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Experimental investigation and finite element modeling of mixed-mode delamination in a moisture-exposed carbon/epoxy composite

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ABSTRACT

An investigation of the effects of moisture on mixed-mode I/II delamination growth in a carbon/epoxy composite is presented. Experimental quasi-static and fatigue delamination tests were carried out on composite specimens. The quasi-static fracture test results showed that exposure to moisture led to a decrease in mode II and mixed-mode delamination toughness while mode I toughness was enhanced. The fatigue tests revealed an adverse effect of moisture on delamination growth under mixed-mode loadings. Existing delamination criteria and growth rate models were evaluated to determine which ones best predict delamination toughness and growth, respectively, at any given mixed-mode ratio. Quasi-static and fatigue simulations with a cohesive zone-based finite element model that incorporated the selected mixed-mode delamination models were performed and good agreement between experimental and numerical data was shown for dry and moisture-exposed specimens.

1. Introduction

A great number of advanced aerospace structures are fabricated with laminated carbon fiber composites for their high stiffness- and strength-to-weight ratios, which reduce aircraft weight and increase fuel economy. However, these composites are prone to delamination, which can occur in three distinct loading modes: I (opening), II (sliding shear) and III (tearing shear). In most cases, composites are affected by combinations of mode I and mode II delamination, while mode III effects are negligible. Hence, mixed-mode I/II delamination toughness and fatigue growth have extensively been studied for fiber reinforced epoxy matrix composites [1–5].

Aerospace composites can be exposed to environmental elements and studies have shown that moisture exposure reduces mode II delamination toughness (G_{IIc}) in composites [4–9]. Conversely, it appears that moisture can increase mode I delamination toughness (G_{Ic}) [4,6–8], although some studies found that moisture had a negative [10] or little to no [11,12] effect on mode I delamination toughness. The effects of moisture on fatigue delamination growth in composites have been studied by Landry et al. [9] and by LaPlante and Landry [10]. These studies showed that moisture accelerated mode I and mode II fatigue delamination growth. To the authors' knowledge, no studies have been published on the effects of moisture on mixed-mode I/II fatigue delamination growth rates.

Several criteria have been proposed to predict delamination toughness at given mixed-mode ratios [1,13], each including a different number of parameters. Such criteria are used in finite element (FE) models to determine delamination toughness for a full range of mixed-mode ratios. Models have also been proposed to calculate delamination growth rates at any given mixed-mode ratios [2,3,14]. These delamination growth rate models also have different parameters and are utilized in FE models.

Reliable prediction tools are needed to accurately predict delamination growth in composites structures that are prone to moisture degradation for any mixed-mode loadings. The ability to model delamination growth is important to avoid the overdesign of composite structures and to set inspection intervals for crack monitoring in critical components. Cohesive zone models (CZM) are often used in FE analyses to simulate delamination due to their efficiency compared to the virtual crack closure technique (VCCT). By using a bilinear cohesive law, fatigue degradation algorithms are easily integrated to FE models [15–17].

In the present study, moisture effects on delamination toughness and growth rate in a carbon/epoxy composite subjected to mixed-mode I/II loadings have been investigated. Existing mixed-mode delamination criteria and delamination growth rate models were fitted to experimental data and the best models were selected for implementation in a FE model.

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A cohesive zone based FE model was developed for mixed-mode loadings from the approach presented by the authors in [17]. In the FE model, the maximum delamination driving force (G_{max}) during fatigue cycles was determined by a J-integral approach [18] and the mixed-mode bilinear constitutive law was inspired from two existing methods [19,20]. Simulations of delamination progression using the model were performed for quasi-static and fatigue loadings. The simulation results were compared with experimental data for mixed-mode loadings on both dry and conditioned composites.

2. Material and conditioning

The studied material was CYTEC G40-800/5276-1, a unidirectional carbon fiber reinforced epoxy matrix prepreg from Cytec Engineered Materials (Havre de Grace, MD). Five unidirectional laminated plates of 16 plies were cured following the manufacturer's cure procedure [21]. The plates were of a nominal thickness of 2.5 mm and were cut into 20 mm wide by 133 mm long specimens. During fabrication, a 26 μm thick PTFE film was inserted at the midplane at one end of the plate to create an initial delamination. The initial delamination length was 70 mm in mode I specimens and 50 mm in the other specimens.

Half of all specimens from each plate were submerged in a Cole-Parmer Stable Heat (Vernon Hills, IL) distilled water bath set to 70 °C. This temperature was set to accelerate water absorption [22] while being well below the glass transition temperature of the 'wet' epoxy matrix of 154 °C [21]. All other specimens were placed in sealed bags to avoid moisture absorption from ambient air. During conditioning, three specimens per plate were weighed with an Ohaus Adventurer SL (Pine Brook, NJ) electronic balance (resolution of 0.1 mg) at gradually increasing intervals starting from one hour to two weeks, in order to plot a moisture absorption curve. Specimen moisture content was calculated using [23]:

$$M = \frac{W_i - W_0}{W_i} \times 100\% \tag{1}$$

where W_0 represents the initial weight of the specimen and W_i the weight of the specimen at the time of the weighing. The specimens were deemed in a state of effective moisture equilibrium when their moisture content increased by less than 0.02% for a two week interval, as suggested by [23].

3. Experimental procedures

Piano hinges of the same width as the specimens were bonded on the pre-delaminated end of the specimens using a cyanoacrylate based glue. A thin layer of white correction fluid was added on the specimen sides from the initial delamination tip to the un-delaminated end. Markings 5 mm apart were then added starting from the initial delamination tip to facilitate delamination growth measurements. Mode I precracks of 3–5 mm were created on each specimen to ensure a sharp delamination tip. Mode I precracks were selected to avoid unstable delamination during precracking. They also produce conservative values of delamination toughness in mode II and mixed-mode fracture tests [24]. All experimental tests were done using a MTS (Eden Prairie, MN) loadframe equipped with a 2.5 kN load cell. Delamination progression was monitored with a Dino-Lite AM413MT (ANMO Electronics Corporation, Taiwan) digital microscope.

In this paper, delamination toughness and delamination growth rate tests were conducted for mode I, mode II and mixed-mode loading ratios (G_{II}/G_T) of 0.25, 0.50 and 0.75. Test configurations were double cantilever beam (DCB) for mode I, end-notched flexure (ENF) for mode II and mixed-mode bending (MMB) for mixed-mode delamination.

3.1. Delamination toughness

For all quasi-static delamination toughness tests, the load point displacement rate was set to 0.5 mm/min and displacement stopped at every 0.5 mm to observe delamination progression in the specimen with the digital microscope.

Delamination toughness for mode I loadings G_{Ic} was calculated as [25]:

$$G_{Ic} = \frac{3P_{max}\delta_{max}}{2B(|\Delta| + a)} \tag{2}$$

where P_{max} is the maximum load using the 5%/max method [25], δ_{max} is the displacement at maximum load, a is the delamination length, Δ is the delamination length correction factor and B is the width of the specimen.

A compliance calibration was performed for ENF tests in order to calculate G_{IIc}. Compliance was obtained for three initial delamination lengths of 20, 30 and 40 mm obtained by moving the specimen in the ENF fixture. To prevent specimen damage, a maximum load equal to half of the calculated critical load was applied for compliance calibration at the three delamination lengths. The critical load was estimated as [26]:

$$P_c = \frac{4B}{3a}\sqrt{G_{IIc}E_{1f}h^3} \tag{3}$$

where G_{IIc} is an estimated value of mode II delamination toughness, E_{1f} is the flexural modulus and h is half of the specimen thickness. A linear regression analysis of the compliance, C, versus the delamination length cubed, a^3, was performed to obtain the coefficient m used to determine delamination toughness, where C has the form:

$$C = A + ma^3 \tag{4}$$

Delamination toughness was then determined as [26]:

$$G_{IIc} = \frac{3mP_{max}^2 a^2}{2B} \tag{5}$$

where P_{max} is the maximum load determined by the 5%/max method [25] and a is the delamination length (in this case 30 mm).

Mixed-mode delamination toughness tests were based on [27]. All three mixed-mode ratios (0.25, 0.50 and 0.75) were attained by adjusting the loading lever position, c, of the MMB loading fixture. The loading lever position was estimated as [27]:

$$c = \left(0.167 + 0.000137\tilde{a}^2 - 0.108\sqrt{\ln(\tilde{a})}\left(\frac{G_{II}}{G_T}\right)^4 + \frac{-1400 + 0.725\tilde{a}^2 - 141\ln(\tilde{a}) - 302\ln\left(\frac{G_{II}}{G_T}\right)}{219 - 5000\frac{G_{II}}{G_T} + 55\ln(\tilde{a})}\right)L \tag{6}$$

where $\tilde{a}$ is a nondimensionalized delamination length and G_{II}/G_T is a given mixed-mode ratio. The delamination toughness was then calculated as [27]:

$$G_T = \frac{12[P_{max}(3c - L) + P_g(3c_g - L)]^2}{16B^2h^3L^2E_{1f}}(a + \chi h)^2 + \frac{9[P_{max}(c + L) + P_g(c_g + L)]^2}{16B^2h^3L^2E_{1f}}(a + 0.42\chi h)^2 \tag{7}$$

where P_{max} is the maximum load using the 5%/max method [25], P_g is the weight of the lever, c_g is the lever length to center of gravity of the lever, L is the half span length of the MMB testing apparatus and χ is a crack length correction parameter.