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A new device for determining the compression after impact strength in thin laminates

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ABSTRACT

In this work a new device has been developed to estimate compression-after-impact (CAI) strength. This device allows the testing of laminates thinner than those recommended by CAI test standards. The proposed device is composed of a support structure, with a set of vertical ribs that stabilize the specimen during the test, increasing the buckling load. A numerical analysis was made to ensure that global buckling does not occur in the laminate during the CAI test, and that there is no interference with the damage area. Laminate specimens were tested with the proposed device and the ASTM device. For specimens 4.416 mm thick (thickness according to ASTM D7137 standard), the test results were similar with both devices. For thinner laminates, higher CAI strength was estimated with the proposed device than with the ASTM device, showing that the global buckling was delayed.

1. Introduction

Composite laminates are particularly sensitive to low-velocity impacts due to low out-of-plane strength. No clear definition of a low-velocity impact is available, nor is a distinction between high- or low-velocity impact. Usually, if the duration of the impact is long enough so that the response of the structure plays a role, the impact is considered to be low velocity. In this case, the behaviour of the laminate is highly influenced by the boundary conditions [1]. Impact damage begins by the matrix cracking, which generates delamination at the interfaces between layers with different fibre orientations, and this could eventually lead to fibre failure [2]. Fibre failure (intra-laminar damage) affects mainly tensile strength, while delamination (inter-laminar damage) decreases mainly compression strength.

A low-velocity impact on a composite structure can cause interlaminar damage that diminishes the residual strength. This type of impact is especially dangerous because of its difficult detectability. Therefore, low-velocity-impact tests should be performed on composite structures, and subsequently damage progression should be evaluated under different load conditions, to determine the residual strength value of the component. The compression-after-impact (CAI) test is of great interest within the aeronautical industry, since the residual compressive strength of the damaged component is the property that decreases the most.

In a CAI test, a compressive load is applied to a damaged laminate. As the applied load becomes greater, local buckling occurs, generating out-of-plane stresses around the delaminated area [3]. When the load increases, more out-of-plane stresses appear around the delaminated area. The post-buckling continues until out-of-plane stress exceeds the critical strain-energy-release mode I value or interlaminar strength. Final failure occurs because the delamination propagates perpendicularly to the applied load, and the laminate collapses [4].

Composite structure design requires knowing the CAI strength of the laminates comprising it. The CAI strength is not a material property, since it is strongly influenced by the geometry of the impacted structure, support conditions, and the characteristics of the impactor. To measure this strength a uniaxial compression test is made on an impacted plate specimen. This test could be carried out according to several standards [5–9], such as ASTM D7137 "Standard Test Method for Compressive Residual Strength Properties of Damaged Polymer Matrix Composite Plates" [5].

All of these standards use a symmetrical and balanced laminate specimen, in which the side edges are supported and the upper and lower edges are fixed. ASTM defines the specimen geometry and characteristics of pre-impact test. Currently, this CAI test methodology [5] employs a laminate thickness greater than 4 mm. When samples of less than 4 mm thick are tested using existing standards, global buckling occurs. However, most laminates from the aerospace industry are very thin. The typical thickness of laminates in the horizontal tail plane, vertical tail plane, and fuselage are between 2 mm and 6 mm, and even zones of these primary

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structures may be less than 2 mm thick. Also, for control surfaces, laminates can be 1–3 mm thick. Thin laminates require an alternative method to estimate this property in order to prevent global buckling prior to the damage spread caused by an impact. Some authors have employed the method of the ASTM standard to analyse the buckling of thin laminates damaged by impact [10], although global buckling occurred during the compression test of all specimens, both impacted and unimpacted.

The scientific literature offers several proposals for the CAI test of thin specimens [11–17]. Some researchers [11,12] have used devices with anti-buckling supports similar to ASTM device, to test thinner and smaller specimens.

Sjöblom and Hwang [13] proposed the use of a steel anti-buckling support with a central hole so as not to interfere with the damage, but the use of strain gauges is not possible. Also, this device needs narrow specimens with end tabs, which could mean a change in their geometry after the impact test, and thus additional damage can be generated during the cutting process [18].

Sanchez-Saez et al. [14] proposed a CAI device that stabilizes the specimen by four anti-buckling plates placed on both sides of the specimen. These plates have cut-outs intended not to interfere with the damage. This device, which ensures that the failure will occur in the affected area, has been used to determine the CAI strength of laminates between 1.6 and 2.2 mm and different lay-ups of carbon/epoxy, and low temperature [19]. This device is designed for testing specimens of different dimensions from ASTM, making the comparison of the results more difficult.

The compression device with horizontal rolls from ESWNM department of Airbus Operations SL [15] also increases the critical buckling load to test thinner specimens. This device has lateral guides and rolls to prevent the buckling of the specimen [20]. The method of fixing is by means of screws and, therefore, the specimen edges need not be perfectly parallel for the load application, but drilling the specimen is needed to fix it to the clamping system. The main disadvantages are that the device allows the testing of only a specific thickness, it does not allow proper placement of the strain gauges, and the specimen size is larger than recommended by the ASTM standard, and therefore the comparison of the results becomes more difficult.

Other authors use sandwich specimens made by joining a damaged laminate to a core that stabilizes it, and test the ensemble under compression [16,17]. The sandwich structure is much more stable for being thicker, and this would allow the testing of very thin laminates. The problem with this test methodology is the interaction of the damaged area of the laminate with the core of the sandwich, producing failure modes that are not representative of the actual structure. The sandwich stabilizes the sub-laminates created by delamination, delaying its progression, so that there is a risk of finding higher and deceptive residual-strength results.

This paper proposes a new CAI test methodology to test thin laminates, by employing the specimen geometry recommended in the ASTM D7137 standard. The design and validation process of a new device that allows testing laminates under 4 mm thick is described. The proposed device prevents the global buckling in the damaged specimen, ensuring that the failure is due to compression. This approach was experimentally validated, testing quasi-isotropic laminates with three different thicknesses. The results using the developed and the standard devices were compared.

2. Device description

A CAI device was designed, after analysing the damage-progression mechanisms in a CAI test, according to the following requirements:

- The laminate should not reach the critical buckling load, which in a thin laminate is lower than in standard thicknesses.
- The failure does not occur in the load application zone. Crush failure or local buckling should not appear in this zone.
- An accurate alignment between the specimen and the load applied is needed to ensure a state of uniaxial compression stress.
- The device should not interfere with the damaged area, allowing the local buckling of sub-laminates and the progression of the delamination.
- The friction should not be a source of uncertainty in the results.
- It should be possible to place strain gauges to check the validity of the test.

In addition to the above features, other relevant aspects can improve issues such as manageability or time savings: the device weight, ease of use and installation, visibility of the test, safety of use, device robustness, and ease of industrialization.

In the proposed device, specimen stability was improved by a support structure, with a set of vertical ribs that increase the buckling load. Global buckling of the test specimen must be greater than the local buckling of delaminated sub-laminate or the compressive failure load. In the modelling the laminate, in simplified form, as an isotropic and homogeneous material, the critical buckling stress σ_{crit} can be estimated by Eq. (1) [21]:

$$\sigma_{crit} = K \cdot E_{eq} \cdot \left(\frac{t}{b}\right) \tag{1}$$

where E_{eq} is the equivalent Young's modulus of the laminate in the load direction, b is the buckling distance, which corresponds to the width between supports, and K is a constant that depends on the boundary conditions, the geometry, and the material.

Therefore, to increase the specimen critical buckling load, the buckling distance b (Eq. (1)) should be reduced (Fig. 1). For this purpose, a device with vertical intermediate elements was proposed (Fig. 2).

The device was designed for testing specimens having the same geometry of the specimens used in the ASTM standard (i.e. 100 mm × 150 mm) and a wide range of thicknesses.

A numerical simulation in Abaqus Standard [22] was performed in order to define the position of the vertical elements. Two-dimensional models were formulated using the module "Linear Perturbation, Buckle" to estimate the critical buckling load of the laminate. Two laminate plates, one subjected to the boundary conditions as proposed by the CAI ASTM standard and another considering the existence of intermediate vertical ribs, were simulated.

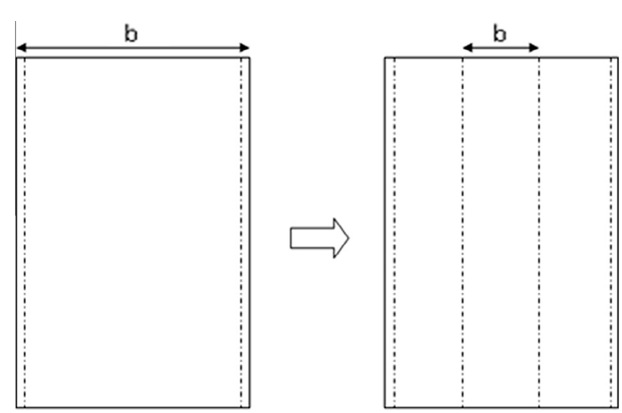

Fig. 1. Reduction of buckling distance in the specimen by intermediate supports.