Composites Science and Technology 84 (2013) 44–50

Contents lists available at SciVerse ScienceDirect

Composites Science and Technology

journal homepage: www.elsevier.com/locate/compscitech

Assessment of the influence of the crack monitoring method in interlaminar fatigue tests using fiber Bragg grating sensors

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ARTICLE INFO

Article history:
Received 28 February 2013
Received in revised form 22 April 2013
Accepted 27 April 2013
Available online 18 May 2013

Keywords:
B. Fatigue
B. Delamination
A. Smart materials
A. Polymer–matrix composites (PMCs)

ABSTRACT

One of the main experimental problems in performing delamination fatigue tests on composite materials is monitoring the crack length. Crack length is commonly monitored by means of traveling optical devices in a discrete representation and/or is derived from the specimen's compliance previously calibrated. In this paper, we propose an accurate method, based on the use of fiber Bragg grating sensors, and we apply it to a carbon reinforced composite. Then, the obtained results are compared to the results achieved by the visual inspection method in order to analyze the influence of the crack growth monitoring on the crack growth rate characteristics determination: Paris law material constants and energy threshold. Results indicate that optical inspection methods predict well the exponent in the Paris law equation, but the energy threshold is strongly dependent on the method used to measure the crack growth.

1. Introduction

High-cycle fatigue is a well known phenomena of damage initiation and propagation in composites [1–5]. The test to measure the onset of damage is standardized [6], whereas there is a lack of a standard procedure to determine the crack growth rate (da/dN), even though research efforts have been focused on fatigue propagation standardization in recent years [7,8]. One of the most common approaches for the analysis of delamination under mode I fatigue loading is the fracture mechanics approach, which relates the fatigue crack growth rate, da/dN, to the amplitude of the energy release rate, ΔG. The log (da/dN)-log (ΔG) plot can be divided into three regions: the energy threshold where the crack growth rate becomes unmeasurable (I), the region close to static failure (III), and, in between, the linear propagation zone (II), well described by the Paris law [9,10]

$$\frac{da}{dN} = Q\left(\frac{\Delta G}{G_C}\right)^m \tag{1}$$

where a is the crack length, N the number of load cycles, and Q and m empirical material constants. The cyclic variation of the energy release rate (ΔG) is dependent on the loading conditions, and G_C is the static fracture toughness of the material. The loading term in the Paris law may be also expressed as a function of the maximum energy release rate G_{Imax}, or by means of the stress intensity factor, K_{Imax} or ΔK_{I} [2].

In order to measure the crack growth rate, information on the crack length over the whole fatigue test is required. As specimen compliance can be easily monitored during the test, and there is a unique relationship between compliance and crack length, it is preferable to monitor compliance and then infer crack length [11]. Only a small set of crack tip positions and the corresponding specimen compliance values are needed to fit both parameters [2]. Crack tip positions are commonly determined by means of visual methods such as traveling cameras or microscopes [2,3,7]. Such methods mainly introduce two uncertainties. On the one hand, monitoring the crack length by means of visual methods does not constitute a robust method since it is considered operator-dependent [8]. On the other hand, as reported in [12], the fact that the crack length is measured at the edge of the coupons adds imprecision to the measurement because the crack front is not straight. The use of fiber Bragg grating sensors (FBGs) has been proved to overcome these limitations in fatigue propagation monitoring [13–16] as it provides a direct and objective measurement of the crack length. In addition, this method is completely independent of the operator and the location of the sensor at the center of the crack front avoids any problem associated with the crack tip monitoring through the edge.

FBG sensors are being increasingly used to measure the internal strain field of composite structures [17–19] mainly due to their low intrusiveness and their accuracy [20,21]. [12,22,23] demonstrate that, the disturbance of the optical fiber to the energy release rate is minimal and very local in quasi-static delamination tests under different crack propagation modes. In addition, these works demonstrate that a direct determination of the strain field with

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http://dx.doi.org/10.1016/j.compscitech.2013.04.022

long FBG sensors is possible through the Optical Low Coherence Reflectometry (OLCR) interrogation technique. This technique enables the measurement of the length, location and local Bragg wavelength (i.e. local strains distribution) of the FBGs [22–25]. The measurements of non-homogeneous strain fields are the principal benefit of this method [26], as the full strain distribution can be measured without the need to know the initial strain state.

In relation to the use of FBGs to monitor fatigue delamination, Epaarachichi et al. analyzed the response of long FBGs embedded in glass fiber cross-ply composites [13] concluding that the shape of the output FBG spectra contained valuable information about the composite structure such as local crack initiation/propagation stage. In [14], multiplexed 6 mm long FBG sensors were used to monitor the fatigue crack growth in adhesively bonded joints of thick composite laminates, and achieved a resolution similar to that of ultrasonic testing. In the work presented by Stutz et al. [16], FBG arrays (each FBG was 1 mm long) were used in composite samples to determine the bridging traction present in mode I fatigue crack propagation. The authors demonstrate that, strain measurements near the delamination zone are feasible by using multiplexed short FBG sensors to construct quasi-continuous strain profiles along the sensor. A quasi-continuous strain evolution over the number of cycles was also obtained by means of multiplexed FBGs in [15], where the fatigue delamination was monitored in open-hole specimens.

In this paper, we propose using FBGs to monitor the crack growth in mode I fatigue tests and then, using that information to construct the crack growth rate curves. This method is compared to common techniques, which are based on the optical measurements at the edge of the coupons. Results indicate that, even though all curves show the same slope, the energy thresholds are strongly dependent on the crack measurement method. Taking into account the high accuracy of the measurements given by the FBGs, the present work shows that, for the CFRP studied, the errors in the energy threshold calculations reached about 11% when using visual inspection methods.

2. Methodology

2.1. Specimens

Carbon/epoxy unidirectional specimens were cut from a single plate manufactured by stacking 36 UD layers of AS4/8552 unidirectional pre-pregs. A Teflon film 20 μm thick and 60 mm long was placed at the midplane, between layers 18 and 19, to act as pre-crack insert. Two instrumented samples (FAT1 and FAT2) and one non-instrumented sample (FAT3), which was used to check the effects of the optical fiber into the coupons' behavior, were tested. The initial dimensions of the coupons were 200 × 25 mm with a total thickness of 4.5 mm.

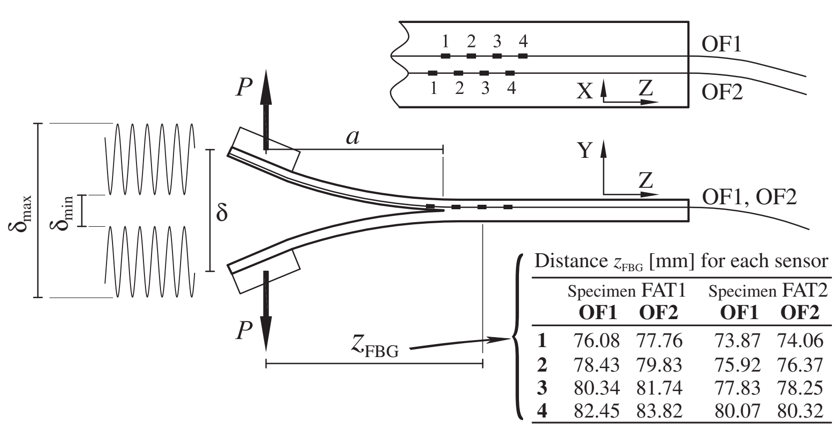
Two parallel FBG arrays were embedded two layers above the crack plane (between layers 20 and 21) in each instrumented sample, and aligned to the reinforcing fibers. The separation between the optical fibers in the *X* direction was 2 mm. Each FBG array consisted of 4 FBG sensors written into a single mode fiber SM28 with a diameter of 125 μm. The length of each FBG sensor was 1 mm, the Bragg peaks were located between 1525 and 1540 nm and spaced by 5 nm. The distance between FBGs' centers was 2 mm in the *Z* direction, as the manufacturer recommended a separation of 1 mm between each sensor in the same fiber. The two parallel arrays were embedded in each specimen (see Fig. 1) in order to monitor the crack length every millimeter. However, as the placement of the fibers is a manual process, this 1 mm offset was not fully achieved. The exact position of each one of the FBG sensors was accurately determined by means of the OLCR technique [22–26]. As the optical fiber was cut at the sample end (left part of the specimens shown in Fig. 1), the OLCR interrogation gave a peak of intensity for the fiber end, and a peak of intensity for each FBG in a distance scale. The location of each FBG was converted to crack tip positions by taking into account the location of the load introduction point. The position of each FBG, in relation to the loading blocks, is reported in Fig. 1.

2.2. Fatigue tests parameters

The crack length increment in a fatigue test under stroke control with constant maximum and minimum displacement, can be estimated by means of the expression of the energy release rate for a DCB specimen assuming single beam theory as

$$a_f - a_0 = a_0\left[\left(\frac{G^0_{\mathrm{Imax}}}{G_{\mathrm{Ith}}}\right)^{1/4} - 1\right] \qquad (2)$$

where a_0 is the initial crack length, a_f is the final crack length, G^0_{Imax} is the maximum energy release rate during each cycle at the beginning of the test and G_{Ith} is the energy threshold for which the crack no longer grows. The crack tip was placed 3–5 mm away from the first FBG sensor in order to avoid the loss of data due to an initial rapid crack propagation. Due to the spatial distribution of FBGs, the extension of crack length, a_f–a_0, was set to 13 mm. As the preliminary tests showed that $G^0_{\mathrm{Imax}}/G_{\mathrm{Ith}}$ was around 2, the desired initial crack length, a_0, resulted to be 70 mm.



Distance z_{FBG} [mm] for each sensor	Specimen FAT1 OF1	Specimen FAT1 OF2	Specimen FAT2 OF1	Specimen FAT2 OF2
1	76.08	77.76	73.87	74.06
2	78.43	79.83	75.92	76.37
3	80.34	81.74	77.83	78.25
4	82.45	83.82	80.07	80.32

Fig. 1. Schematic of the experimental setup with the *z* positions of the FBGs (distance z_{FBG}) in the two parallel optical fibers. 1,2,3 and 4 are the four FBGs in each optical fiber. Photographs were taken from the edge of the *Y–Z* plane.