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Mode I delamination fatigue properties of interlayer-toughened CF/epoxy laminates

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Abstract

Mode I delamination fatigue crack growth behavior was investigated in carbon fiber (CF)/epoxy laminates with two kinds of interlayer/interleaf. One was with heterogeneous interlayer with fine polyamide particles, T800H/3900-2, and the other was with interleaf of new types of thermoplastic resin, ionomer, UT500/111/ionomer. Tests were carried out using double cantilever beam specimens. For T800H/3900-2 laminates, the crack path shifted from the heterogeneous interlayer region (Stage I) to the interlayer/base lamina interface (Stage II) with the increase of the crack length. The delamination fatigue crack growth resistance of the T800H/3900-2 laminates was about 3 times higher than that of the reference CFRP for Stage I. This ratio decreased to 1.5 times for Stage II. For UT500/111/ionomer laminates, the high level of the fatigue crack growth resistance was kept without respect to the crack length. The threshold value of UT500/111/ionomer laminates was about 3 times higher than base UT500/111 laminates. The mechanism of the difference of the toughening mechanism for these interlayer/interleaf laminates was discussed on the bases of fractrographic observation and mechanism consideration.

Keywords: Polymer–matrix composites; Fatigue crack growth; Delamination; Interlaminar fracture; Interlayer; Interleaf

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1. Introduction

Although two decades have passed since the importance of the interlaminar fracture was recognized [1,2], interlaminar strength is still one of the design limiting factors in structural composite laminates [3]. A large number of research works have been carried out on static interlaminar properties of toughened laminates [4,5]. Current topics are the effects of through the thickness reinforcement such as stitching, Z-pin and three-dimensional fabric on the interlaminar strength [6–9]. However, only little has been reported on delamination properties of interlayer/interleaf-toughened laminates under fatigue loading [10–12]. Since new generation commercial aircraft such as A380 and B787 are reported to increase application of composite materials to structural parts, the understanding of fatigue properties is urgently required for interlayer/interleaf-toughened laminates.

One of the established ways to increase the interlaminar strength is to replace resin at prepreg interface to a tougher system [13–15]. This method is called as "interleaf" or "interlayer". A full commercial product, T800H/3900-2, has heterogeneous interlayer including fine thermoplastic particles, and has already been used in the primary structures of Boeing 777 [16,17]. Though the mode II interlaminar fracture toughness for T800H/3900-2 indicated excellent properties, the mode I fracture toughness decreased with the increment of the crack length [10]. We

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have only carried out detailed researches on mode II delamination fatigue crack growth properties [11]. Here, the threshold value increased only 1.5 times, and this increase was much smaller than that of static interlaminar fracture toughness (2.4 times for initial and 3.9 times for propagation values) [10,11]. However, only little has been reported on the fatigue properties under mode I loading [10], and the mechanism of delamination fatigue crack growth is still not understood.

The static results of T800H/3900-2 under mode I loading indicate necessity of new interleaf materials with higher ductility and adhesion strength to the base CFRP lamina [18]. A new type of thermoplastic resin, ionomer, has high ductility and good adhesion strength to epoxy resin [19]. In addition, ionomer forms the toughened interphase at the ionomer/base lamina interface [20]. We have already reported that both mode I and II fracture toughness of ionomer-interleaved CFRP laminates greatly increased from the base laminates [18,20]. Specially, the higher mode I fracture toughness did not decrease with the increment of the crack length [20].

The objective of this study is to clarify the effect of the heterogeneous interlayer and the ionomer interleaf on the mode I delamination fatigue crack growth behavior in CFRP laminates. The toughening mechanisms were discussed on the bases of mechanism consideration and the microscopic observation.

2. Experimental procedure

2.1. Materials and specimens

For the case of laminates with heterogeneous interlayer, unidirectional laminates of nominal thickness of 3 mm, $(0)_{16}$ were made from carbon fiber/epoxy prepregs of Toray T800H/3900-2 by using an autoclave. The details of the mechanical properties of the unidirectional T800H/3900-2 laminates are given in a separate paper [11]. Fig. 1(a) schematically shows the transverse section of T800H/3900-2 laminates. The thickness of the heterogeneous interlayer was about 30 μm. This interlayer with fine polyamide particles was inserted in every ply interface between the base CF/epoxy lamina. Starter slits were introduced into the laminates by inserting single 7.5 μm thick polyimide film at midplane during molding.

For the case of ionomer-interleaved laminates, unidirectional laminates of nominal thickness of 3 mm, $(0)_{24}$ were fabricated from carbon fiber/epoxy prepregs of Toho UT500/111 by using a hot press. The details of the laminates and ionomer are explained in a separate paper [20]. The ionomer film was inserted only at the midplane of the laminates during molding. The thickness of the ionomer film was 25 and 100 μm. These laminates are indicated as UT500/111/ionomer (25 or 100 μm). For reference, the base laminates without interleaf films, UT500/111, were also fabricated. In each laminate, a polyimide film of 13 μm thickness was inserted during molding at the midplane as a starter slit. Fig. 1(b) depicts the schematic structure of the transverse section near the interfaces. It is known that there is an interphase region of one- or two-carbon fiber thickness next to the ionomer region, where epoxy and ionomer are mixed [20].

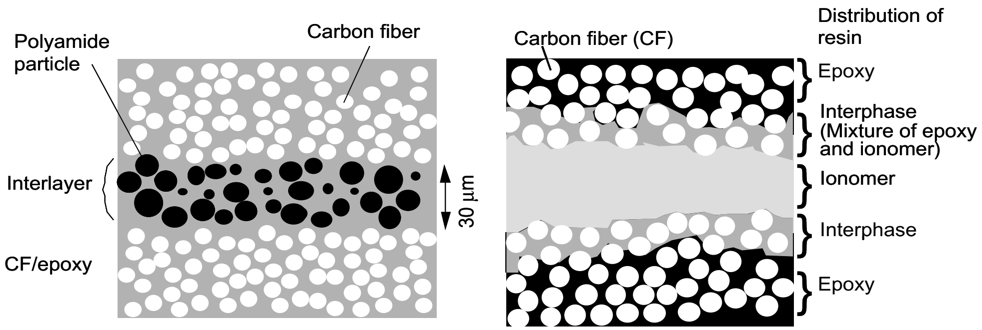
Double cantilever beam (DCB) specimens (width $B = 20$ mm, length $L = 140$ mm, and nominal thickness $2h = 3$ mm) were used for the tests of both laminates under static and fatigue loadings. Fig. 2 shows the DCB specimen and aluminum blocks for load introduction. Special loading apparatus with universal joints were used for tests [21,22]. The side surfaces of the specimens were polished with abrasive papers and diamond paste (1 and 6 μm). Then, white brittle paint was coated on both side surfaces of the test specimen to enhance the crack length measurement. The length of the initial crack was about 20–25 mm.

2.2. Fracture toughness test and fatigue test

The energy release rate, G, was calculated using the modified compliance calibration method [23,24]. The stress intensity factor, K, was calculated using the relation between G and K as follows [25,26]:

$$G = HK^2, \tag{1}$$

where H is a function of elastic moduli (E_{ij}, ν_{ij}). The H value for T800H/3900-2 was calculated as 6.83×10^{-11} Pa^{-1}.



a T800H3900-2 b UT500/111/ionomer

Fig. 1. Schematics of transverse section of laminates.