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Experimental methodology for obtaining fatigue crack growth rate curves in mixed-mode I-II by means of variable cyclic displacement tests

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ABSTRACT

This work presents a novel procedure to characterize the crack growth rate curve under fatigue mixed mode I + II loading conditions with only one specimen. The procedure is based on applying a variable cyclic displacement during a Mixed Mode Bending (MMB) test together with a real time monitoring of the specimen's compliance. The method introduces a dynamic compliance calibration for the crack length monitoring that relates the dynamic compliance to the visually obtained crack length using digital recording of the crack tip region during the fatigue test. The testing procedure is validated to be efficient in terms of testing time and required material.

1. Introduction

Interlaminar stresses cause delamination, which is considered to be the most damaging failure in composites and leads to a reduction in strength and stability of structures. In real-life composite components, delaminations usually grow under the influence of fatigue load and propagate under a combination of mode I (opening) and mode II and III (shear) loads [1,2].

Crack growth rate curves provide information about the delamination growth of composite materials under cyclic loading and relate the crack growth rate, da/dN, with the maximum cyclic energy release rate normalized to the fracture toughness, $\mathscr{G}_{max}/\mathscr{G}_c$. For the reader's convenience, the authors recall from [3] the term 'severity' to refer, from now on, to the ratio between the maximum cyclic energy release rate and the fracture toughness, which provides an idea of how far is the fatigue loading from the static limit. The crack growth rate curve is used to determine the number of load cycles required for a crack to lead to an unsafe size under a damage tolerant approach [4]. It is usually sectioned into three stages that span from the lowest value of severity to the highest: In Stage I, there is no crack propagation and it is characterized by the threshold value, $\mathscr{G}_{th}$, below which no propagation occurs. In Stage II, the propagation can be described by a modified Paris' law expression [5]. In Stage III, the crack growth curve rises to an asymptote which corresponds to the critical fracture toughness value, $\mathscr{G}_c$, where static fracture is achieved [6].

The presentation of both da/dN and the severity requires to monitor the crack length, a, during the fatigue test. Conventionally, a is optically measured by locating the crack tip at the edge of the specimen by means of a large distance microscope. The fatigue test is interrupted every certain number of cycles to observe the crack tip position [7–10]. Therefore, this methodology provides low frequency measurements which leads to a discontinuous set of $a(N)$ data points and, consequently, to a large scatter of the derivative da/dN in the Paris' law curve [11].

As an alternative, the crack length can be estimated from the compliance of the specimen [12–14]. One option is performing a series of static tests with sub-critical loading, usually performed before the fatigue test, at different initial crack lengths, to obtain the relation between the compliance and the crack length. This procedure is called compliance calibration (CC) [15]. Another option to relate the specimen compliance with the crack length, named Compliance Based Beam Method [16], is using the Timonshenko beam theory. In any case, during the fatigue test, the compliance can be obtained stopping the test in order to statically load and unload the specimen. This leads to scattered crack length data, and thus, scattered crack growth rate data. To avoid stopping the fatigue test, Renart et al. [17] introduced the continuous monitoring of the dynamic compliance, where the dynamic compliance is measured during the fatigue test at a frequency of 1 cycle. With this method, a continuous curve for the evolution of the specimen's compliance with the number of cycles is obtained, thus having a continuous crack growth rate curve.

The delamination behavior for different mode mixities can be

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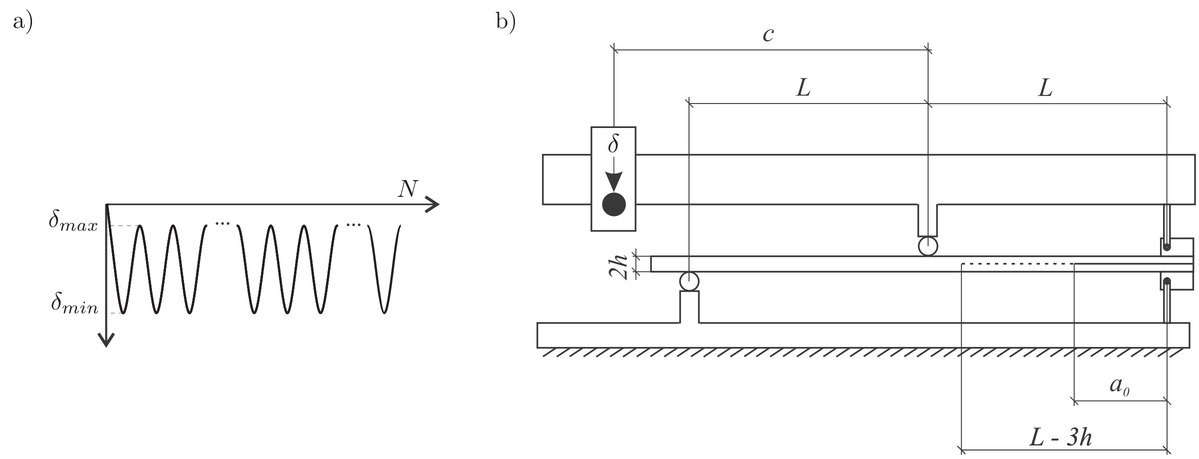

Fig. 1. (a) The displacement is applied in sinusoidal loading cycles on the lever arm. (b) MMB test setup, where L is the midspan length, a_0 is the initial crack length and $2h$ is the specimen's total thickness. $[a_0, L-3h]$ is the feasible propagation region [19].

characterized with a mixed-mode bending (MMB) test. MMB fatigue test are usually carried out under displacement control with sinusoidal shaped loading cycles of constant displacement [18,2]. In Fig. 1a a typical curve of applied displacement, δ, versus the number of cycles, N, is shown and, in Fig. 1b, the test setup. The feasible crack propagation spans between the tip of the initial crack, a_0, and the proximities of the loading roller, at $L-3h$, where the through-thickness compression arrests the crack propagation [19].

For End Notched Flexure (ENF) and for MMB tests conducted under constant cyclic displacement conditions, it is technically unfeasible to generate the linear part of the crack growth rate curve (Paris' law curve) with a single test due to the geometry of the specimen and the test configuration. Instead, only small segments of the crack growth rate curve can be generated with a single test on one specimen.

Fig. 2 shows the evolution of the severity with the crack length, a, for three initial severities. Under mixed-mode conditions and constant cyclic displacement, the severity increases and then decreases with the crack extension. Therefore, the same segment of the crack growth rate curve is tracked twice by the same test. Indeed, the higher the mixed mode ratio is, the smaller is the explored range of severity in a single test, and the more constant cyclic displacement tests at different initial severities are required to create the full Paris' law curve. The limiting case is a pure Mode II test.

In a recent paper, Carreras et al. [3] approached this problem and carried out fatigue 3-ENF tests with a variable cyclic displacement that enabled a methodology to measure the Paris' law curve in a single test. The procedure is based on varying the applied cyclic displacement, δ_{min} and δ_{max}, while keeping the displacement ratio, $R = \delta_{min}/\delta_{max}$, constant. The displacement variation is calculated in advance and implemented in the control software of the testing machine, thus avoiding any human intervention during the fatigue test.

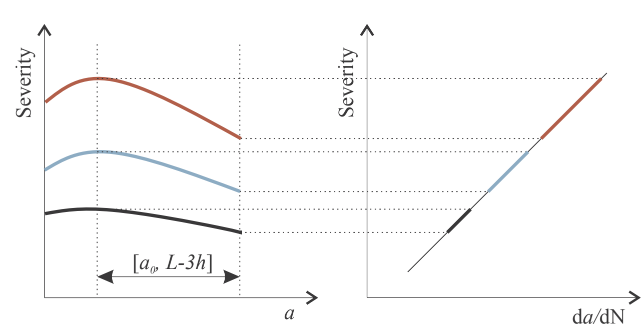

Fig. 2. (a) Severity, $\mathcal{G}_{max}/\mathcal{G}_c$, versus the crack length, a, for three MMB tests at different initial severities. (b) Range of crack growth rate curve explored in each test.

In this paper, the methodology derived by Carreras et al. [3] for the mode II test, is extended for MMB tests. The presented methodology allows to obtain the major part of the Paris' curve, from a high severity to the threshold value in a single MMB fatigue test. The contribution of the present work relies in the compliance calibration to obtain a continuous crack length curve, $a(N)$. This compliance calibration is carried out by relating the dynamic compliance recorded during the fatigue test [17] to the crack length extracted from photos that are taken while the fatigue test is running. The methodology is verified in a test campaign for two mode mixities. This paper is structured as follows: firstly, the methodology is presented, followed by a description of the experimental campaign. Finally, the results obtained are presented and discussed.

2. Methodology

2.1. Mixed mode I – mode II test

The mixed-mode I-II interlaminar fracture toughness tests are conducted according to ASTM D6671 standard [19] by using the test fixture shown in Fig. 1b. The lower roller is attached to the base setting a span length of $2L$ to the lower block. The displacement is applied at the lever arm. The lever length, c, can be adjusted by changing the position of the saddle in order to obtain the desired mode mixity, $\mathcal{G}_{II}/(\mathcal{G}_I + \mathcal{G}_{II})$. The blocks, bonded to the specimen, are connected with a metal pin to the test rig. The initial crack length, a_0, can be varied by bonding the block at a certain distance to the crack tip.

2.2. Monitoring the crack length with the compliance method

The compliance calibration (CC) method is used for calculating the crack length and, thus, obtaining a continuous $a(N)$ curve by means of the real time monitoring of the specimen's compliance [17]. Assuming linear elastic behavior, there is a direct relationship between the crack length and the specimen's compliance:

$$C(a) = m_{cc} a^3 + C_0 \tag{1}$$

where m_{cc} and C_0 are fitting parameters.

Two methodologies to experimentally determine the CC parameters are analyzed in this work: The static-CC and the dynamic-CC.

The static-CC is done by carrying out a series of non-destructive static tests at different crack lengths prior to the fatigue test [19,11]. The blocks are bonded and debonded from the specimen several times to create different crack lengths. The compliance of the specimen is determined for each of the tested crack lengths as the slope of the load–displacement curve.