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A new testing device to simultaneously measure the mode I fatigue delamination behavior of a batch of specimens

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ABSTRACT

Determining fatigue onset and crack propagation curves for delamination in composites requires time-consuming test campaigns. This work presents a new test rig and its associated methodology to test several mode I specimens simultaneously in a universal testing machine. The novelty of the solution relies on being able to test several specimens at different levels of load ratio and energy release rates in a single run. The performance of the system is exemplified by measuring the complete onset and crack growth rate curves of a batch of 12 carbon fibre reinforced specimens in only two test runs.

1. Introduction

Most structural components are subjected to dynamic loads during their service life. Fatigue loading may cause a structure to fail at a stress level that is merely a small percentage of its quasi-static strength. Therefore, structural design procedures include measuring a structure's fatigue behaviour and assessing its lifetime.

In composite materials, a lot of attention has been devoted to the fatigue behaviour of interlaminar cracks [1–5], where fatigue is divided into 2 phases: onset and crack propagation.

Onset refers to the initiation of crack propagation [6]. Onset curves indicate the number of cycles required to make an existing crack (film insert [7,8], or pre-crack [9]) to start to propagate for a certain load level (usually expressed by means of the energy release rate). Because results are highly disperse, the existing standard for mode I [8] requires testing 6 to 12 specimens for exploratory tests and 12 to 24 coupons to obtain reliable data.

Crack propagation curves, however, provide information once damage has been initiated, i.e. the crack growth rate (da/dN) under a certain load level (energy release rate) [6,10]. The two key data generated by the test are: (i) the slope of the crack growth rate in the linear propagation regime of the log-log curve (following the Paris law) and, (ii) the load threshold below which the crack growth rate is immeasurable. In composite materials the slope is higher than in metals [11], and small variations in the test cause large errors when determining the slope. Because of that, various curves are required to obtain reliable material data. New testing methodologies aim to reduce data scattering by making use of automatic and real time measurements of the crack growth rate, for example by continuous monitoring of the compliance [12]. Such tests, however, must be long in duration and have a large number of cycles if the threshold is to be reached, which means, in most cases, between 1 and 10 million cycles [13,14].

Whatever the result to be obtained (i.e., onset or crack growth rate), a very long fatigue testing period is usually required. However, by increasing test frequency, test time could be reduced. In metallic components, test frequency can be increased beyond 10 Hz, but the organic matrix of CFRP laminates is very sensitive to frequency, and so heating problems may arise if increased beyond those levels [15]. An alternative to overcome this problem is to test a number of specimens simultaneously.

Using a multispecimen testing device is convenient for various reasons: the need for a small frequency [16,17], the high number of specimens that are required to qualify a component/material [18] or the need to reach a very high number of cycles [19]. In the literature, there are various fixtures with which to test multiple specimens and some commercial solutions are available as well. However, most of them are for tests other than interlaminar fracture ones, such as Compact Tension (CT) [16,17,20], traction [19], compression [21] or 3-Point Bending Tests (3-PBT) [18,22]. Depending on the nature of the tests, the solutions adopted to apply to the loads differ. For example, using a rotating bending test apparatus actioned by a motor [18,22], a motor turning a camshaft to apply a linear displacement [21], or even, a full system to carry out a specific test and apply different levels of load/displacement to each specimen simultaneously [16,19]. On the other hand, most of the commercial solutions are, because of their popularity, devoted to tensile tests.

With interlaminar fatigue testing, there is a study in which several DCB specimens are tested in parallel [23]. The authors describe two

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testing systems, the first of which is capable of testing 6 specimens at the same time with each specimen being tested and monitored independently. This system is used for tests that require a large number of cycles (10^8 and 10^9 cycles). For other tests (10^6 cycles), the authors use another system which is mounted on a servohydraulic universal testing machine. In this second case, the system allows 4 specimens to be tested at the same time, however, all the specimens are tested at the same energy release rate and the same load/displacement range (R-ratio), i.e. 'replicates' of the same test are carried out. The advantage of this test (over a single-specimen test), is that it provides statistics on the material behaviour for the same number of tests, however, it is limited in that, in one run, all the specimens are tested in the same conditions.

To overcome these limitations, this work presents a test methodology to investigate onset and crack growth rate curves for multiple specimens, simultaneously tested in a single universal testing machine. The method is able to test the specimens at different loads and energy release rates in the same run. The paper presents the step-by-step approach to test multiple specimens in the newly devised multi-fatigue test set-up and the corresponding data reduction procedures. This methodology has been implemented for mode I Double Cantilever Beam (DCB) fatigue tests. The results from a batch of 12 CFRP specimens tested with the multi-fatigue device are analysed and discussed.

2. Multispecimen test rig

The test rig is designed to fit in a universal servo-hydraulic testing machine. It comprises two circular steel plates (A in Fig. 1, A and H in Fig. 2), 198 mm in diameter and 34 mm thick, which are attached to the top and bottom fixtures of the machine with an M12 screw. The plates allow the fixtures for different test configurations, (such as DCB (Double Cantilever Beam), 3ENF (End-Notch Flexure) or ELS (End Load Split)), to be assembled. This work presents a solution for DCB specimens, where 6 coupons can be tested at the same time. The specimens are mounted in an outward direction in a hexagonal distribution to avoid any interference between them. A schematic plain view of this distribution is shown in Fig. 1, and a schema of the full device and the detail of one of the test arms are shown in Fig. 2.

To align the plates (A and H), each has two 28 mm in diameter open holes. The plates are aligned by introducing two calibrated cylindrical bars in the holes. Once aligned, the plates are fastened to the top and bottom fixtures of the machine.

In the mode I case, 6 steel beams (B) are attached to each plate. The end of each beam was machined to act as a clamp, where a cylindrical support (C and G) is attached. This clamping system allows the supports to be rotated to align the top and bottom specimen fixtures. The system has been designed to be stiff enough to support loads up to 5 kN in any of the arms without any significant deflection.

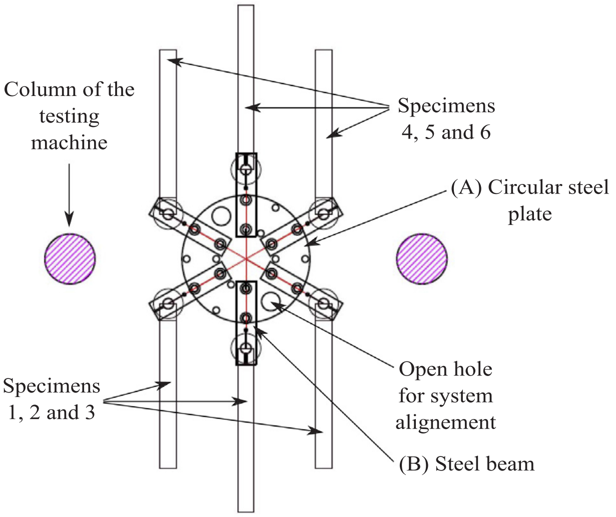

Fig. 1. Top view of the specimen distribution for a test set-up with 6 mode I DCB fracture tests.

On each of the bottom cylindrical supports (G), a 1.25 kN load cell (F) has been attached. At the same time, each load cell is connected to an adaptor (E), which connects to the specimen clamping system by means of an articulated joint. A set of 6 cylindrical supports (C) and adaptors (D) are attached to the upper hand rails (B). In addition to rotation, this set allows vertical displacement, which is controlled by a knob (I) located at the end of each upper support (C). In this way, the zero force, and also the displacement ratio, can be individually set for each specimen.

An upgraded version of the hinge presented by the authors in a previous study [24] is used to mechanically clamp the specimen through its edges (Fig. 3). In the earlier study [24], the hinge was proved to correspond to the fixture systems included in the DCB standards [25–27]. This hinge has since been introduced in the Airbus International Test Method AITM1-0053 [28]. By loosening the clamping of the hinge, the operator can slide the specimen horizontally to adjust the initial crack length.

The mechanism to hold the specimen works as a holding dovetail grip. The point of rotation has been moved from the version in [24] to the corner closest to the crack front in order to minimize the stiffening effects induced by the fixture.

To prevent their release during the cyclic test, the pins that articulate the joint between the hinge and the adaptors (D, E), are fixed to the adaptor (D, E) with an M3 screw. A Clip-On-Gage (COD) attached to the pin ends through two screwed wedges, measures the displacement (Fig. 4).

In a fatigue test, the load ratio (R) is defined as the ratio between the minimum ($P_{\min}$) and peak ($P_{\max}$) loads. For linear elasticity and small deflections, this is identical to the displacement ratio [8]:

$$R = \frac{\delta_{\min}}{\delta_{\max}} \tag{1}$$

For the multi-fatigue test, the displacement span ($\Delta\delta = \delta_{\max} - \delta_{\min}$) is identical for all the specimens. However, it is possible to add an additional displacement to each specimen by rotating the knob (I) located at the top part of the test fixture, see Fig. 2. This additional displacement can be set up before the test and can be measured by a COD attached to the rotation pin between the hinge and the adaptor (D, E). A schematic on how the ratio R can be modified is shown in Fig. 5.

The displacement amplitude ($\Delta\delta$) will be the same but the values of $\delta_{\min}$ and $\delta_{\max}$ will change, thus having a different load/displacement ratio (R).

3. Test procedure

3.1. Determining the crack length

Monitoring specimen crack length is essential to obtain the crack growth rate curve (da/dN vs. G_{Imax}). Although this can be done optically with a device of the proper resolution [3,5,6,29–31], the measurement taken from the specimen's side does not represent the crack tip position for most of the crack fronts [32,33] and it is not feasible for a multi-fatigue test rig.

An alternative method consists of estimating the crack length through specimen compliance (C) [12,32]. Taking into account the beam theory approach, the relationship between the compliance (C) and the crack length (a) is:

$$C^{1/3} = m(a + \Delta) \tag{2}$$

where Δ is the crack length correction [25–27], and m the slope of the curve. If the compliance is measured continuously during the test, $C(N)$, a continuous curve for $a(N)$ can be derived [12,32].