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A new in situ peeling test for the characterisation of composite bonded joints

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ABSTRACT

At the moment, bonded joints quality on composites used in aeronautical industry is verified based on the determination of the interlaminar fracture toughness (G_c) obtained by means of the Double Cantilever Beam (DCB) or the Climbing Drum Peel (CDP) tests. Although they are well-established tests, they have known limitations. This investigation presents the design and validation of a new device that carries out a peeling test, its main advantage being the capability to perform the test in situ, i.e. directly on the actual aircraft production line without the necessity to extract coupons for a laboratory test. An experimental campaign has been carried out, the obtained results being comparable to those obtained with the traditional DCB and CDP procedures. Numerical studies have allowed to understand the delamination mechanisms presented at the different tests, confirming that experimental G_c evaluation obtained is adequate.

1. Introduction

The evaluation of composite-composite bonded joints quality is a major problem for the industry, in particular for the aerospace sector where the use of composite materials in primary structures has considerably increased. Given by the fact that a defective joint not only could paralyze the productive process, but it could also involve very high repairing costs. Experimental tests and numerical tools have been implemented in order to understand the failure modes and critical loads in this kind of component/structures [1–3].

A very common aeronautical structural components are the stiffened panels which include a skin reinforced by the addition of a set of stringers which are usually bonded. The main advantages of bonded joints against bolted joints are the relevant reduction of production time and that holes and other disruptions are avoided. On the contrary, the quality of the bonded joint cannot be guaranteed by usual non-destructive tests (NDTs). This kind of tests are only able to determine if a large discontinuity (interface crack) between the adherent parts exists, but they are not capable to guarantee the conditions of these bonded joints. Thus, a quality control of the bonding process are demanded for Certification Authorities. Then, a test that should be able to evaluate the quality of the resulting joint of the whole process is necessary. The results of the test will capture any deficiency derived from: store conditions of the materials before the process itself, the use of an inadequate combination adherent-adhesive, the presence of pollutant agents within the bonded joint, among others.

Currently, the quality of a bonded joint in aeronautical industry is quantified by interlaminar fracture toughness (G_c) tests. The most commonly used are the Double Cantilever Beam (DCB) [4–9] and the Climbing Drum Peel (CDP) [10,11] tests. These tests measure G_c in a specimen that is bonded suppositionally under the same conditions as actual parts (usually taken from these components). One disadvantage on both tests is that they cannot be carried out “in situ”, i.e. on specimens over actual parts. Moreover, there are still some open questions e.g. regarding the way G_c is calculated and the actual fracture mode occurring on the tests, among others. Although DCB and CDP are the most common tests, there are some alternatives as the peel test [12] or the mandrel peel test [13] but they also have similar disadvantages.

The aim of the present investigation is to design and validate a new device able to determine G_c “in situ”, preserving the advantages of the DCB and CDP tests and also overcome some of their drawbacks.

The paper is organized as follows. The main characteristics of the currently used tests (DCB and CDP) are described in Section 2. Then, the principles for the new test are discussed in Section 3. The results for the test campaign are presented in Section 4 and the numerical results (virtual testing) are included in Section 5. Finally, Section 6 contains the conclusions of the present investigation. Some Appendices A–C are also presented with the aim to answer some of the questions raised on the new test concept.

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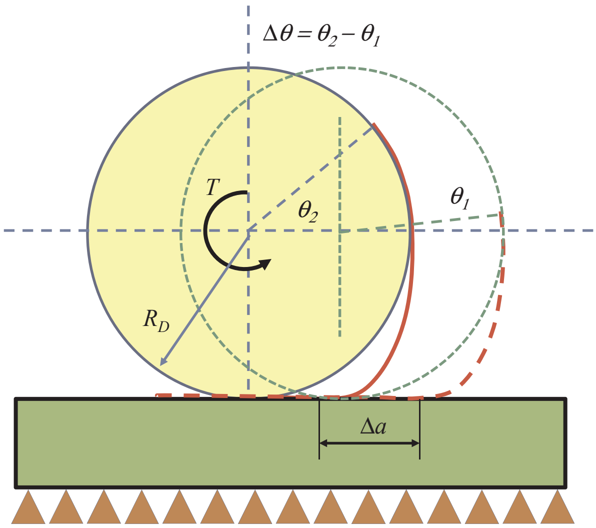

Fig. 1. Scheme of the HDP concept. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 2. CDP test experimental set-up. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. G_c tests overview

In general terms, DCB and CDP tests relies on the fracture toughness calculus defined as the released energy by area unit within an interface crack Gc, defined as:

$$G_c = \frac{\Delta E}{\Delta S} = \frac{\Delta E}{b\Delta a} \tag{1}$$

where E is the energy necessary for crack propagation as function of the load and associated displacement, S is the surface formed due to crack propagation, a is the crack length and b is the specimen width. Previous expression assumes that the crack extends across the whole width of the specimen. Usually on every test configuration this assumption is correct as the crack front is regular.

In the following the main aspects of both tests are described. It is important to recall that G_c only equals G_{Ic} (fracture toughness in pure fracture mode I) under very specific loading and geometrical conditions of the specimens, as it will be discussed later on.

2.1. DCB test

The widest used test to obtain the fracture toughness is the DCB test. This test is used to determine the interlaminar fracture toughness in a composite material (i.e. between two laminaes within a laminate) [4,6,7] or to determine the interface fracture toughness of adhesively bonded joints (i.e. an interface crack grows along an adhesive layer) [5].

In the aeronautical industry, usually companies use their own standards [4,5]. These standards use the load - displacement plot, obtained during the test, to calculate the fracture toughness using:

$$G_c = \frac{A}{ba} \tag{2}$$

where A is the area of the pseudo-triangle defined by the origin and the load- displacement plot between two points, b is the specimen width and a is the increment of the crack length between the chosen points (usually 60 mm).

Nowadays, DCB is the reference test to evaluate G_c. Its main advantages includes: (i) it is able to determine the fracture toughness in pure mode I ($G_c = G_{Ic}$) when symmetrical configurations are used, (ii) it is easy to perform, moreover expensive tooling is not necessary. Nevertheless, it also has some disadvantages: (i) standards require to measure the crack length which is not always an easy task, (ii) for thin laminates (when finite displacements appear) G_c formulae in the standards are not adequate even using the correction factors included there [14], (iii) when non-symmetrical laminates are used the way fracture toughness is calculated is not adequate due to $G_c \neq G_{Ic}$ [15,16], (iv) it is not possible to perform the test "in situ".

2.2. CDP test

An alternative to the DCB test is the so-called Climbing Drum Peel (CDP) test [11]. This test was originally conceived to evaluate the bonded joints between a flexible adherent and a rigid adherent or between the skin (laminate) and the core in a sandwich panel [10]. The test consists in winding a flexible laminate (which peels at the same time it winds) using a drum with two different radii ($r_2 > r_1$). The laminate is fixed to the drum in its central part which has radius r_1. The outer parts (borders) of the drum (with larger radius, r_2) includes two loading straps which will apply the torque required for the drum progression along the specimen. The ends of the loading straps are fixed at the bottom of a universal testing machine, while the un-cracked end of the specimen is attached to the upper jaws of the machine. Once the specimen is collocated, the upper cross-head of the machine moves up provoking that the flexible laminate gets into contact (winds) with the inner part of the drum. Then, the drum "climbs" along the specimen propagating the initial pre-cracked zone while the flexible laminates winds. A scheme of the test can be found in [11].

In the load-displacements plots obtained during the tests, two constant load levels can be clearly observed. One associated to the winding load (F_w) and the other one associated to the winding + delamination process (F_d). Usually, F_w is calculated on a second stage of the test once a very large pre-cracked zone is presented. Then, the fracture toughness is evaluated using (3).

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