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In situ crack growth observation and fracture behavior of short carbon fiber reinforced geopolymer matrix composites

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ABSTRACT

The crack initiation and propagation of short carbon fiber reinforced geopolymer matrix composites (C_f/geopolymer composites) during bending test were observed in situ by environmental scanning electron microscope (ESEM). Lots of micro cracks initiate, and then propagate on the side of the beam sample with the increase of the bending load. A nearly elastic response of load–displacement curve and significant deformation of the composites are observed at the initial stages. The propagation of the micro cracks ceases, and these cracks tend to close to some extent while the main crack forms. The fiber bridging effect in the micro and main cracks effectively keeps the composites integrity and makes the composites exhibit a non-catastrophic fracture behavior. A simple mode for the damage behavior of the composites during the bending test is discussed.

1. Introduction

Short fiber reinforced composites are an important category of materials for engineering applications because of their adaptability to conventional manufacturing techniques and low cost of fabrication [1,2]. The increasing applications of short fiber reinforced composites show the great importance of the fracture mechanisms investigation [3,4]. Over the past years, many researches on the failure mechanisms of short fiber reinforced composites have been conducted [5–12]. These research results have demonstrated that the cracks play an important role in the mechanical properties and fracture behavior of the composites. In addition, some macroscopic and theoretical relations between the cracks and the fracture mechanism of the composites have been proposed [7–10]. However, the details of failure mechanism, especially for the effects of micro cracks propagation and distribution on fracture behavior of the composites, are unspecified up to now.

In the present study, the bending test of short fiber reinforced composites was firstly employed on an environmental scanning electron microscope (ESEM) to determine the crack growth and the fracture behavior with increasing displacement of the crosshead. Relations between the crack growth and the fracture behavior of the composites were discussed.

2. Experimental

Short carbon fibers with an average length of 7 mm are used in this study. The short carbon fibers are distributed in the composites uniformly. The volume fraction of short carbon fibers in the as-prepared composites is 3.5 vol.%. The preparation process of the composites was described in the previous study [13]. Mechanical testing and in situ observation are conducted on the specimens ($4 \times 2 \times 36\,mm^3$) using a three-point bend flexure inside a Quanta 200 ESEM with a span length of 30 mm at a crosshead speed of 0.5 mm/min. All flexural bars are machined with the tensile surface perpendicular to the direction of lamination. Images of the crack initiation and propagation on the surface of lamination direction are in situ taken and the load/displacement curves are recorded simultaneously.

3. Results and discussion

The typical load/displacement curve for the C_f/geopolymer composites is given in Fig. 1 Fig. 2. The composites exhibit a significant deformation and an obvious non-catastrophic fracture behavior during the bending test, which is regard as a great toughening effect for the short carbon fiber with such a low volume percentage (3.5 vol.%). The composites exhibit a nearly elastic response in the initial stages (stages I and II) though a change appears at a load of about 6 N, which is similar to that of unidirectional continuous fiber reinforced composites [14]. Beyond the elastic limit, the applied load produces plastic deformation until the maximum load is reached. Then the load gradually

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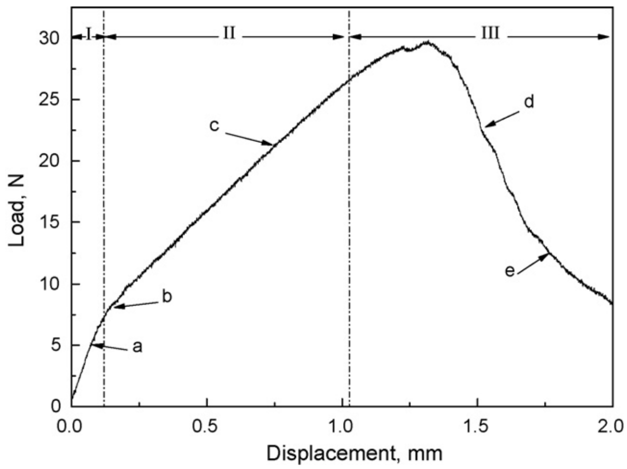

Fig. 1. Load/displacement curve for the C_f/geopolymer composites.

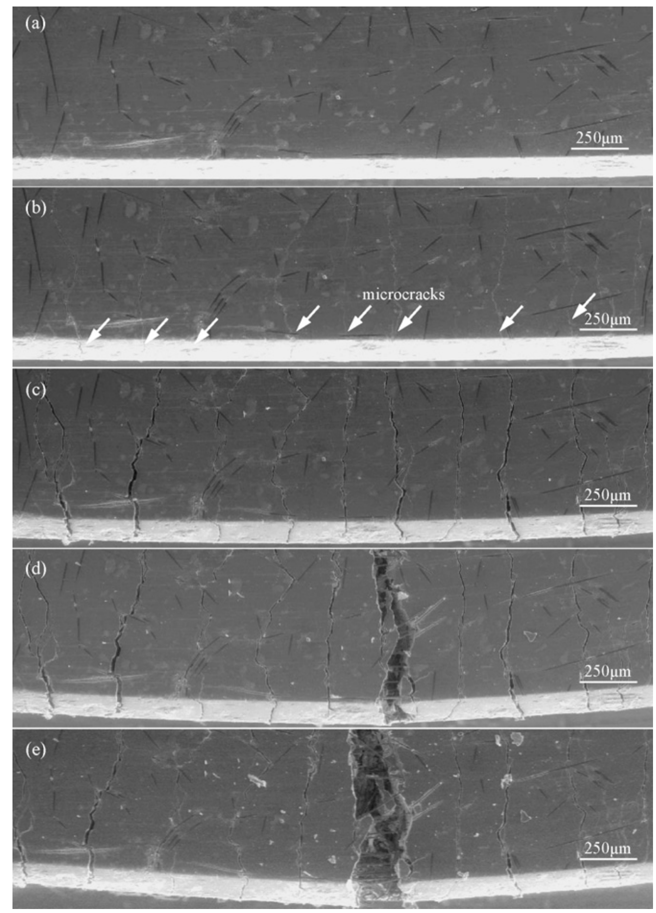

Fig. 2. Series of ESEM images (a)–(e) of crack initiation and propagation process on the side of a beam sample of the C_f/geopolymer composites corresponding to the position a–e of the load/displacement curve in Fig. 1 separately.

decreases with the increasing displacement, and forms a long tail (stage III).

shows a series of ESEM images of crack initiation and propagation process on the side of the beam sample of the composites, which corresponds to the test points in the load/displacement curve in Fig. 1. At the first elastic stage (stage I), no crack is found on the beam sample as shown in Fig. 2(a). However, at the beginning of the second elastic stage (stage II), a lot of micro cracks (Fig. 2(b)) appear on the side of the beam sample.

To encourage a crack growth, the increasing energy is required. When the bending stress is higher than the strength of the geopolymer matrix, a micro crack will initiates firstly in the geopolymer matrix of on sample beam surface. With higher load applied, the micro crack will propagate and meet with the reinforced fibers inevitably. Due to their high mechanical strength, the reinforced fibers will try to keep the composite integrity instead of being broken. Hence, the micro crack growth will be greatly slow down and an internal stress will be cumulated between the matrix and the reinforced fibers. When the increasing cumulation internal stress in the matrix is high enough (the mechanical strength of the reinforced fiber is much higher than that of the matrix), other new micro cracks will occur on the beam surface, as shown in Fig. 2(b). This interesting phenomenon indicates that the stress distribution in the matrix has been well changed due to the enhancement effect of the reinforced fibers. The study on this phenomenon will be carried out in the future.

Though the formation of these micro cracks reduces the matrix elastic modulus, as indicated by the load/displacement curve slopes in Fig. 1, the sample still keep a nearly elastic deformation behavior companying with the propagation of the micro cracks (Fig. 2(c)). Under the increasing bending load, the micro cracks are grown up with similar rates. This unconventional fracture behavior is supposed to be attributed to the following reasons. The short carbon fibers used in this study have a length of 7 mm and the gap lengths are 300–500 μm, as shown in Fig. 2(c). Hence, the fibers are long enough to bridge several micro cracks together. As discussed above, the fibers have a far higher mechanical strength than that of the matrix. Thus, the bridging fibers in the micro cracks are difficult to be fractured, which is helpful to keep the composites integrity and to retard the formation of a main crack. The significant deformation of the composites can be attributed to the large number of the micro cracks during the bending test.

A schematic drawing of the fiber bridging cracks is shown in Fig. 3. Assuming the fiber is rigid and its elastic deformation during the bending test can be neglected. The fibers which bridge more than two micro cracks are under the effects of the tension

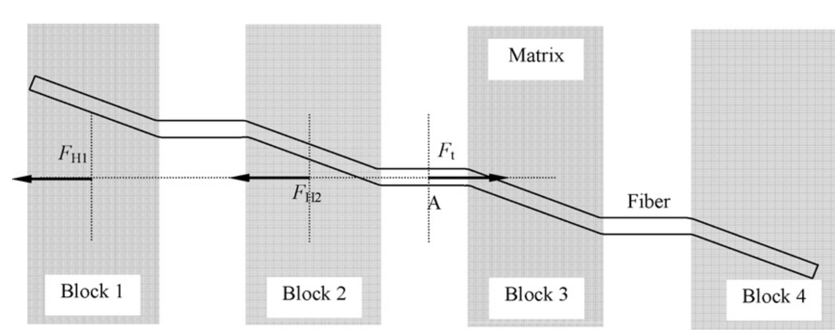

Fig. 3. Analytical models of a fiber bridging cracks and the forces appearing in the fiber: (a) a fiber bridging a crack; (b) a fiber bridging two cracks.