DAMAGE AND STRENGTH ANALYSIS OF OPEN-HOLE LAMINATED PLATES UNDER TENSILE, COMPRESSIVE AND BENDING LOADINGS

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Abstract
The present paper deals with an experimental study on the damage and failure mechanisms encountered in laminated open-hole plates subjected bending loading. An original experimental device has been proposed and consists in applying compression with pivots, as an alternative to four-point bending tests. Its main advantage is that there is no contact between cylindrical bars and the sample and thus no local indentation. Moreover, the tests have been multi-instrumented with stereo-digital images correlation, acoustic emission, strain gauges and LVDT sensor to establish the damage and failure scenarios under bending loading. The influence of the hole diameter and of the total thickness on the failure load have been experimentally studied. The present experimental configurations are interesting test cases for advanced modelling because two stress gradients are generated in the sample, one through-the-thickness due to the bending and another one in-the-plane due to the geometrical singularities.

1. Introduction

In the latest generation of civil aircraft (B787 Dreamliner or A350-XWB), some primary structures (such as the centre wing box, the wings or the fuselage) are manufactured with laminated composite materials. These composite components present complex geometries, with geometrical singularities, but are also subjected to complex multiaxial loadings. In the literature, the analysis of damage and failure of open-hole laminated plates under uniaxial tensile loading with different configurations (hole diameter, thickness of the ply,…) has been widely studied both from an experimental and numerical point of view [1-3]. Moreover, few experimental studies have been performed to study the global response of open-hole plates subjected to uniaxial compressive loadings, especially for different hole diameters [4,5].

However, to our knowledge, the strength analysis of open-hole plates subjected to bending loadings has not been deeply studied in the existing literature. These test configurations on open-hole plates are still challenging for the current advanced damage and failure approaches. Indeed, a stress gradient is generated in the vicinity of the perforation and an additional stress gradient through-the-thickness is induced by the bending loading.

Therefore, a large test campaign on laminated open-hole plates subjected to tension, compression and bending loading has been performed at Onera to establish clearly the damage and failure scenario.

In the section 2.1, an original experimental device to apply bending to open-hole plates, which is an alternative to the classical four-point bending loading device, is presented. In the section 2.2, the tested specimens, presenting different hole diameters, different total thicknesses and different lay-ups, are detailed. All the tests have been multi-instrumented (see section 2.3) using different measurement techniques, such as stereo-digital images correlation, acoustic emission, LVDT sensor to establish the

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damage and failure scenarios for such a loading. The test results are presented in section 3. Firstly, the damage and failure scenario are presented in section 3.1 for specimens manufactured only with UD plies. Secondly, the damage and failure scenario for multi-layered specimens manufactured with 0°, ±45° and 90° plies, are presented in section 3.2. Finally, in section 3.3, for the different tested lay-ups, the influence of the hole diameter and of the total thickness are discussed.

2. Specimens and experimental devices

2.1. Presentation of the compression with pivots experimental device

Three different test devices have been used in this study to subject laminated open-hole plates respectively to tension, compression and bending. An electro-mechanical Schenck machine (150 kN maximum capacity) is used for the three kinds of loading. The tests are performed in the machine controlled displacement mode and a constant displacement rate is imposed at 0.01 mm/s. The tension and compression experimental devices ensure the existing norms [6,7] and are quite similar to those used in previous experimental studies [1,5].
Nevertheless, for bending loadings, there are some alternatives to the classical four-point bending experimental device. Fig. 1 presents an original experimental device of compression with pivots. The idea consists in applying a uniform compression to an open-hole plate clamped in two jaws with pivots. The eccentricity of a given test relates to the offset of the mid-surface of the plate, imposes the ratio of compression versus bending that is imposed to the specimen. It is controlled through the use of a couple of wedges that are inserted adequately in the jaws of the tabs. For a large eccentricity, the specimen is subjected to a quasi-pure bending moment (as encountered with the four-point-bending test device), while for small eccentricity the test tends to a pure compression test. In the present study, large eccentricities, equal to half of the total thickness of the tested specimen, are used in order to obtain quasi-pure bending moment in the gauge length.
One of the main advantage of this experimental device, compared to the four-point bending device, consists in avoiding contact between cylindrical bars and the sample and thus preventing local indentation which leads to premature final failure of the specimen. Moreover, another advantage consists in observing easily, during the loading, the two faces of a specimen, subjected respectively to tension and compression, and therefore to establish in a precise manner the damage and failure scenario for such complex bending loading.

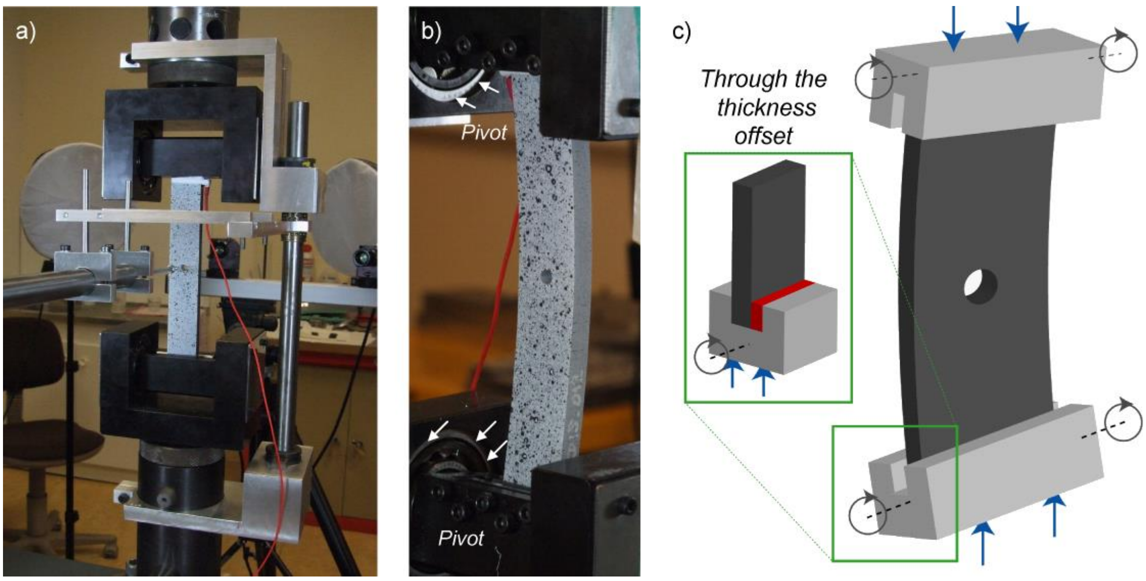

Figure 1. a) Presentation of the compression with pivots experimental device, b) zoom on the jaws with pivots, c) general principle of the TTS offset compression test with pivots.

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2.2. Presentation of the tested open-hole plates

The specimens have been manufactured from T700GC/M21 UD prepreg plies with an aerial weight of 268 g/m^2. The nominal ply thickness is assumed equal to 0.262 mm. The choice of the lay-ups has been made in order to cover the usual stacking sequences used in industries. Four different symmetrical lay-ups, constituted of 0°, ±45° and 90° plies, have been tested: (i) a unidirectional $[0_8°]_{ns}$ ply noted 100/0/0, (ii) a quasi-isotropic $[(45°/90°/135°/0°)_{2n}]_s$ laminate noted 25/50/25 usually used in order to be subjected to complex multiaxial loadings, (iii) a highly oriented $[(45°/0_2°/135°/90°/45°/0°/135°/0°)_n]_s$ laminate noted 50/40/10 usually used to be subjected to high uniaxial tensile loading, and (iv) a highly disoriented $[(45°/90°/135_2°/ 0°/45_2°/90°/135°/0°)_n]_s$ laminate noted 20/60/20,designed mainly to be subjected to in-plane shear loading. The parameter n is associated with the number of repetition of the main sequence in each laminate. The different considered stacking sequences are noted X/Y/Z with X% of 0°plies, Y% of ±45° plies and Z% of 90° plies. For each lay-up, two different thicknesses have been considered with n={1,2}, meaning that the 100/0/0 and 25/50/25 laminates are constituted with either 16 plies or 32 plies and the 50/40/10 and 20/60/20 laminates with 20 or 40 plies.
For each lay-up and each total thickness, unnotched specimens are firstly tested as a reference. Then, tests on the open-hole plates, with two different hole diameters (6.35mm and 12.7mm) and a w/d ratio constant and equal to 5, are performed. Each test configuration on unnotched and open-hole specimens is repeated, respectively three or four times, in order to obtain an estimate of scattering, meaning that 72 specimens have been subjected to bending loading. It is worth mentioning that the length of the specimens has been optimised through the analysis of preliminary finite element simulations in order to avoid large deflection (superior to 15mm) at failure (to simplify the analysis of the tests). For the thinnest specimens (n=1), the length is equal to 130 mm while it is equal to 210 mm for the thickest specimens (n=2).

2.3. Instrumentation of the bending tests

Different measurement techniques have been used to improve the understanding of the involved physical mechanisms and to obtain global and local information: (i) LVDT sensor for measuring the evolution of the maximum deflection of the unnotched specimens, (ii) acoustic emission for the detection of damage events during loading, (iii) strain gauges, bonded on the upper and lower faces of the unnotched specimens, for strain measurements, (iv) stereo Digital Image Correlation (performed with the Vic3D system) on the two faces of the specimen with black and white paint speckle for tracking the global displacement, the curvature and to obtain an estimate of the in-plane strains and finally (v) post-mortem micrographs in order to study the failure pattern of the specimens. This multi-instrumentation is an absolute necessity in order to establish the damage and failure scenario for the tested specimens under bending.

3. Test results

In this section, the damage and failure scenarios are established for the laminates manufactured only with 0° plies and then for the other multi-layered laminates manufactured with 0°, ±45° and 90° plies, representative of industrial applications.

3.1 Damage and failure scenario for the 100/0/0 laminate

The 100/0/0 unnotched specimens failed due to fibre failure in compression that is due to kinking of the fibres. The first ply failure in fibre mode is catastrophic for the tested structures. The load/displacement curves are very non-linear. Nevertheless, no significant acoustic event (EA) is recorded prior to the failure. Moreover, stereo Digital Images Correlation (DIC) has also shown that no splitting cracks appear in the upper ply subjected locally to tensile loading before the final failure. The measured non-linear load/displacement curves can easily be described with finite element simulations using (i) shell elements, (ii) assuming a linear elastic behaviour for the UD plies until the

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final failure and (iii) by taking into account the geometrical non linearity for the current test case. This last point is essential to describe accurately these tests.

For the 100/0/0 open-hole plates, damage and failure scenario is rather different, as reported in Fig. 2. The non-linear response of the structure prior to 80% of the failure load can be again described accurately only by taking into account the geometrical non linearity. For higher levels of applied loading, significant acoustic events are recorded. Splitting cracks are observed on the tension face in the vicinity of the hole due to the induced local in-plane shear stresses. The propagation of the splitting cracks can be observed and measured with DIC through the analysis of the discontinuity of the displacement field U_y. Moreover, using the out-of-plane displacement field U_z measured on the two faces, it is possible to estimate the delaminated area which is here strongly linked to the splitting cracks. It can also be noticed that no transverse cracks are observed on the other face subjected to compression (the measured displacement with DIC prior the final failure presents no discontinuity on this face). The absence of splitting cracks on this face is due to the apparent reinforcement of the interfibre strengths for combined compression and in-plane shear stresses [8]. The failure occurs when the upper 0° ply fails in longitudinal compression.

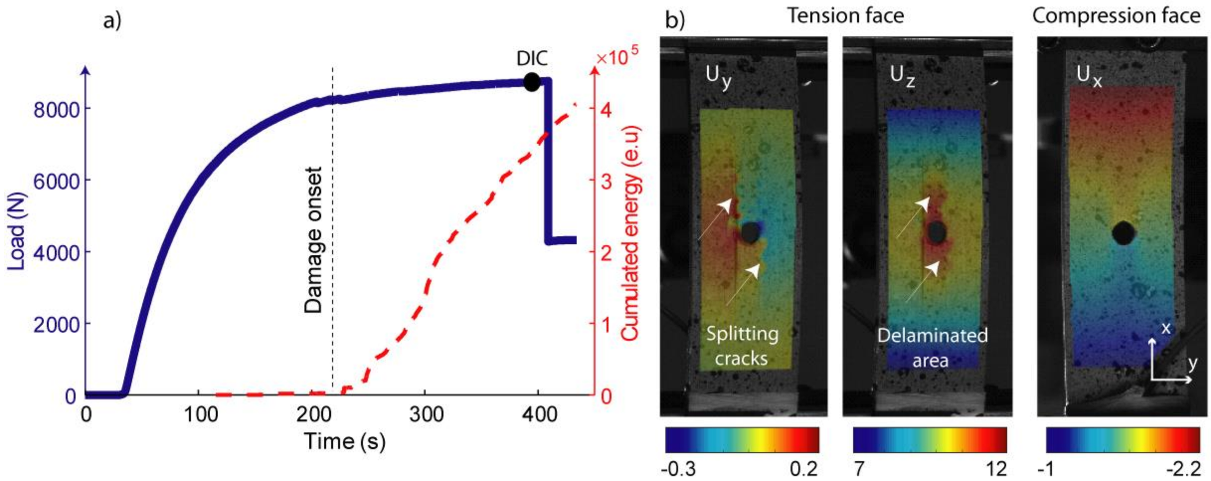

Figure 2. a) Time / load curve for a thin 100/0/0 open-hole plate with a hole diameter equal to 6.35mm and (b) observation of the different damage mechanisms using the displacement fields measured by DIC on the two faces at 8670N (99% of failure load).

For the 100/0/0 laminate, the damage and failure scenario is the same for both thicknesses and both hole diameters. The macroscopic stress / displacement curves for all the tested 100/0/0 open-hole plates are reported in Fig 3a. The macroscopic stress is defined by the load divided by the real section. The influence of the hole diameter on the strength is rather limited as compared to the influence of the total thickness as illustrated in Fig. 3a. Moreover, as illustrated in Fig. 3b, which reports the evolution of the cumulated acoustic energy as a function of the applied stress, the onset of matrix damage occurs around 80% of the failure stress for all the tested configurations. Therefore, the influence of the stress gradient through the thickness seems to be predominant as compared with the in-plane stress gradient due to the presence of the perforation. Finite element simulations have to be performed to confirm these preliminary conclusions.

To conclude, the damage and failure scenario observed for 100/0/0 open-hole plates subjected to bending loading is quite complex and constitutes an interesting test case to evaluate the predictive capabilities of the existing damage approaches [9].

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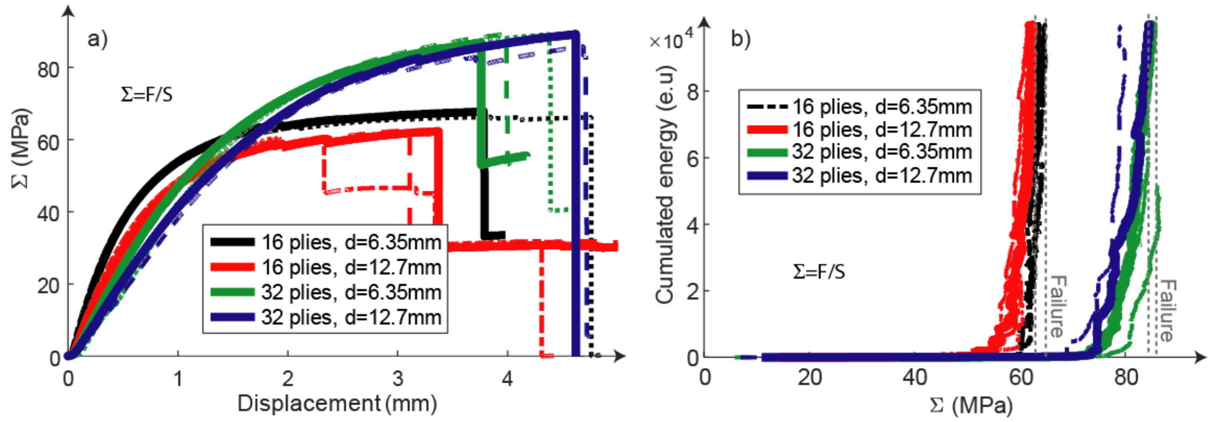

Figure 3. a) Macroscopic stress / displacement curves and (b) evolution of the cumulated acoustic energy as a function of the applied macroscopic stress for the different tested 100/0/0 open-hole plates subjected to bending.

3.2. Damage and failure scenario for the multi-layered laminates

For the multi-layered unnotched specimens (noted 50/40/10, 25/50/25 and 20/60/20 laminates), the final failure of the specimen is due to the first ply failure in compression fibre mode. The observed non linearity of the load/displacement curves is again due to the geometrical non linearity of the problem. Indeed, no significant acoustic event (EA) is recorded prior to the failure while none of the faces show cracking before failure. The damage and failure scenario for the UD or the multi-layered laminates are rather similar for unnotched specimens.
Nevertheless, for open-hole plates, very little damage is observed prior to the final failure for multi-layered laminates. Indeed, because of the insertion of ±45° plies, the splitting cracks induced by shear stresses around the hole are very limited and occur only at 90% of the failure load for the most disoriented laminates, as illustrated in Fig. 4b. Therefore, the non-linear response of the disoriented laminated open-hole plates, observed in Fig. 4a, is again due to the geometrical non linearity. For the oriented and the quasi-isotropic laminates, the onset of damage occurs after 95% of the failure load. In order to analyse the influence of the hole diameter and of the total thickness on the global response of the structure, the macroscopic stress / displacement curves are reported in Fig. 4a. For the 20-ply specimens, as well as the 40-ply specimens, the global response is hardly dependent on the hole radius. Therefore, it is mainly the total thickness that drives the global response of the structure subjected to bending. Those conclusions are consistent with those determined previously on 100/0/0 laminates.

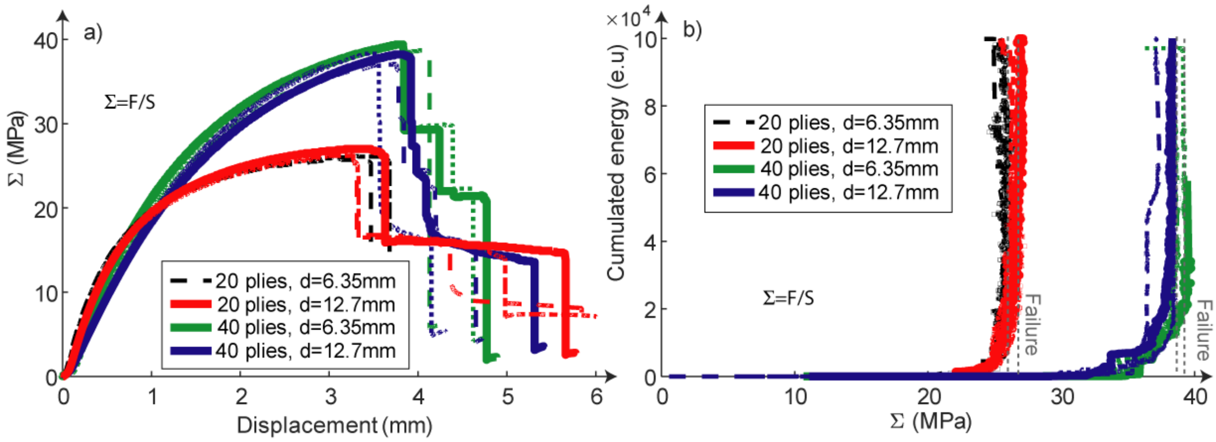

Figure 4. a) Macroscopic stress / displacement curves and (b) cumulated acoustic energy as a function of the macroscopic stress for the tested 20/60/20 open-hole plates subjected to bending.

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Moreover, very few localised transverse cracks are observed prior the final failure through the analysis of the strain field ε_{xx} in the vicinity of the hole as proposed in [10]. No significant delamination can be detected using the out-of-plane displacement field U_z prior the final failure. Moreover, the face under compression shows no sign of transverse cracking.

The failure pattern of the tested multi-layered open-hole plates is detailed in Fig. 5. On one hand, the face, subjected locally to compressive stress, fails due to fibre kinking in the 0° ply closest to the surface. This failure mechanism induces a catastrophic decrease of the global rigidity and the observed failure pattern is oriented normal to the compressive loading. On the other hand, due to load transfers, the face, subjected to tension, also fails but due to both transverse cracking (especially in the upper 45° ply as observed in Fig. 5), and tensile fibre failure in 0° plies close the surface. Large delamination cracks are also observed for these specimens. The failure patterns are very similar for every test configuration, as reported in Fig. 5a and Fig. 5b, excepted for 100/0/0 open-hole plates. Indeed, for the latter specimens, on the face subjected to tension, many long splitting cracks and large associated delamination cracks can be observed. On the other face, failure of the 0° plies in compression induces the final failure of the ligament as illustrated in Fig. 5c.

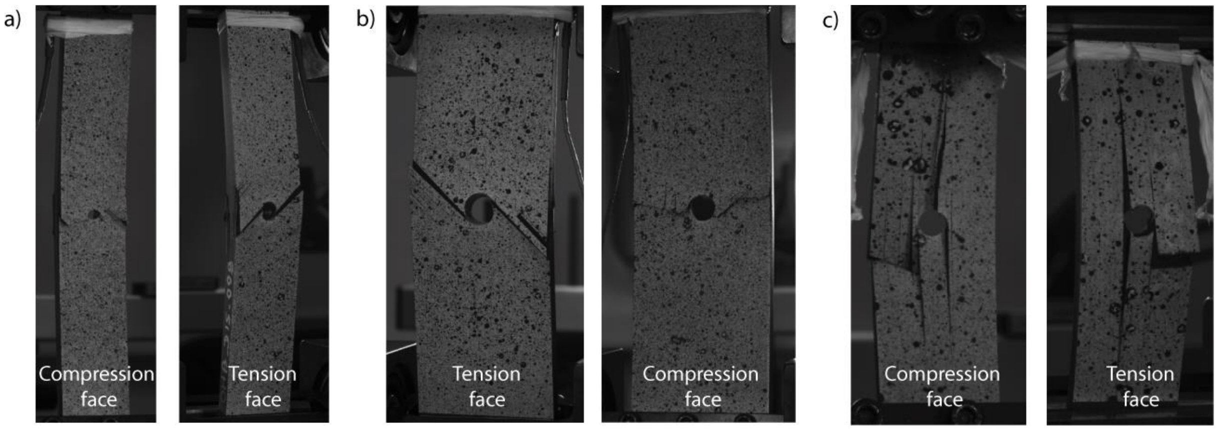

Figure 5. Failure pattern observed on the tension and compression faces a) for a thick disoriented 20/60/20 open-hole plate with d=6.35 mm, b) for a thick oriented 50/40/10 open-hole plate with d=12.7 mm and c) for a thin 100/0/0 open-hole plate with d=6.35 mm.

3.3 Influence of the hole diameter and of the total thickness on the macroscopic stress at failure

This section is dedicated to the influence of the hole diameter on the strength of open-hole plates subjected to bending. The influence of the total thickness on the apparent strength is also considered. Fig. 6 presents the evolution of the apparent stress at failure as a function of the hole diameter for the two different considered total thicknesses. Firstly, the influence of the hole on the apparent strength is clearly observed experimentally, especially for the most oriented laminates and is quite similar to that observed for open-hole plates subjected to pure compressive loading. Moreover, the thicker the specimen is, the higher the apparent stress at failure is. The influence of the total thickness on the stress at failure can explain why the apparent strengths of the disoriented laminate (20 or 40 plies) are higher than those of the quasi-isotropic laminate (16 or 32 plies), which seems counterintuitive. Finite element simulations have to be performed in order to improve the explanation of the influence of the hole diameter and of the total thickness on the apparent strength of open-hole plates subjected to bending loading.

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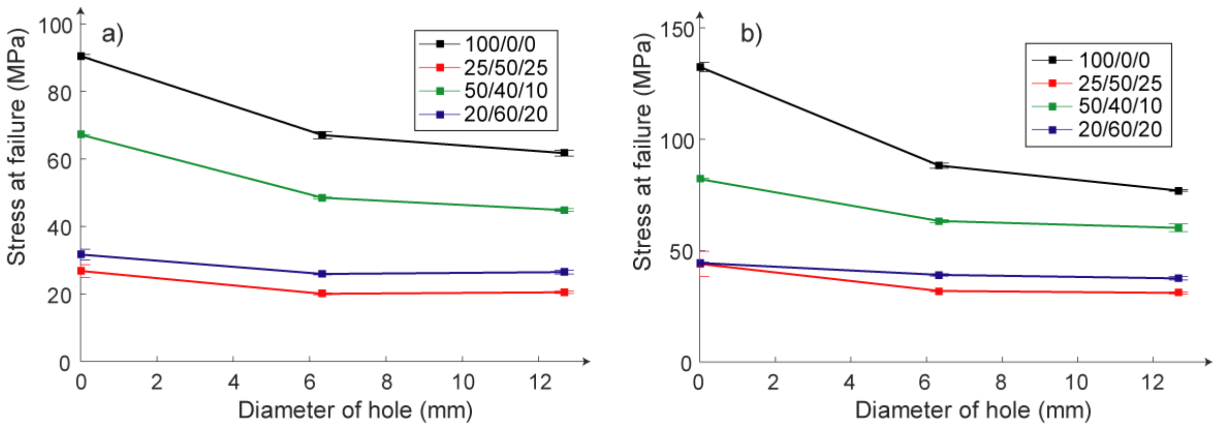

Figure 6. Macroscopic stress at failure as a function of the hole diameter (a) for the thinnest laminates (n=1) and b) for the thickest ones (n=2).

4. Conclusions / Perspectives

A large experimental test campaign on laminated open-hole plates has been performed at Onera. Multi-layered laminates have been manufactured with T700GC/M21 unidirectional plies. To apply a bending loading, an original experimental device has been proposed as an alternative to the classical four-point bending setup. It consists in applying a compressive load, offset with respect to the mid-plane, using jaws with pivots and permits to avoid premature failure under the cylindrical bars and to observe during loading the damage mechanisms occurring at the two different faces of the tested specimen. Open-hole plates have been tested with different stacking sequences, different total thicknesses and different diameters of perforation. These tests have been multi-instrumented with LVDT sensor, stereo-digital images correlation, acoustic emission, and in-situ optical observations to understand the damage and failure mechanisms.
Further works should consist in validating the damage and failure scenarios established through the analysis of these tests through finite element simulations using an advanced damage and failure approach already developed at Onera [11] and validated on uniaxial tensile or compressive tests on open-hole plates.

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