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Fatigue delamination growth in woven glass/epoxy composite laminates under mixed-mode II/III loading conditions at cryogenic temperatures

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ABSTRACT

We investigate the cryogenic delamination growth behavior in woven glass fiber reinforced polymer (GFRP) composite laminates under mixed-mode II/III fatigue loading. Fatigue delamination tests were conducted with six-point bending plate (6PBP) specimens at room temperature, liquid nitrogen temperature (77 K) and liquid helium temperature (4 K), and the delamination growth rate data for various mixed-mode ratios of Modes II and III were obtained. The energy release rate was evaluated using the three-dimensional finite element method. In addition, the fatigue delamination growth mechanisms were characterized by scanning electron microscopic observations of the specimen fracture surfaces.

1. Introduction

Woven fabric composites are employed in a variety of engineering applications due to their excellent physical and mechanical properties. For example, woven glass fiber reinforced polymer (GFRP) composite laminates are used in superconducting magnets of the International Thermonuclear Experimental Reactor (ITER) since they provide not only electrical and thermal insulation, but also the mechanical strength necessary to withstand the magnetic forces present during coil operation at cryogenic temperatures. Delamination represents one of the most critical failure modes in laminated composites, and delamination onset and growth are particularly sensitive to the application of fatigue loading [1,2]. In order to establish design allowable and damage tolerance guidelines for cryogenic composite structures, an in-depth understanding of the fatigue delamination growth behavior in woven composite laminates at cryogenic temperatures is necessary [3–5].

In-service delaminations often occur under complex load conditions and may be subjected to combinations of Modes I–III loadings. A number of investigators have studied the fatigue delamination growth in composite laminates under mixed-mode I/II loading at room temperature [6–8]. Recently, our research group has examined the mixed-mode I/II fatigue delamination growth behavior in woven GFRP laminates at cryogenic temperatures [9]. By contrast, no study has focused on the fatigue delamination growth behavior under mixed-mode conditions that involve Mode III. In order to investigate the mixed-mode II/III delamination fracture response under static loading at room temperature, several tests have been proposed: a six-point bending plate (6PBP) method [10], a double-notched split cantilever beam test method [11], a shear-torsion-bending (STB) test method [12] and a prestressed split-cantilever beam (PSCB) test method [13]. Comparing these test methods, the 6PBP method is the simplest: the specimen is simple to fabricate and the test is easy to perform. Thus, the 6PBP appears to be a promising test for examining the cryogenic delamination growth under mixed-mode II/III fatigue loading.

This paper studies the fatigue delamination growth behavior in woven GFRP laminates under mixed-mode II/III loading conditions at cryogenic temperatures. The fatigue delamination tests were conducted at room temperature, liquid nitrogen temperature (77 K) and liquid helium temperature (4 K) using the 6PBP method, in order to obtain the delamination growth rate as a function of the energy release rate range. The energy release rate was determined by the three-dimensional finite element method. The fractographic examinations by scanning electron microscopy (SEM) were also performed to assess the mechanisms of the fatigue delamination growth.

2. Experimental procedure

2.1. Material and specimen preparation

National Electrical Manufacturers Association (NEMA) grade G-11 woven GFRP laminates (Toyo Lite Co., Ltd., Japan) were employed for the fatigue delamination tests. The fiber reinforcement

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was a plain weave E-glass fabric composed of two sets of interlaced mutually orthogonal fiber bundles, i.e., warp and fill fiber bundles. The matrix was a bisphenol-A epoxy resin. The overall fiber volume fraction was about 39%.

Fig. 1 shows the 6PBP specimen geometry. The specimens were produced from the woven GFRP panel with a thickness of $2H = 3.85$ mm, and the panel consisted of 20 plies. A polymer film made of fluorinated ethylene propylene (FEP) was placed at the midplane of the panel to serve as a delamination initiator and its thickness was no greater than 13 μm. The panel was cut into the specimens with a length of $L = 38$ mm and with three different widths of $B = 36$, 44 and 52 mm, respectively. Because of the space limitation in existing helium cryostat, these specimens were smaller than the original ones [10]. The specimen length direction was parallel to the direction of warp fiber bundles. Each specimen was precracked to produce an initial delamination. The precracking was performed by pushing a razor blade into a clamped specimen at room temperature.

2.2. Fatigue delamination test and fractography

Fig. 2 shows the 6PBP test configuration. The specimen was supported at four points and loaded at two points. A schematic of the test fixture is presented in Fig. 3. In order to change the mixed-mode II/III ratio, the load span length s was adjusted according to the relation $s = B - 8$ mm. That is, the load span lengths s were 28, 36 and 44 mm for the specimen widths $B = 36$, 44 and 52 mm, respectively. The initial delamination length a_0 was determined visually and was about 9 mm.

The 6PBP specimens were tested at room temperature, 77 K and 4 K using a 30 kN capacity servo-hydraulic testing machine. Cryogenic temperature environments were achieved by immersing the test specimen and fixture in liquid nitrogen or liquid helium. To keep the specimen fully submerged in liquid helium during the fatigue delamination test, an automatic refill system (TRG-350D, Taiyo Nippon Sanso Co., Ltd., Japan) was incorporated. The tests were performed in sinusoidal load control at a frequency of 2 Hz and a load ratio R of 0.1. The load ratio is defined as $R = P_{min}/P_{max}$,

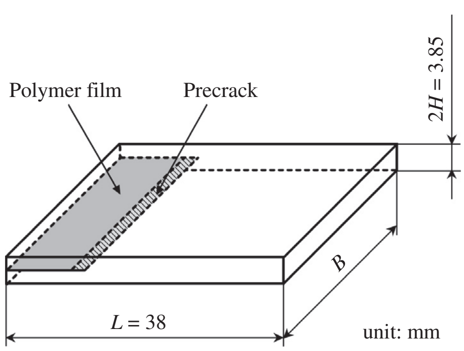

Fig. 1. 6PBP specimen geometry.

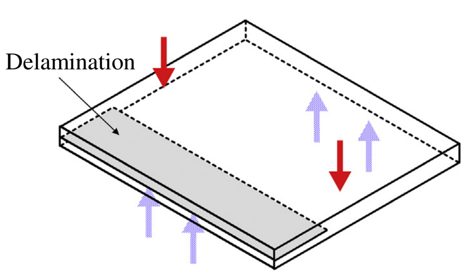

Fig. 2. 6PBP test configuration.

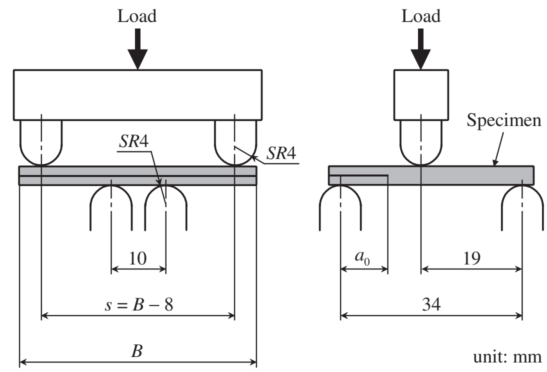

Fig. 3. Schematic of the 6PBP test fixture.

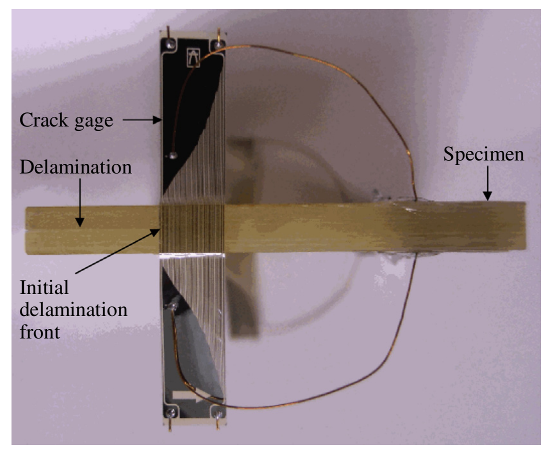

Fig. 4. Side view of the 6PBP specimen.

where P_{max} and P_{min} are the maximum and minimum applied loads, respectively. The load ratio effects were observed on the fatigue delamination growth behaviors in composite laminates at room temperature, e.g., for Mode III condition [14]. However, the load ratio was fixed at $R = 0.1$ for all experiments because, in this study, we focus on the dependence of the delamination growth behavior on the temperature and the mixed-mode II/III ratio. To monitor delamination length during the test, crack gages (KV-5C, Kyowa Electronic Instruments Co., Ltd., Japan) were applied to both side surfaces of the specimen as shown in Fig. 4. The crack gage consists of 46 grid lines. The distance between two adjacent grid lines is 0.1 mm, i.e., the gage has a crack length resolution of 0.1 mm. When a grid line is broken by the advancing delamination, the resistance of the gage changes. The delamination length can be determined on the basis of the linear relationship between gage resistance change and delamination extension amount. Here, the delamination length a was obtained as the average of the values measured on the both sides of the specimen. The delamination growth rate da/dN was calculated from delamination length a versus number of cycles N data. The number of specimens was limited to two for each condition, i.e., combination of test temperature (room temperature, 77 K and 4 K) and load span length ($s = 28$, 36 and 44 mm). Thus, the total number of specimens was 18. After the tests, the specimens were split completely and SEM fracture surface observations were carried out.

3. Finite element analysis

A three-dimensional finite element model of the 6PBP specimen was constructed using ANSYS finite element code. The woven GFRP