MODE I, MODE II, AND MIXED-MODE I/II INTERLAMINAR FRACTURE TOUGHNESS OF GFRP INFLUENCED BY FIBER SURFACE TREATMENT


The interlaminar fracture behavior of unidirectional glass fiber reinforced composites with fiber surface treatment has been investigated in modes I and II and for fixed mode I to mode II ratio of 1.33. The data obtained from these tests have been analyzed by using different analytical approaches. The present investigation is focused on the influence of the glass fiber surface treatment on the interlaminar fracture toughness of unidirectional laminates. Glass fibers with two different fiber surface treatments have been investigated. Fiber surface treatment was carried out by using a polyethylene or silane coupling agent in combination with modifying agents. The glass fibers were embedded in the brittle epoxy matrix. Mode I, mode II, and mixed-mode I/II tests were performed in order to determine critical strain energy release rates. Double cantilever beam (DCB), end-notched flexure (ENF), and mixed-mode flexure (MMF) specimens were used. For both types of fiber surface treatment about the same values of mode I initiation fracture toughness \( G_{IC}^{\text{init}} \) were obtained. It was observed that in mode I interlaminar crack growth in the DCB test for the composite sized by polyethylene, the crack propagation is accompanied by extensive fiber bridging. For both fiber surface treatments interlaminar fracture toughness increases considerably with increasing of crack length. For the fiber surface treatment with the silane coupling agent, the value of mode II initiation fracture toughness \( G_{IIc}^{\text{init}} \) was about 2.5-times higher in comparison with that of a composite sized by polyethylene. For both types of fiber surface treatments the mixed-mode I/II test has shown a similar behavior to the mode I DCB test.

1. INTRODUCTION

One of the major disadvantages of laminated composites is their tendency to delaminate. In composites containing brittle matrices, delamination can propagate even more readily compared to cracks that are perpendicular to the plane of the laminate. Initiation and growth of delamination can reduce considerably the stiffness and compressive strength of composites.

Macroscopic properties of fiber-reinforced composites are dependent on the micromechanics of the fiber/matrix interphase. Therefore, the adhesion between fibers and matrix is very important for the mechanical behavior of fiber reinforced laminated polymeric composites.

There are several test methods to determine the fiber/matrix adhesion properties. Widely used are such test methods as pull-out, fragmentation, microtension, microcompression [1]. From macrotest methods the fiber/matrix adhesion properties can be obtained indirectly. For example, such tests are transverse tension or interlaminar shear experiments. Information about fiber/matrix adhesion can be obtained also from delamination crack propagation experiments. These experiments are used in the present investigation.

The quality of the fiber/matrix interface will influence the initiation and propagation of delamination cracks. The resistance of delamination growth has been characterized by fracture toughness or critical energy release rates under modes I, II, III and mixed-mode loading conditions. In composite structures, for example under impact loading, mixed-mode
fracture is observed. Therefore, the interlaminar fracture toughness has been identified as a prime factor in controlling the growth of delamination in laminated composites.

The significant role of delamination in the fracture of composites is reflected in the large number of papers on the subject [2-17]. In these investigations, delamination or interlaminar fracture toughness properties of different fiber reinforced composites was investigated. Modes I, II, III and mixed-mode loading conditions were used to determine the corresponding critical energy release rates or fracture toughness.

There are a number of investigations concerned with the measurement of mode I interlaminar fracture toughness in composite materials [3-5, 7, 9, 11, 14, 15, 17, 18]. Mode I (crack opening) loading conditions are used as a basic test to evaluate the fiber/matrix adhesion properties of the composite. The double cantilever beam (DCB) type configuration was one of the most common specimen geometries to determine the critical energy release rate $G_{IC}$. Advantage of the DCB test is simple specimen geometry and stable crack growth in loading under displacement control.

Mode II (crack sliding or in plane shear) loading conditions are used for evaluation of the critical energy release rate $G_{IC}$. For this the end-notched flexure (ENF) specimen was commonly used [3, 7, 12, 14, 16, 19]. An advantage of the ENF test is simple three point bending specimen geometry. Disadvantage is unstable crack growth in loading under displacement control and some influence of friction at the crack sides on the support. Therefore, by using the ENF test only, crack initiation critical energy release rates $G_{IC}^{init}$ can be determined. In this case the crack propagation critical energy release rates can be obtained from other tests. Mode II loading conditions can be achieved also by using an end loaded split (ELS) specimen [3, 7]. For the mode II test the lower arm of the ELS specimen is loaded. In general in the ELS test there is also unstable crack growth in loading under displacement control. However, the ELS test allows stable crack growth for some ratios of initial crack length. Different modification of the ENF specimen is the so-called center notch flexural (CNF) test specimen [20], which also can be used to obtain the mode II critical energy release rates.

In real loading conditions, it is very unlikely that pure mode I or mode II conditions will occur. Therefore, it is important to know how the fracture toughness changes as the loading transforms from pure mode I to pure mode II loading conditions. Mixed-mode I/II tests are characterized by the ratio $G_I/G_{II}$ that is driving the crack. Various mixed-mode ratios $G_I/G_{II}$ can be obtained by using different specimens. Mixed-mode flexure (MMF) test is mode I dominated with the ratio $G_I/G_{II} = 1.33$ [3]. This ratio is in the case when upper and lower parts of the specimen are of equal thickness. Varying the thickness ratio of the lower and upper parts, different mode I to mode II ratios can be obtained [10]. The MMF specimen is very similar to the ENF specimen, i.e., this is a simple three point bending test. However, in the MMF specimen the crack growth is stable, and crack initiation as well as crack propagation values for the critical energy release rates can be obtained. In the case when the ELS specimen is loaded by the upper arm, the mixed-mode loading conditions at the crack-tip are achieved. For symmetrical crack (upper and lower arms of the specimen are of equal thickness) the mixed-mode I/II ratio is $G_I/G_{II} = 1.33$ [7].

For mixed-mode tests other specimens are also used. Very similar to the MMF specimen is the so-called single leg bending (SLB) specimen [10]. Actually, the SLB specimen is the same MMF specimen. The only difference is that in the case of SLB test the supports are of different heights. With this specimen different mode I to mode II ratios can be achieved. However, this test is also mode I dominated. The crack lap shear (CLS) test is mode II dominated [3]. For this test various $G_I/G_{II}$ ratios can be achieved by varying a stepped thickness ratio. The crack growth for the CLS test is semi-stable, and it is possible to record several data points with crack growth. However, measurements for this test suffer from large scatter with increasing of crack length [3]. Mixed-mode loading conditions can be also generated by using the edge delamination tension (EDT) specimen [21].

For all mixed-mode specimens discussed above there are limited possibilities to get the different mixed-mode ratios. By loading the ENF specimen with a special loading lever, different mixed-mode ratios can be achieved. This is the so-called mixed-mode bending (MMB) test, which was proposed in [13]. The MMB test simply combines the mode I DCB and the mode II ENF tests. The different loading positions determine the various mixed-mode delamination ratios. In paper [13] the experiments were carried out with $G_I/G_{II}$ ratios from 0.25 to 4. In the investigation [22] the mixed-mode $G_I/G_{II}$ ratios were even from 0.002 to 35. In this case more detailed information about the material behavior under mixed-mode loading conditions at the crack-tip can be obtained. Now the MMB specimen is widely used to obtain the mixed-mode critical energy release rates for different composites [6, 13, 22].

However, as may be seen from the data reported in the literature, the values of critical energy release rates are frequently dependent on the method of analysis employed for the data reduction. For example, it has been observed that the area and compliance calibration methods, which are two direct approaches for calculating the critical energy release rates.