Cryogenic Delamination Growth in Woven Glass/Epoxy Composite Laminates under Mixed-mode I/II Fatigue Loading

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1. Introduction

Woven glass fiber reinforced polymer (GFRP) composite laminates provide good electrical and thermal insulation together with adequate load-carrying ability and are used as insulation and structural support in superconducting magnets. In particular, the insulation systems of the International Thermonuclear Experimental Reactor (ITER) must meet high performance requirements at cryogenic temperatures. In laminated composites, delamination is one of the major failure modes. Various external loadings or manufacturing defects (e.g., matrix voids) can cause delaminations in laminated composite structures which can reduce the ability of the structures to withstand load. Hence, understanding of initiation and propagation of delaminations under static and cyclic loads at cryogenic temperatures is essential for damage tolerant design of cryogenic composite structures. The purpose of this paper is to investigate the mixed-mode I/II fatigue delamination growth behavior in woven GFRP laminates at cryogenic temperatures.

2. Experimental Procedure

In this work, National Electrical Manufacturers Association (NEMA) grade G-11 woven GFRP laminates (Toyo Lite Co., Ltd., Japan) were employed for the tests. The fiber reinforcement in G-11 was a plain weave E-glass fabric. The G-11 matrix was a bisphenol-A epoxy resin. The specimens for the mixed-mode bending (MMB) tests were produced from panels of G-11 woven laminates. The panel was prepared from 20 plies and had a nominal thickness, \( 2H \), of 3.85 mm. The specimen length, \( L \), and width, \( B \), were 70 and 20 mm, respectively, and the specimens were cut with the length parallel to the warp direction. A polymer film was placed at the specimen midplane which serves as a delamination initiator. To produce an initial delamination, each specimen was precracked. Aluminum end blocks were adhesively bonded to the specimens to enable load application.

The mixed-mode I/II fatigue delamination tests were conducted using a MMB apparatus shown in Fig. 1. The half-span length \( l \) was chosen to be 25 mm. The lever arm length \( c \) determines the relative magnitudes of the Mode I and II loads on the specimen and these loads then determine the mode I/II ratio. In the present study, the lever arm lengths of 12.5, 19.0 and 25.2 mm were selected. The G-11 specimens were tested at room temperature, liquid nitrogen...
temperature (77 K) and liquid helium temperature (4 K). Testing at 77 K was accomplished by submerging the MMB test apparatus and specimen in liquid nitrogen, and the 4-K tests were conducted in liquid helium. All fatigue tests were performed in sinusoidal load control at a test frequency of 2 Hz and a constant load ratio $R$ of 0.1. The load ratio is defined as $R = P_{\text{min}} / P_{\text{max}}$, where $P_{\text{max}}$ and $P_{\text{min}}$ are the maximum and minimum applied loads, respectively. The compliance $C$ was generated for all corresponding values of the number of cycles $N$, and the delamination length $a$ was monitored using the following relationship between compliance and delamination length:

$$C = C_0 + C_1a^3, \quad (1)$$

where $C_0$ and $C_1$ are the material constants depending on the mode I/II ratio. The compliance-delamination length relationships for each lever arm length, i.e., mode I/II ratio, at room temperature and 77 K were determined prior to fatigue testing, where the compliance $C$ was measured on the load-displacement curve and the delamination length $a$ was determined visually. According to the previous experimental study, the compliance-delamination length relationship at 77 K was used to determine the delamination length during the fatigue testing at 4 K. After the fatigue delamination tests, microscopic observations of the specimen fracture surfaces were made with scanning electron microscopy (SEM).

3. Finite Element Analysis

The test specimen and apparatus were modeled. Because of symmetry, only a half of the test geometry was considered. The test apparatus was treated as an extremely stiff elastic body. Eight-noded three-dimensional solid elements were used for meshing the specimen and the apparatus. Contact elements were employed at the delaminated interface, as well as for the contact region between the apparatus and the specimen. All contact surfaces were assumed to be frictionless. The orthotropic elastic properties of G-11 woven laminates for the finite element analysis were determined from the micromechanics model of Hahn and Pandey.

Fatigue delamination growth under mixed-mode loading is typically described in terms of a power law relationship:

$$\frac{da}{dN} = A(\Delta G_T)^m, \quad (2)$$

where $\Delta G_T$ is the range of the total energy release rate $G_T$, i.e., the sum of Mode I, Mode II and Mode III energy release rates for the MMB test, and $A$ and $m$ are constants determined from the curve fit to the fatigue test data. The total energy release rate range $\Delta G_T$ can be obtained as

$$\Delta G_T = G_{T_{\text{max}}} - G_{T_{\text{min}}} = (1 - R^2)G_{T_{\text{max}}}, \quad (3)$$

where $G_{T_{\text{max}}}$ and $G_{T_{\text{min}}}$ are the maximum and minimum total energy release rates corresponding to the maximum and minimum applied loads, respectively. The virtual crack closure technique (VCCT) was used to calculate the Mode I, Mode II and Mode III components of the energy release rate.

4. Results and Discussion

Fig. 2 presents the plot of delamination growth rate $da/dN$ versus total energy release rate range $\Delta G_T$ data at room temperature (RT), 77 K and 4 K for $G_{II}/G_T = 0.53$ (c = 19.0 mm). The total energy release rate at the center of the specimen was used to determine the energy release rate range $\Delta G_T$. Although $da/dN$ versus $\Delta G_T$ data exhibit some scatter, the data have a linear relationship on a log-log scale. The lines in the figure represent the power law relationships. The delamination growth rates at 77 K and 4 K are lower than that at room temperature, as observed for the woven GFRP laminate specimens under pure Mode I or Mode II conditions. That is, the resistance to fatigue delamination growth at cryogenic temperatures is higher than that at room temperature. Also, the delamination growth behavior is influenced by the mixed-mode ratio of Mode I and Mode II. In addition, the hagge pattern on the fracture surfaces becomes more pronounced with an increasing component of Mode II loading, and the delamination growth mainly occurs by fiber/matrix debonding.

References