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Effects of large scale bridging in load controlled fatigue delamination of unidirectional carbon-epoxy specimens

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Fatigue delamination growth in composites is accompanied by large scale bridging (LSB) that yields important toughening effects. However, the extent of this mechanism depends on the laminate geometry rendering its modeling a challenging task. This work presents a combined experimental/numerical study on characterization of specimen thickness dependence of LSB in fatigue delamination. Double cantilever beam specimens of different thicknesses ($h = 2$, 4 and 8 mm), equipped with arrays of multiplexed fiber Bragg grating sensors, are subjected to mode I fatigue loads. Measured strain data with the sensors are employed to identify the bridging tractions and subsequently compute the energy release rate (ERR) due to the bridging as well as the ERR at the crack tip. The obtained results confirm that fatigue delamination growth strongly depends on the specimen geometry when LSB prevails. It is shown that both the extent of bridging and critical ERR at failure increase by increasing the specimen thickness while the maximum bridging traction at the crack tip is found independent of the specimen geometry. The identified traction-separation relations serve to establish a power correlation, between the crack growth rate and ERR at the crack tip which is independent of the specimen thickness.

1. Introduction

Delamination under fatigue loads is widely recognized as a critical failure mode of fiber-reinforced laminates. Significant progress has been achieved on this matter over the past few decades as recently reviewed in Ref. [1]. In particular, a wealth of literature exists on modeling and experimentation of fatigue delamination based on the fracture mechanics concepts [1–6]. Yet, a thorough characterization of governing mechanisms on delamination growth under cyclic loading is still lacking. Moreover, the standardized experimental methods for characterization of fatigue delamination, such as ASTM D6115, are limited only to the onset of delamination. These limitations are primarily due to the complexity of damage events that take place in the wake of the crack during delamination growth. An important damage mechanism that can accompany fatigue delamination propagation in fibrous laminates is crack bridging by intact fibers. Bridging fibers effectively reduce the stress level at the vicinity of the crack tip and consequently contribute to crack growth resistance: under fatigue loads, development of the bridging zone affects the rate of crack growth and can lead to crack deceleration and even crack arrest. Hence, assessment of bridging effects is of particular importance in the characterization of fatigue delamination in composite laminates. In the literature, several semi-empirical relationships between the cyclic loading parameters and delamination growth rate are proposed. These models often employ a Paris-Erdogan relation between the rate of crack growth and applied cyclic energy release rate (ERR) or stress intensity factor [1]. However, the applicability of such relations is often limited to the experimental conditions in which they are established. Moreover, such an approach cannot predict crack growth deceleration while the total applied ERR increases.

In contemporary approaches, bridging effects are described by a distribution of tractions over the crack faces. The relationship between the bridging tractions and corresponding crack opening displacements (COD), called traction separation relation, can serve in computational methods to model delamination [4,7–9]. A direct experimental assessment of crack-bridging tractions in fatigue delamination is, however, a challenging task, as it requires precise local measurements of strains or displacements along the bridging zone under alternating loads. As a consequence, the modeling efforts accounting for bridging do not always rely on such local

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measurements and for convenience bridging tractions are often estimated from the global response of the specimen [10–12]. Yet, distribution and intensity of bridging in fatigue delamination may differ from bridging in monotonic delamination fracture [13–15]. Moreover, when large scale bridging (LSB) prevails, it can be influenced by the laminate geometry [7,16–18]. In these studies, identification of traction-separation relations is based on COD measurement at the notch root [7] or distributed strains along the bridging zone under monotonic loads [13,16,17]. Here, the latter method [13] is adopted to identify the bridging traction contribution in fatigue fracture of carbon-epoxy composite specimens, due to its ease of implementation and data acquisition as well as versatility especially in fatigue tests: it is based on distributed strain measurements, with wavelength multiplexed fiber Bragg grating (FBG) sensors, along the crack propagation direction and subsequent inverse identification of bridging tractions using parametric finite element (FE) modeling. Employing such an approach in the analysis of monotonic fracture it is demonstrated that both the bridging zone length and steady state ERR significantly increase by increasing the specimen thickness while the crack initiation ERR, as well as the maximum bridging traction at the crack tip, are independent of the specimen geometry [16,17]. A recent micromechanical analysis of LSB supports the specimen thickness dependence of bridging during fracture [19]. Although progress has been reported on understanding bridging phenomena, studies on load-controlled fatigue delamination are very scarce. Thus, in this work, LSB effects and the specimen thickness dependence in fatigue delamination are investigated. Unidirectional carbon epoxy specimens of different thicknesses, equipped with arrays of multiplexed FBGs, are subjected to mode I force-controlled fatigue loads. Measured strain data with FBG sensors are employed to identify the bridging tractions and subsequently quantify the crack tip ERR as well as the ERR due to bridging. The results allow elucidating bridging effects in delamination growth.

2. Materials and methods

2.1. Specimens

Unidirectional carbon epoxy laminates with thicknesses of $h = 2, 4$ and 8 mm are fabricated by stacking prepreg layers of SE 70 from Gurit ST™. An initial crack starter is introduced at the mid-plane of the laminates by inserting a 60 mm long and 13 μm thick release film from Aerovac®. The laminates of different thicknesses are cured using the same standard procedure suggested by the prepreg manufacturer so that the variation of fiber volume fraction between the composite plates is less than 1% and the maximum variation in thickness for any given specimen does not exceed 0.1 mm. Double cantilever beam (DCB) specimens are prepared by cutting the cured composite plates into 25 mm wide beams and bonding steel loading blocks (10 × 25 × 10 mm) to the beams end. One side of each specimen, normal to the crack plane, is painted white and marked with black thin lines at every millimeter to provide a clear image of the crack tip location during the tests. The specimens with $h = 2$ and 4 mm, are equipped with optical fibers (SM28, 125 μm in diameter), each containing 10 wavelength multiplexed FBG sensors. The sensors are equally spaced at 3 mm center to center and each one has a gauge length of 1 mm. In case the of the 2 mm thick specimen, the optical fiber (with the coating removed) is embedded four layers away from the crack plane. For the $h = 4$ mm specimen, the array of sensors is bonded to the specimen surface using a liquid cyanoacrylate instant adhesive (Loctite® 401). In both cases, the optical fibers are aligned parallel to the carbon fibers' direction and centered in the width of the specimen. The exact position of FBGs along the longitudinal axis of the beam is measured using the optical low-coherence reflectometry technique with a step length of 25 μm. The following elastic constants are used for the numerical analysis: longitudinal modulus $E_z = 120.2$ GPa, transverse moduli $E_y = E_x = 7.3$ GPa, shear moduli $G_{zy} = G_{zx} = 3.9$ GPa and Poisson's ratios $\nu_{zy} = \nu_{zx} = 0.28$, $\nu_{yx} = 0.48$ (Fig. 1) [20].

2.2. Fatigue testing

Mode I fatigue tests are performed using an Instron® machine equipped with a 500 N load cell in force control. A schematic of the fatigue testing configuration is shown in Fig. 1a. In total, nine specimens (three specimens per laminate thickness) are tested. Prior to fatigue testing, the specimens are ramp loaded in displacement control (3 mm/min) to initiate a natural crack from the end of the insert film. The load at crack initiation under monotonic loading of each specimen is reduced by 20% and applied in the subsequent fatigue experiment as the maximum cyclic load. Loading consists of a sinusoidal waveform with a frequency of $f = 2$ Hz and a minimum to maximum load ratio of $R = 0.5$. The experiments are terminated at total fracture of the specimen which is the result of unstable crack growth at the end of each fatigue test. Crack propagation is followed throughout the tests using a high resolution CCD camera. The rate of crack growth, $\Delta a/\Delta N$, is determined from the crack length data, a, at every millimeter and number of elapsed cycles, N. It is experimentally observed that the specimens behave linearly elastic in loading/unloading cycles with negligible energy dissipation. Thus peak values of load, P, and displacement, Δ, are acquired at each fatigue cycle and subsequently combined with the corresponding crack length data to obtain the maximum cyclic values of the total applied ERR, G_t, as follows:

$$G_t = G_{I,tip} + G_{I,b} = \frac{P^2}{2b}\frac{dC}{da} \tag{1}$$

Here b is the width and $C = \Delta/P$ is the compliance of the specimen. To obtain smooth data for subsequent differentiation, the measured crack length data and corresponding compliance values are fitted to the following power expression: $C = Ba^n$ where B and n are the fitting constants. Axial strains along the crack propagation direction are monitored by means of the integrated multiplexed FBG sensors. The initial Bragg wavelengths, λ_{B0}, are between 1520 and 1565 nm (spaced by 5 nm) with a bandwidth of 1.5 nm. The Bragg wavelengths emitted during the fatigue loading are detected using the Micron Optics SM130® interrogator with a frequency of 15.8 Hz. It is experimentally observed that the Bragg peaks only shift in response to fatigue crack growth and do not split up. The latter indicates a uniform strain field on the short gratings used. Hence, considering the axial strain, ε_z, as the dominant strain component in the optical fiber, the measured shifts of Bragg wavelength, $\Delta\lambda_B$, are converted to axial strains as follows: $\Delta\lambda_{\mathrm{Bi}}/\lambda_{\mathrm{B0,i}} = (1-\mathrm{p_e})\varepsilon_{\mathrm{z,i}}$, where $i = 1, \ldots, 10$, indicates an FBG sensor along the optical fiber and p_e is the effective photo-elastic constant, equal to 0.2148 for the optical fibers used herein. Subsequently, the measured strains are expressed in the local crack tip coordinate system, as previously described in Ref. [13], to obtain a quasi-continuous strain distribution for inverse identification of bridging tractions in fatigue.

2.3. Identification of the bridging tractions

To identify the bridging tractions, FE models representing the DCB specimens of each thickness, at the crack lengths of interest, are built in Abaqus® Standard v 6.12. The maximum cyclic strain values are taken as the objective data for the identification