven plain fabric carbon and basalt with epoxy resin matrices were fabricated, and coded as CFRP and BFRP respectively. Eighty layers of both fabrics were laminated. Basalt fabrics replaced the carbon fabrics by 10% to 40%. Hybrid composite panels were fabricated according to weight fraction in the filler (i.e. woven fabrics carbon and basalt) to matrix (i.e. epoxy resin and hardener in ratio 5:1 wt.%) ratio of 60 to 40.). Basalt fabrics layered according to their weight fraction values and positioned as the core of laminates were coded as CF/BF/CF, while basalt fabrics positioned on the external laminates were coded as BF/CF/BF.

Figure 1 shows the injection molding process of interlaminated hybrid composites. The process begins with fiber lamination, and is followed by mold preparation. In this experiment a mold base of Aluminum with size 500 mm x 500 mm and thickness 5 mm was employed. Plastics bags of size 600 mm x 600 mm were prepared for wrapping the fabric laminates. The epoxy and the hardener were mixed in the weighted ratio of 100:20, and the mixture was inserted into a desiccator at a pressure of 70 cmHg for 40 min to release all the bubbles and flatten the mixture. The mixture was then injected through a vacuum pump (Air-tech Uluna G-100D) at a pressure of 80 KPa for 45 minutes. During the process, a steady density of mixtures should be controlled in order to cover all the reinforcements. Also, the
conditions during the injection process should be kept steady at room temperature (28°C). As the next step, the panels are cured inside an oven at a constant temperature of 65°C for at least 2 hours (see Figure 1e). The hybrid composite panel is then released from the mold and cut using a water cutter machine into CT shapes with geometry as shown in the inset of Figure 2 [22]. A diamond cutter was used to produce a pre-crack \((a = 1 \text{ mm})\) in all the CT specimens.

![Figure 1. Schematic of Vacuum Injection molding processes.](image)

### 2.3. Test setup

Figure 2 shows the tension test setup of the CT specimen. A universal testing machine (Unitec-M, R&B) with two tons of load cells and a cross head speed of 1 mm/min was employed. The crack propagation of the CT specimen was measured using a 0.25 mm clip-on gauge (epsilon, technology corp. Jackson, WY USA). The CT specimen based on the ASTM standard is shown in Figure 2b.

The fracture toughness of hybrid laminated composites for materials with thick sizes has been calculated using the formula:

\[
K_Q \geq 2.5 \left( \frac{K_O}{\sigma_s} \right)^2 = K_{ic} \tag{1}
\]

where \(K_Q\) is fracture toughness, \(\sigma_s\) is the yield stress, \(a\) is the crack length, and \(w\) is the specimen width. The width of the specimen is defined as:

\[
w \geq 2.5 \left( \frac{K_Q}{\sigma_s} \right)^2 \geq 2B \tag{2}
\]

The stress intensity factor is usually expressed as:

\[
K_Q = \frac{P_Q}{Bw^{0.5}} f(x) \tag{3}
\]

The toughness of the CT specimen is calculated using Eq. (4)

\[
f(\delta) = \frac{(2 + \delta)}{(1 - \delta)^{0.5}} \left[ 0.886 + 4.64(\delta) - 13.32(\delta)^2 + 14.72(\delta)^3 - 5.60(\delta)^4 \right] \tag{4}
\]

\[
\delta = \left( \frac{a}{w} \right) \tag{5}
\]

\(P_Q\) is the critical load measured by projecting a line whose slope is 5% less than the original slope of
curve, $f(\delta)$ is the polynomial function, and $B$ is the specimen thickness (mm). The crack length, $a$, is selected as per the rule, $0.45 < a/w < 0.55$ [23].

Table 1. Interlaminated configuration and strength fracture toughness of hybrid composites.

| Laminates  | Code | CT Geometry | $x = (a/w)$ | $A = \frac{P_{Q}}{Bw^{3/2}}$ | $f(a/w)$ | $K_{Q}$ (MPa.√m) |
|------------|------|-------------|------------|-----------------|----------|------------------|
| [CFRP]$_{80}$ | CF   | 17.39       | 3.82       | 0.55            | 3.23     | 11.37            | 36.69          |
| [BFRP]$_{80}$ | BF   | 14.00       | 5.60       | 0.55            | 2.33     | 11.19            | 26.04          |
| C$_{36}$/B$_{16}$/C$_{36}$ | C1   | 17.11       | 6.84       | 0.53            | 3.13     | 11.38            | 35.57          |
| C$_{32}$/B$_{16}$/C$_{32}$ | C2   | 16.23       | 6.49       | 0.53            | 3.27     | 10.65            | 34.78          |
| C$_{32}$/B$_{24}$/C$_{28}$ | C3   | 15.85       | 6.34       | 0.54            | 3.13     | 10.74            | 33.69          |
| C$_{28}$/B$_{24}$/C$_{24}$ | C4   | 15.23       | 6.15       | 0.54            | 3.15     | 10.83            | 34.11          |
| B$_{16}$/C$_{48}$/B$_{16}$ | B1   | 15.04       | 6.00       | 0.54            | 3.25     | 10.83            | 35.38          |
| B$_{16}$/C$_{48}$/B$_{16}$/B$_{16}$ | B2   | 15.00       | 6.00       | 0.55            | 3.28     | 11.02            | 36.08          |

Figure 2. Geometry of Compact Tension (CT)

3. Results and discussion

3.1. Mode-I Fracture toughness behavior of Interlaminated hybrid composites

Table 1 summarizes the mode-I fracture toughness results calculated using equations 1-4. The 5% secant lines to predict the $P_{Q}$ of each hybrid interlaminated composite specimen have been derived using the formula $P_{Q} = 1.1$, implying that $P_{5} = P_{Q}$. Figures 3a and 3b show the tension curves of CT-CFRP and CT-BFRP respectively. The curves have been compared on the basis of the load and the displacement of the CT specimen during the tests. The crack propagation of CT-CFRP started without plastic deformation, implying that the CT-CFRP was brittle during the tension. In contrast, the CT-BFRP crack propagation started with a little plastic deformation in the initial crack, implying that it is more deformable. In this test, the loads have resulted in higher crack propagation in the CT-CFRP as compared to the CT-BFRP, but the displacement of CT-BFRP was longer than CT-CFRP. Additionally, from figures 3a and 3b it can also be observed that the CT-BFRP crack propagation is more stable than the CT-CFRP. In this case, jump crack propagation of CT-CFRP occurred during the mode-I test. This result shows that brittle materials have a higher stress intensity factor than ductile materials. The results are consistent with previous results [3, 24-26].
Figure 3. Load vs displacement curves of a) CT-CFRP; b) CT-BFRP.

Figures 4a and 4b show the graphic average values for the stress intensity factor of interlaminated hybrid composites tested on Mode-I. First, five interlaminated variations with basalt fiber as the core of the composite were tested, followed by three interlaminated with stacking modes CBC, BCB, and CBCBC. Figure 4a shows the average stress intensity factor for the interlaminated variation with added basalt fiber on the carbon fiber core of reinforced plastics. Clearly the stress intensity factor ($K_Q$) of the interlaminated hybrid composite with 20–40 wt. % basalt fiber added on the core carbon fiber gradually decreases. The results show that the interlaminated hybrid composite [C$_{36}$/B$_8$/C$_{36}$] (C1) has strength toughness lower than CFRP by 3.15%. Further, the basalt fabric content rises by 20%, 30%, and 40% in the CFRP, resulting in the decrease of the fracture toughness by 5.46%, 8.87%, and 7.56% respectively. This shows that the presence of interlaminated basalt fabric in the place of 10 – 40 wt. % of the carbon fibers does not significantly influence the fracture toughness of the composite during the Mode-I loading due to its brittleness. This is consistent with previous studies [19, 27-30]. However, the mechanical properties of the interlaminate during the Mode-I test show an increase in its durability, as shown before in previous tests [27, 31].
Figure 4b shows the average of the stress intensity factor for interlaminated hybrid composites with stacking sequences fibers. Clearly, the basalt fabrics laminated in the external positions sharply increase the strength of toughness. Table 1 summarizes the stress intensity factors for interlaminated hybrid composites, which are 3.589% lower than B1 for C4, and compared with CFRP, the hybrid composite (B1) is lower by about 3.56%. The hybrid composite (B2) has strength intensity factor 5.772% greater than C4, and about 1.975% higher than (B1). This suggests that hybrid interlaminated composites with alternate stacking of carbon and basalt fabrics can potentially improve the toughness properties of the composites.

![Figure 4. Average stress intensity factor values for a) Interlaminate of basalt fibers into the CFRP, b) Interlaminate fibers based on the stacking sequence (CBC, BCB and CBCBC)](image)

According to the results of each \( K_{IC} \) with Mode-I loads, the difference between experimental and numerical methods were exploited to determine the error of the fracture toughness for various specimens. We can approximate the relationship between the experimental and numerical values of the mode I fracture toughness by the formula

\[
K_{IC} = -7.0358(X) + 36.38 \quad (MPa \cdot \sqrt{m})
\]  

\[
X = \frac{w_B}{W_F}
\]

where, \( X \), \( w_B \), and \( W_F \) are the total basalt fabric, the number of basalt fabrics, and the total number of fabrics, respectively.

The comparison of the results shows that the hybrid laminated composite with configuration C27:B25:C27 (C4) has the highest error of 3.99%. Based on these test results we can summarize that the stress intensity factor is a function of loading, crack size, and structural geometry.

3.2. Failure behavior of Interlaminated hybrid composite

The surface morphology of an interlaminated hybrid composite epoxy resin matrix, containing interlaminated carbon-basalt fabrics reinforced on mode-I load was studied using SEM (JEOL JSM 5900). Figure 5 shows the CT specimen failures for CFRP and BFRP composites after Mode-1 tests. A flat failure surface is visible on the CFRP composite, resembling a dog-tooth (see Figure 5a). On the other hand, a rupture-like failure is visible on the BFRP composite (see Figure 5b). In fact, BFRP exhibited a failure which is more ductile than the CFRP composites, although the stress intensity factor of CFRP is higher than the BFRP composites. The propagation cracks of the basalt fabric are quite similar to glass fabric reinforced composites [20, 32].
Figure 5. SEM analysis of failures a) the CFRP composites, b) the BFRP composites.

Figure 6. SEM images interlaminated hybrid composites; a) 10 wt.% Basalt Fibers, b) 20 wt.% Basalt fibers, c) 30 wt.% Basalt fibers, d) 40 wt.% Basalt fibers, e) BCB configuration, f) CBCBC configuration.
Figure 6 shows the fracture failure of an interlaminated hybrid composite epoxy matrix based on the enhancement of basalt fabric content and stacking sequence configuration. Figures 6a, b, c, and d show the failures for interlaminated basalt fibers on a CFRP composite. Each interlaminated configuration clearly has a unique pattern. Fiber pull-out, debonding, fiber unraveling, and fabric delamination are common features shown by the hybrid composite carbon-fabric epoxy resin matrix in post-mode-I loads. Additionally, a shear hackle of the matrix is also visible on specimens C2, C3, and C4, caused by matrix cracks under maximum tension, perpendicular to the delamination direction. This indicates that the hybridization of basalt fabrics with carbon fabric epoxy matrix significantly influences the fracture toughness of the hybrid composites, even though there is a slight decrease in strength. The failure fracture on mode-I loading with stacking sequence between the carbon and basalt fabrics (C/B/C, B/C/B and C/B/C/B/C) is shown in Figures 6e and f. Evidently many delaminates and longitudinal cracks occur in the B/C/B model, and fiber pull-out is shown by the hybrid composite in C/B/C/B/C configuration. Additionally, shear hackles influenced by shear stress during the mode-I loading test are also visible. These results are consistent with the mode I fracture toughness test in Figure 4. The hybrid composite with C/B/C/B/C stacking showed better fracture mechanics and toughness as compared to C/B/C and B/C/B stacking modes.

4. Conclusions
In this study, we have successfully investigated the fracture toughness and failure characteristics of hybrid interlaminated composite epoxies containing reinforced carbon-basalt fabrics. Three types of hybrid interlaminated composite modes were studied. Vacuum resin transfer molding was used to manufacture all variations of interlaminated hybrid composites. CT was performed for Mode-I fracture toughness tests.

Hybridization between carbon and basalt fibers has been effectively exploited to modify the mechanical properties, and has contributed well towards the reduction in the cost of production of the composites. The stress intensity factor during the Mode-I test of CFRP showed a higher value than the BFRP. The $K_{IC}$ of 20, 30, and 40 wt.% inserted CFRP has decreased linearly by 5.46%, 8.87%, and 7.56%, respectively. Hybrid interlaminated composites with added basalt fibers show decreased strength toughness, but, at the same time, enhance the strain toughness of the hybrid composite. Furthermore, the fiber-stacked laminates have significantly influenced the stress intensity factor values of composites. This is an effective way to improve the toughness properties of the composites. Fiber pull-out, de-bonding, fiber delamination, and epoxy splitting are common failures which occur on hybrid composites after Mode-I loads. Additionally, shears hackles occur due to cracking of the matrix (epoxy) on the plane of maximum tension, perpendicular to the direction of delamination. This is indicative of local shear deformations in structures.

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