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Mixed-mode fracture behavior of glass fiber reinforced polymer concrete

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Abstract

Fracture toughness of chopped strand glass fiber reinforced particle-filled polymer composite beams was investigated in Mode I and Mode III loading conditions using three-point bend tests. Effects of crack angles on fracture behavior were also studied. The specimens, which have inclined crack at an angle θ to the axis of the specimens, were used to carry out the tests. The specimens were tested with inclination angles 30°, 45°, 60° and 75°. The results are compared with the values of K_{IC} obtained using conventional (θ=90°) specimens. In addition, J integrals were also determined. J_{IC} increases continuously with increasing in crack angle from θ=30° to θ=90°. In contrast, J_{IIIC} decreases with the crack inclination angle θ from 30° to 90°.
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1. Introduction

Polymer concrete, a mix of polymers and mineral aggregates, is becoming attractive due to its good properties, such as rapid setting, high strength, corrosion and water resistance for various applications. Because of these, the polymer concrete is being used in various constructions, rehabilitation, repair of pipelines, bridges and roads [1–7].

In order to obtain good properties of the polymer concrete, it is necessary to know the types and sizes of fillers and percentages of components, which play an important role in the composition [1]. The enormous potential of high-performance fibers that is so successfully exploited in the conventional polymer composites has not been widely used in the polymer concretes. Nevertheless, the fiber reinforcement of the polymer concrete is not a new concept, the chopped strand glass fiber has been applied to the polymer composites for improving the strength and controlling the cracking [8,9]. To characterize the failure behavior of the polymer composites in terms of the constituents, some attempts have been made for efficient use [10,11].

Mode I fracture type according to loading condition is taken into consideration in most of the study performed in the fracture mechanics. However, there occur random cracks in general loading conditions.

This type of cracks must be explained with Mode I, Mode II and Mode III. There is a very limited number of studies where Mode I and Mode II type fracture are together. In addition to Mode I loading, there is no tendency in the explanation of the effect of Mode III. Kamat et al. [12] show that addition of Mode III has little effect on Mode I for aluminium alloy metal–matrix composites. Manoharan and Lewandowski [13] investigated experimentally fracture toughness in Mode I and Mode III loading conditions, together in particulate metal–matrix composites and they demonstrated that Mode I loading condition is very effective. Moreover, addition of Mode III to the system does not affect the critic fracture criterion.

Under shear forces, cracks tend to propagate in Mode I, Mode II and Mode III configuration. Attempts to

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apply fracture mechanics concepts to study mixed-mode failure and crack propagation of concrete have been made [14–18].

In this study, Mode I and Mode III fracture behaviors of the chopped strand glass fiber reinforced polymer concrete were investigated using single edge notched beams loaded three-point bending. The effects of the crack angles on the fracture behaviors of the polymer concrete system were analysed. The fracture toughness values of the combined Modes K_{IC} and K_{IIIC} and J_C integrals (J_{IC} and J_{IIIC}) were determined for the same materials.

2. Experimental

2.1. Specimen preparation

In this study, chopped strand glass fiber in combination with an isophtalic polyester resin Neoxile 266 (Cam Elyaf) and sand fillers were used. Chemical and sieve analysis of the sand fillers and production details were given in Ref. [8]. E-glass fibers 10–12 mm in length were produced by cutting from continuous fibers. Initially, the composite system was formulated by using only polyester resin and sand. The composition of the composite material used was a weight of 16.50% of the polyester and 84.50% of the sand. The second type of the polymer concrete system was fabricated with a weight of 16.50% of the polyester resin, 1.50% of the glass fiber and 83.00% of the sand.

The glass fibers, sand fillers and polyester resin as indicated ratio were poured into a disposable container and mixed together until the mixture becomes homogeneous. The polymer composite mixture was cast in aluminium trays, 250×50×25 mm, with polyvinyl alcohol film coated to facilitate demoulding. The polymer composite in the trays was compressed and cured at room temperature for 2 days. Postcuring was done at 80 °C for 24 h. The specimens were cut by using a 2-mm-thick diamond saw to create notches 20 mm deep with the inclination angle θ to the beam axis as shown in Fig. 1. The notch tips of the specimen were sharpened with a surgery blade. Because the polymer composite specimens were brittle, there was no need to open a starter fatigue crack.

2.2. Fracture mechanics tests

Mode I fracture toughness tests of the polymer composite system were conducted on three-point bend specimens with the applicable ASTM standard E-399 for evaluation of the K_{IC} [8]. All mixed-mode fracture toughness tests were carried out using a modified three-point bend specimen [13,19]. The modification of the specimen is the slanted starting notch as shown in Fig. 1. The crack inclination angle θ from specimen axis is measured. The conventional three-point bend specimen is obtained at the inclined crack angle 90°. When the crack reduces from the 90° and bending loads are applied, Mode I and Mode III crack surface displacements are present. Therefore, Mode I and Mode III fracture behavior can be investigated. In the mixed-mode situations, crack growth direction can be deviated from the original crack plane.

In order to obtain K_{IC} and K_{IIIC}, the linear elastic fracture mechanics tests on inclined cracks on the modified three-point bend specimens for θ=30°, 45°,60°,75° and 90° according to ASTM E 399 and the ratio a/W=0.40 were carried out. The cross-head speed of the test machine was 0.05 mm/min. All beams were tested to maintain a constant rate of increase of the crack mouth opening displacement (CMOD) measured by a clip

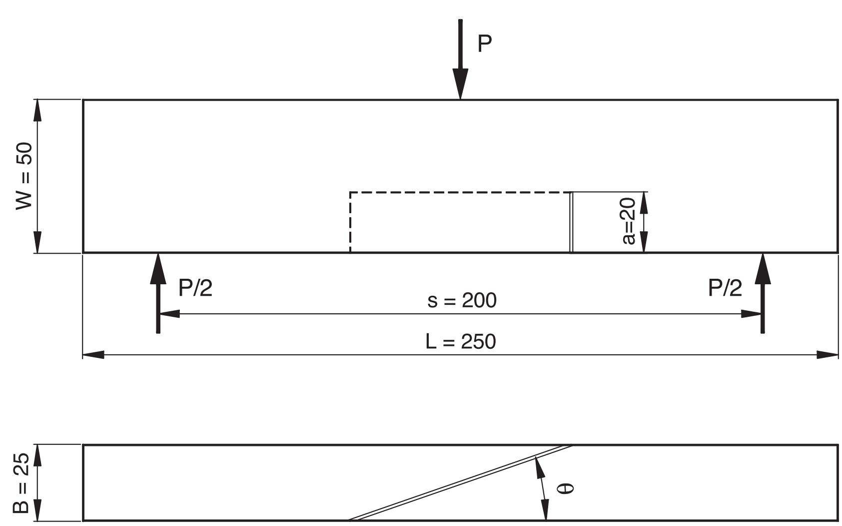

Fig. 1. Sketch of three-point bending specimen.

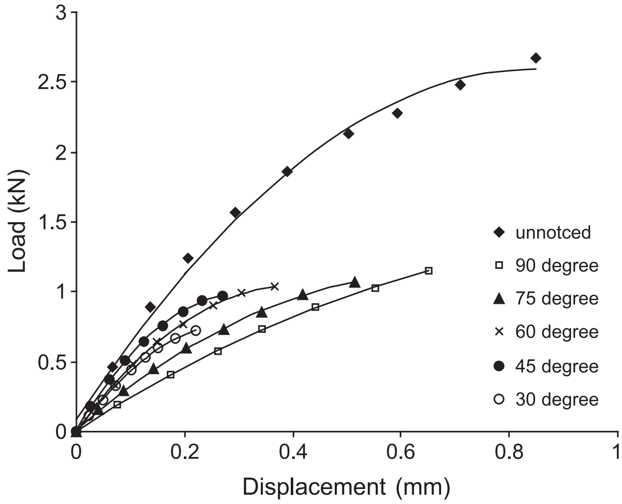

Fig. 2. Load–displacement curves for the Three-Point Bend test configuration.

gage mounted on the knife edge. During the test, the deflections of the beam were measured by a linear variable differential transformer (LVDT) located 5 mm under the centre line of the beam from the notch. Under the mixed-mode conditions, the crack plane may change due to the crack rotation. Manoharan et al. [19] stated that this event was a particular problem for Mode III components. By arranging the loading line parallel to the crack front, the crack can be grown in Mode I and then resolved into the values of K_{I} and K_{III} for the original case.

Three-point bend tests were conducted for each type of the specimens at room temperature. Three replicate tests were performed for each type of the specimens, and the average of the test results was used in the evaluation. The typical load versus the deflection curves and the crack mouth opening displacement curves are presented in Figs. 2 and 3. All of the load–deflection and the load–crack mouth opening displacement curves have a linear response, because the composite system is brittle.

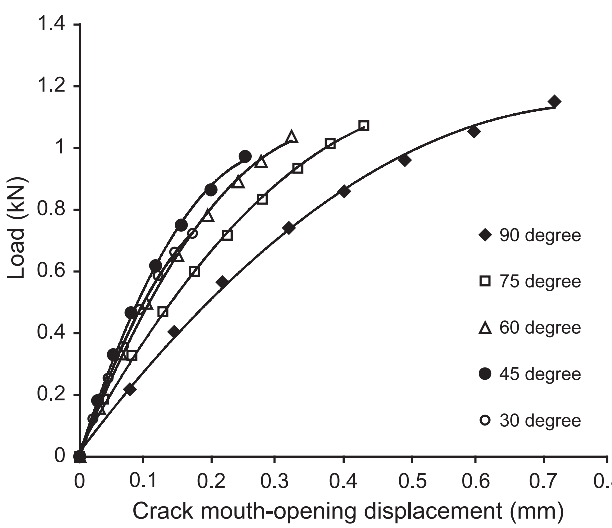

Fig. 3. Load–crack mouth opening displacement curves for the TPB test configuration.

3. Numerical results and discussion

3.1. Determination of critical stress intensity factors

Linear elastic fracture mechanics stress intensity factors for three-point bend beam were developed by Tada et al. [20]. This method is based on calculation of stress intensity factor by using initial crack depth. Mode I stress intensity factor K_{I} was carried out in accordance with this procedure and can be calculated from the following equation.

$$K_{\mathrm{I}} = \left(\frac{3Ps}{2W^{3/2}B}\right) f\left(\frac{a}{W}\right) \tag{1}$$

Where P is the necessary peak load for crack propagation, s is the beneath length of the beam, B is the specimen width, W is the specimen thickness. F (a/W) is the correction factor depending on the finite notched to depth ratio as shown in Fig. 1

$$F\left(\frac{a}{W}\right) = \frac{1}{\sqrt{\pi}} \frac{1.99 - A(1-A)(2.15 - 3.93A + 2.7A^2)}{(1+2A)(1-A)^{3/2}} \tag{2}$$

$$A = \frac{a}{W}$$

There is no standard method to calculate the mixed-mode stress intensity factors. However, Pook [21] and Manoharan and Lewandowski [13] for an inclined crack pointed out that, the apparent stress intensity factor K_{A}

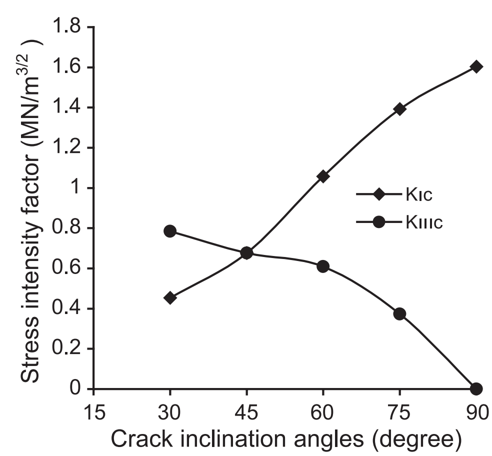

Fig. 4. Critical stress intensity factor–crack inclination angles (degrees) for Mode I and Mode III.

can be calculated by using Eq. (1) for the conventional crack case. K_A can be resolved into K_I and K_{III} with the following expressions.

$$K_I = K_A \sin^2\theta \quad (3)$$

and

$$K_{III} = K_A \sin\theta\cos\theta \quad (4)$$

From Eqs. (1), (3) and (4), the critical stress intensity factors K_{IC} and K_{IIIC} can be evaluated as,

$$K_{IC} = \left(\frac{3Ps}{2W^{3/2}B}\right) f\left(\frac{a}{W}\right)\sin^2\theta \quad (5)$$

and

$$K_{IC} = \left(\frac{3Ps}{2W^{3/2}B}\right) f\left(\frac{a}{W}\right)\sin\theta\cos\theta \quad (6)$$

The values of Mode I and Mode III stress intensity factors were calculated from Eqs. (5) and (6). The variation of the stress intensity factor with the crack inclination angle θ is displayed in Fig. 4. K_{IC} increases with increase in inclination angle from 30° to 90° and reaches the highest value 0.786 MN/m$^{3/2}$ at θ=90°. On the other hand, K_{IIIC} has the highest value at θ=30° and decreases continuously as the Mode I component is added to the loading system. As expected at θ=90°, K_{IIIC} reaches zero. At θ=45°, the loading conditions are equal to for the Mode I and Mode III components so the values of K_{IC} and K_{IIIC} are equal.

The failure behavior results under the loadings Mode I and Mode III are shown in Fig. 4. In the form of the mixed-mode envelopes where the Mode III stress intensity factor K_{IIIC} is plotted in Fig. 4 as a function of the corresponding the Mode I stress intensity factor K_{IC}. As seen in Fig. 4, the value of K_{IC} is being reduced with increasing K_{IIIC}.

4. Determination of J_{IC}

J-integral method can be applied to find fracture toughness of a nonlinear elastic material [22]. This method is based on determining the change of potential energy when a crack extends. That is,

$$J = -\frac{1}{B}\frac{dU}{da} \quad (7)$$

Where B is width of the specimen, U is the potential energy, and a is the length of the crack.

If the polymer system is assumed to be a linear elastic material, the stress intensity factors can be converted into the strain energy release rate. For linear elastic materials, the strain energy release rate equals to J integral, which can be resolved approximately into J_I and J_{III} as follows.

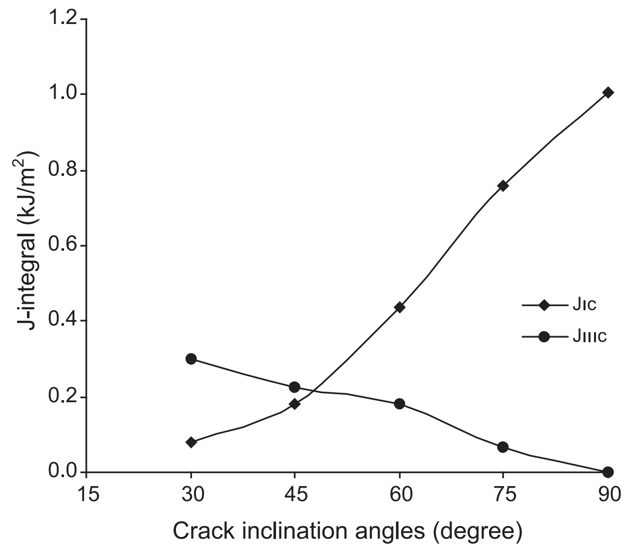

Fig. 5. Critical J integral–crack inclination angles (degrees) for Mode I and Mode III.

$$J_{IC} = \frac{(1-v^2)}{E}K_{IC}^2 \quad (8)$$

$$J_{IIIC} = \frac{(1+v)}{E}K_{IIIC}^2 \quad (9)$$

Where v is the Poisson ratio and E is the flexural modulus of the material. The resolved J-integral values were calculated using the above equations and the obtained results are graphically shown in Fig. 5.

Fig. 5 illustrates the variation of J_{IC} and J_{IIIC} with the crack inclination angle θ for 16.5% polyester and 1.5% glass fiber composite system. J_{IC} increases continuously with increasing crack angle from θ=30° to θ=90°. In contrast, J_{IIIC} decreases with the crack inclination angle θ from 30° to 90°. The highest value of J_{IIIC} is 0.302 kJ/m^2 at θ=30° and reduces to zero at θ=90°. There is a relatively rise in Mode I contribution to the decrease in Mode III contribution.

5. Conclusion

Fracture behaviors of chopped strand glass fiber reinforced polymer concrete under Mode I and Mode III loading conditions were investigated. As a result of the examined cases, minimum energy dissipation of the material occurred at Mode I fracture. From the result of the improved three-point bend tests, both K_{IC} and J_{IC} increase rapidly and K_{IIIC} and J_{IIIC} decrease as the crack angle changing from θ=30° to 90°. The values of K_{IC} and K_{IIIC} are the same at θ=45°.

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