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Full-field measurements and identification in Solid Mechanics

Determination of the properties of composite materials thanks to digital image correlation measurements

F. Laurin[a]*, J.-S. Charrier[a,b], D. Lévêque[a], J.-F. Maire[a], A. Mavel[a], P. Nuñez[a]

[a]*ONERA, 29 avenue de la Division Leclerc, 92322 Châtillon, France*
[b]*AIRBUS, 316 route de Bayonne, 31060 Toulouse Cedex 9, France*

Abstract

Designing composite structures for civil aircrafts necessitates a better understanding of the damage and failure mechanisms occurring in these components through experimental test campaigns and associated numerical simulations. These experimental tests have been performed at Onera using different classical measurement techniques (LVDT sensor, strain gauges…) and digital image correlation (DIC). The additional information provided by DIC allows (i) to validate the boundary conditions of the tests, (ii) to cross-check the measurements with other techniques, (iii) to improve the understanding of the physical mechanisms and (iv) to validate the predictions of the finite element simulations.

Keywords: Digital image correlation, Composite laminated structures, Failure, Damage, Multi-instrumentation.

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1. Introduction

Composite materials are being introduced in primary structures, such as the centre wing box, the fuselage or the wings, in order to answer to the request of aeronautical companies for lighter, safer and less polluting civil aircrafts. In order to design these composite components in design offices, these complex structures are decomposed in some simpler sub-components subjected to complex 3D loadings. It is thus necessary to predict the damage and failure for these different "elementary" test cases, such as

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* Laurin. Tel.: +33 (0)1.46.73.46. 92; fax: +33 (0)1.46.73.46.47.
E-mail address: laurin@onera.fr.

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flat plates, open-hole plates, L-shaped angle specimens. In order to understand the physical mechanisms involved, it is necessary to perform test campaigns on composite structures.

These tests on composite laminated structures, manufactured with carbon fibers and a polymer matrix, are rather complex to analyze due to the different sources of non linearities involved (viscosity of the matrix, intra-ply damage, delamination …). Therefore, in order to understand the physical mechanisms involved, it is necessary to use different classical measurement techniques (Linear Variable Differential Transformer (LVDT) sensor, strain gauges,…) and Digital Image Correlation (DIC) which can provide interesting additional information.

The present paper presents the interest of the DIC measurements in order to analyse the tests performed on composite laminated structures.

The first section is devoted to the presentation of some experimental test campaigns performed at Onera in order to understand the physical mechanisms occurring in open-hole laminated plates subjected to tensile loading, laminated plates subjected to compression after impact and L-shaped angle specimens subjected to four-point bending loading. The classical measurement techniques (LVDT sensor, strain gauges, …) used to analyze these tests are also presented in this section. These tests have also been analyzed through digital image correlation (DIC) which has permitted (i) to validate the boundary conditions of the tests, (ii) to perform a cross-check with other measurement techniques in order to increase the confidence in the test results, (iii) to improve the understanding of the damage mechanisms occurring during the tests and finally (iv) to validate the predictions of the finite element simulations.

2. Presentation of the test campaigns performed at Onera on composite laminated structures

The interests of the DIC for the analysis of tests on composite structures are illustrated, in the present paper, on experimental data extracted from three test campaigns performed at Onera during the last years and illustrated in Fig. 1. The material used for these experimental studies is the T700GC/M21 UD ply with an aerial weight of $268 g/m^2$.

The first presented test campaign has been performed in the framework of the PhD-thesis of Norbert Germain [1]. The objective of this test campaign was to obtain test results on open-hole plates subjected to tensile loading with non conventional configurations of perforation to validate the damage and failure approaches developed at Onera [2]. Three different configurations of perforation have been tested (one hole or two holes with a diameter of d=8mm, and four holes with d=4mm). These tensile tests have been performed on two different stacking sequences: a cross-ply laminate $[0_2°/90_{1/2}°]_s$ and a quasi-isotropic laminate $[0_2°/\pm 60_2°]_s$. The experimental device used for performing these tensile tests is presented in Fig. 1.a and the details of these tests can be found in reference [3].

The second test campaign has been performed in the framework of the PhD-thesis of Mathieu Hautier [4]. The objective of this study was to determine experimentally and numerically the residual properties (stiffness and strength) of impacted laminated plates subjected to compression tests. Two different quasi-isotropic laminated plates are considered, $[45°/90°/-45°/90°]_s$ and $[0_2°/\pm 60_2°]_s$ laminates, with respectively two different thicknesses (4.2mm and 3.14mm). The plates have been first impacted at different energies (18J, 23J and 28J) using a metallic hemispherical impactor and then have been tested in compression with a classical compression after impact (CAI) experimental device [5]. The CAI experimental device of these tests is presented in Fig. 1.b and the details of these tests can be found in reference [6].

The third test campaign has been performed in the framework of the STAF and STRENGTH projects directed by Airbus and under the financial support of DGAC. The objectives of these experimental studies were to understand the physical failure mechanisms (mainly delamination) inducing the final failure of L-shaped angle laminated structures subjected to complex 3D loading and to validate the proposed 3D failure approach proposed by Onera [7,8]. Four different symmetrical lay-ups, composed of 0°, ±45° and 90° plies have been tested: a unidirectional ply $[0_8]_{ns}$ noted UD, a quasi-isotropic laminate $[(45/90/135/0)_2]_{ns}$ noted QI, an oriented laminate $[0_3/45/90_2/-45/0]_{ns}$ noted OR, and a highly disoriented laminate $[45_2/0/-45_3/90/45]_{ns}$ noted DIS. Three different total thicknesses of the specimens have been tested and n is associated with the number of repetition of the main sequence in each laminate (n={1,2,3}). The experimental device for these four-point bending tests on L-angle specimens is presented in Fig. 1.c and the details of these tests can be found in reference [9].

In order to analyse these tests, a LVDT sensor is used to measure the displacement of the structure, strain gauges are used to measure the local stiffness of the material, acoustic emission is used to monitor the evolution of damage in the structure, image analysis also allows to estimate the evolution of the crack density in the composite structures [10]. In the following, the interest of the additional measurements obtained through digital image correlation is discussed and highlighted with examples extracted from these three test campaigns. Up to four CCD cameras with a 4Mpixels resolution are used for the stereo digital image correlation and the images are analysed using the Vic3D©commercial software.

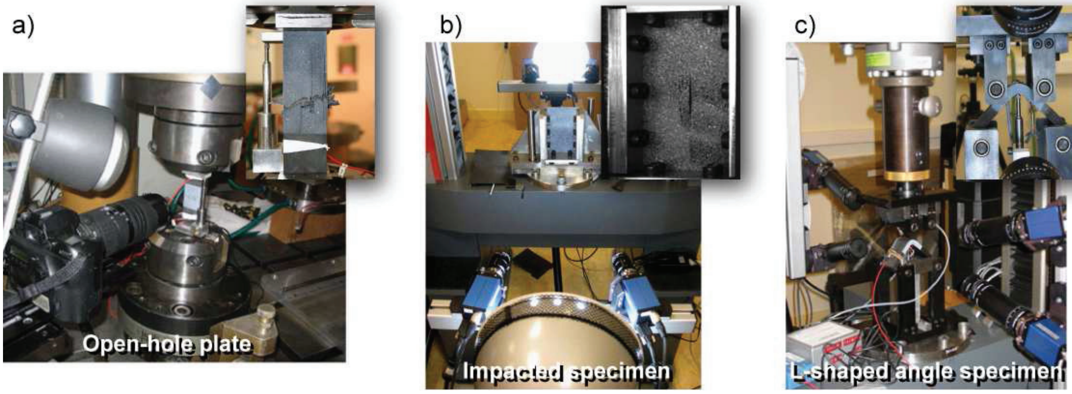

Fig. 1. Experimental device (a) for the multiperforated laminated plates subjected to uniaxial tensile loading; (b) for the laminated plates subjected to compression after impact; (c) for L-shaped angle specimens subjected to a four-point bending test.

3. DIC for validation of the boundary conditions of the tests

The first use of the DIC consists in validating the boundary conditions to be applied in the numerical simulations of the tests performed with complex experimental devices.

For the compression after impact fixture, due to the presence of several anti-buckling guides, it is rather difficult to obtain a perfect alignment of the specimen with the loading axis. Through the analysis of the displacement field measured during the tests, it is possible to measure the initial misalignment of the tested specimens and to introduce it into the finite element (FE) simulation to be representative of the real boundary conditions. Moreover, the DIC can assist in positioning the specimen in the experimental device. In fact, a small level of load is applied first and if the misalignment measured through DIC is reasonable, then the test can be performed, otherwise, the specimen is positioned again and the same procedure is repeated.

For the four-point bending test, the translations and rotations of the loading and support cylindrical noses are measured through DIC during the tests to improve the knowledge of the boundary conditions. The loading noses only translate in the vertical axis of the experimental device (see Fig. 1.c) without rotation, while no translation is observed for the support noses whereas rotation is important. Thanks to the measurement of the rotation of the support noses through DIC, it is possible to determine experimentally the evolution of the contact area between the support noses and the specimen. The evolution of the contact "points" is strongly linked to the friction between the nose and the composite L-shaped angle specimen. In parallel, some FE simulations have been performed with different coefficients of friction and compared through the DIC measurements. In the present case, it has been demonstrated that friction can be neglected, which is in good agreement with the results obtained with the experimental device in which ball bearings have been introduced.

4. Cross-check between the different measurement techniques

The second interest of the digital image correlation consists in performing a cross-check between the different measurement techniques in order to improve the confidence in the test results. This point has been especially addressed in the four-point bending test campaign on L-angle specimens (see Fig. 1.c). In fact, the measurements of the global curvature of the specimen with a LVDT sensor located at the centre of the inner face of the radius have been compared to the displacements measured through the DIC method. As reported in Fig. 2., the obtained measurements are consistent and permit to validate the global response of the structure. Moreover, thanks to the measurement of the displacement on the two edges of the specimen with two stereo systems, it has been demonstrated that there is no additional torsion of the specimen during the tests.

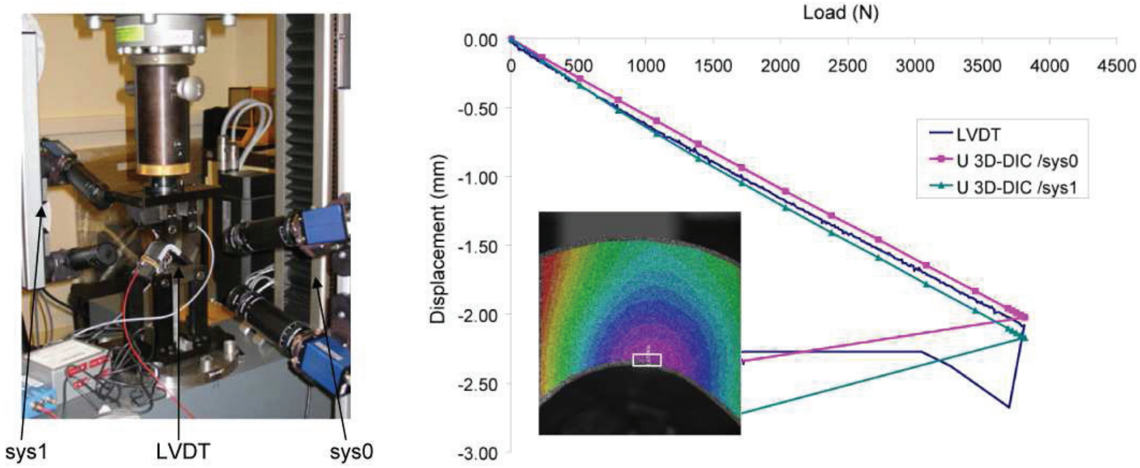

Fig. 2. Comparison of the global curvature measured with a LVDT sensor and that measured through DIC on the two edges of the specimen for the thick oriented laminated L-shaped angle specimen.

Moreover, to measure the material stiffness at the local scale, two strain gauges have been bonded to the inner and outer faces of the specimens. The strain measurements have been compared with those obtained through DIC. Virtual strain gauges have been defined in order to compare the strain measurements, reported in Fig. 3. A good agreement is observed with the measurement of the outer strain gauge and the virtual DIC gauge. Nevertheless, there is an important discrepancy between the measurements of the inner strain gauge and the DIC. This discrepancy has been observed for most of the tested specimens. It has been assumed that it is more difficult to bond a strain gauge (initial misalignment, initial grid bending…) to the inner face because the internal radius is significantly smaller than the outer one.

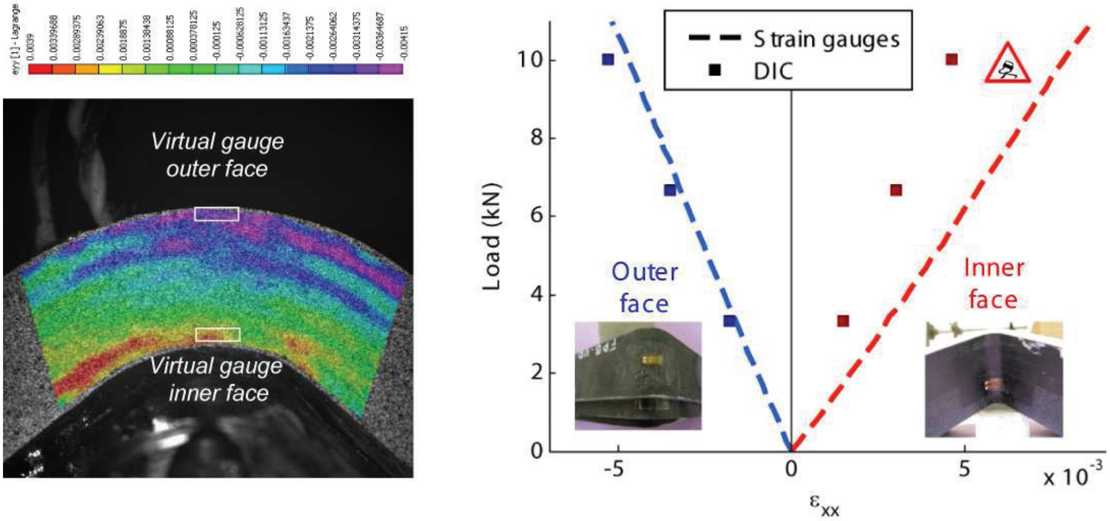

Fig. 3. Comparison of the load/strain curves on the outer and inner faces of the thick oriented laminated L-shaped angle specimen measured with strain gauges and through DIC using virtual gauges.

5. Comprehension of the failure and damage mechanisms

The measurements of the full-field displacement through digital image correlation are very useful to improve the understanding of the different physical mechanisms occurring during tests on composite structures. For many years [11], the measurement of the out-of-plane displacement field has been used to detect the global buckling load of composite structures and the associated buckling mode, as an alternative to the Moiré fringes method. Moreover, using two systems of two cameras to perform stereo correlation on both faces of the specimen, it becomes possible to distinguish a global buckling (i.e. the whole specimen buckles as illustrated in Fig.4.a) from a local wrinkle (due to an initial delamination, only the upper plies of the laminates wrinkle as represented in Fig.4.b). Fig. 4.a presents, through the analysis of the out-of-plane displacement field, the buckling mode of an undamaged laminated $[0_2°/\pm60_2°]_s$ plate subjected to a uniaxial compressive loading (see Fig. 1.b).

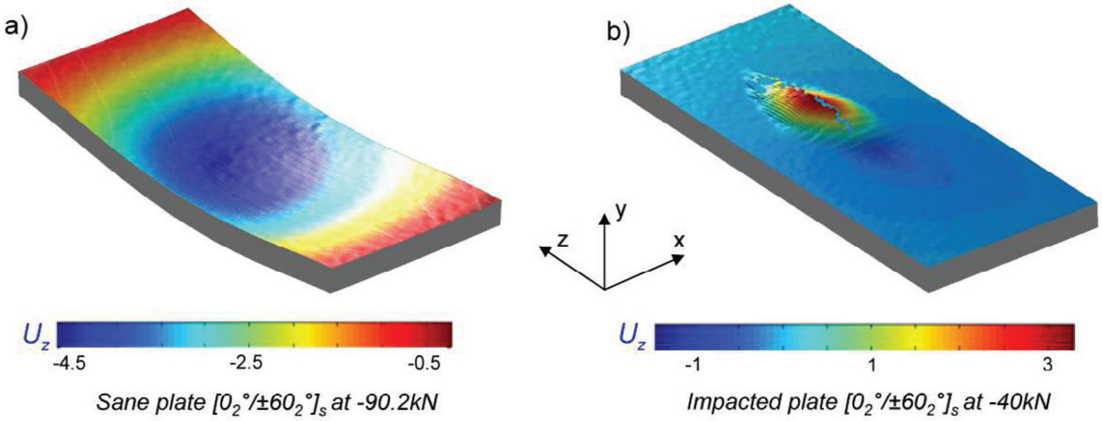

Fig. 4. (a) Determination of the global buckling mode of an undamaged $[0_2°/\pm60_2°]_s$ plate under -90.2kN; (b) determination of the local buckling of an impacted $[0_2°/\pm60_2°]_s$ plate under -40 kN.

A second laminated $[0_2°/\pm60_2°]_s$ plate is first subjected to a low velocity impact inducing delamination between plies and is then tested in compression. In this case, a local buckling is clearly observed (Fig. 4.b) on the opposite face of the impact where the most important delaminated area is located. Moreover, considering the difference between the out-of-plane displacements on the outer and inner faces, it is possible to estimate the evolution of the delaminated area (which induces the local wrinkle of the upper plies of the laminate) until the final failure.

The analysis of the displacement field can also permit to detect mesoscopic intra-laminar cracks in the structures. Indeed, the mesoscopic cracks, which propagate instantaneously through the thickness of the ply, can be detected by analyzing the discontinuity of the displacement field along the mid-plane of each ply. The evolution of the crack density can be automatically measured, after calibration of the critical onset of discontinuity of the displacement to distinguish a crack from noise, using the strain field which permits to detect visually the cracks as illustrated in Fig.5. The measured kinetics of the crack density has been compared successfully in the four-point bending test campaign on L-shaped angle specimens with other techniques such as acoustic emission (as reported in Fig. 5) or micrograph analysis method. Nevertheless, the proposed method can only be used if the cracks are not too close to the inner or outer specimen surfaces and if the crack density remains low (in fact, if the strain gradient of a crack interacts with that of another crack, then the simple proposed method will detect only one crack).

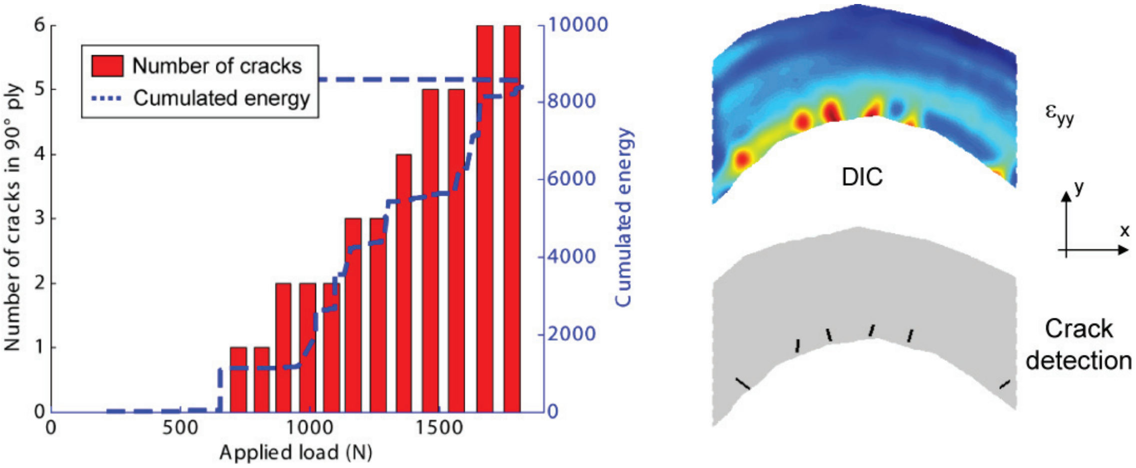

Fig. 5. Comparison between the evolutions of the crack density determined through digital image correlation and measurement of the acoustic emission for the disoriented specimen noted DIS.

6. Validation of the Finite Element simulations

In this section, the validation of finite element simulations on composite structures through comparisons with full-field measurements through Digital Image Correlation is presented and illustrated on the three test campaigns, presented in section 2, performed on coupons subjected to compression after impact, L-angle specimens and open-hole plates.

6.1. Predictions of the global buckling of plates subjected to compressive loading

As mentioned previously, it is possible to measure the onset of global buckling of composite structures and to determine experimentally the associated buckling mode through the analysis of the out-of-plane displacement field. The buckling load, the post-buckling behavior, and the failure of an undamaged $[0_2°/\pm60_2°]_s$ plate subjected to compression using the CAI device are predicted successfully with the FE code ZeBuLoN.

Moreover, simulations taking into account delamination due to a low velocity impact have been performed and the onset of the local buckling (see Fig. 4.b) is also accurately predicted. The post-local buckled behavior and the final failure of impacted specimens subjected to compressive loading is much more complex and this point is currently addressed.

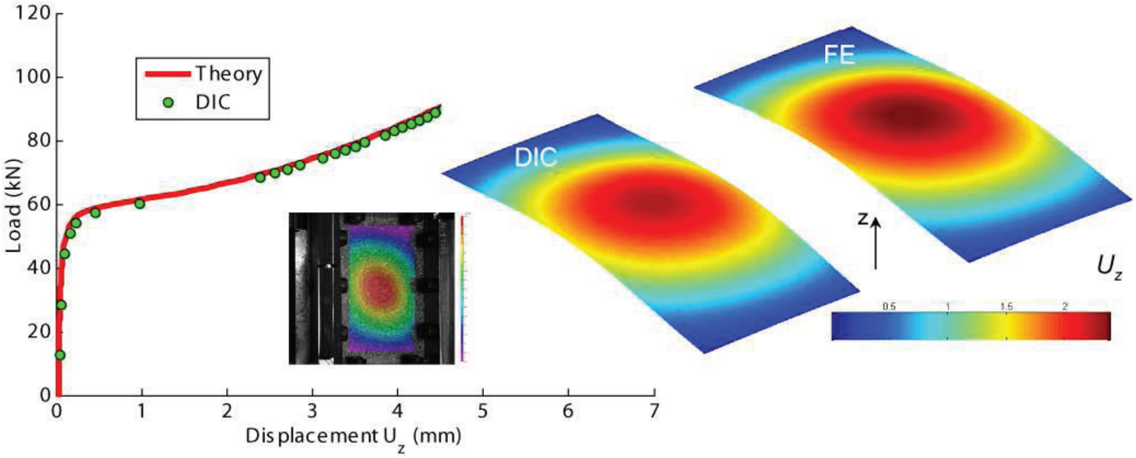

Fig. 6. Validation of the predicted buckling load, buckling mode and post-buckled global response of an undamaged $[0_2°/\pm60_2°]_s$ plate subjected to compressive loading, thanks to the out-of-plane displacement measured with stereo-digital image correlation.

6.2. Predictions of the out-of-plane behavior in L-shaped angle laminated structures

The full displacement or strain field measured through DIC can also be used to validate the predicted local behavior of the composite materials. In the four-point bending test campaign on L-shaped angle specimens, the measured strain field on the edge of a thick UD L-shaped angle specimen is compared with the strain field predicted by FE simulation at 60% of the failure load. The description of the out-of-plane strain gradient with the FE simulations is qualitatively accurate. The final failure of this specimen is due to delamination occurring in the most loaded part of the radius as reported in Fig. 7. The measured and predicted gradients through the thickness of the specimen are also plotted in Fig. 7.b. After a sensitivity study on the 9 elastic properties (E_{11}, E_{22}, E_{33}, ν_{12}, ν_{23}, ν_{31}, G_{12}, G_{23}, G_{31}) performed with finite element simulations, it has been determined that the strain ε_{yy} is only sensitive to the out-of-plane modulus E_{33}. In the FE simulations, the unidirectional ply is assumed to be transversely isotropic, leading to the assumption $E_{22}=E_{33}$ which seems to be relevant, regarding to the accuracy of the strain predictions.

Some additional interlaminar shear stress (ILSS) tests [12] on laminated plates have been performed and in a similar manner the assumption $G_{12}=G_{13}$ (due to the transverse isotropy of the UD ply) has been validated through analysis of the out-of-plane shear strain gradient through the thickness of the laminated UD plate.

Moreover, unfolding tests on L-angle specimens have been performed to validate the proposed 3D damage and failure approach developed at Onera. The lengths of the two legs of the L-shaped angle specimens have been optimized in order to obtain different states of stress into the radius in which the final failure due to delamination occurs. The displacement field measured through DIC has permitted to validate experimentally the FE simulations until the final failure of the specimens.

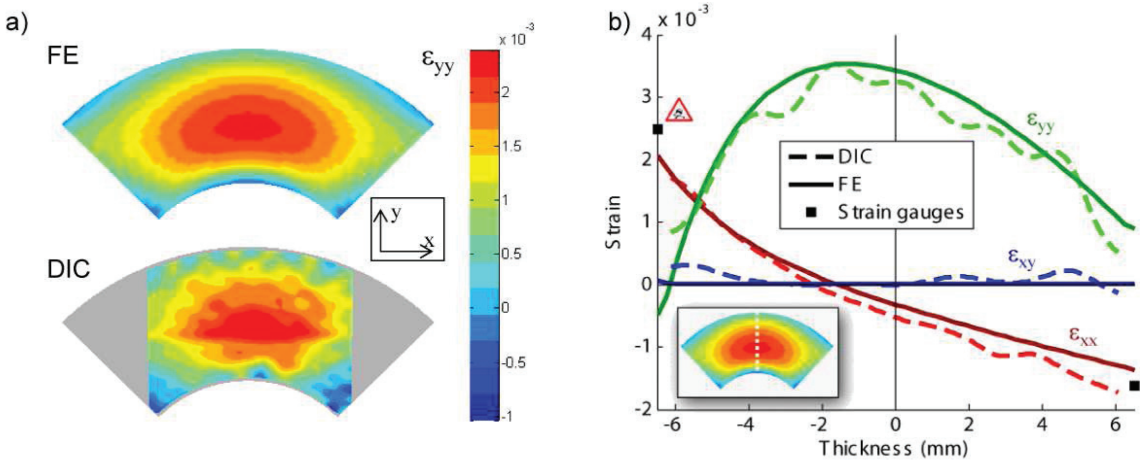

Fig. 7. Comparison (a) between the predicted strain field ε_{yy} with FE simulation and the measurements performed through DIC; and (b) between the predicted gradient through the thickness of the strain fields and those measured through DIC for the thick UD L-shaped angle specimen at 60% of the failure load.

6.3. Predictions of the damage patterns in open-hole plates

As discussed in section 5, digital image correlation can be used to detect cracks and their evolution during loading until the final failure. The test campaign on open-hole plates with many holes subjected to tensile loading has been performed to validate the damage and failure approach developed at Onera during the last few years [2].

Fig. 8 presents, respectively, the qualitative comparisons between the predicted matrix damage pattern (noted d_2) on the upper 0° ply of $[0_2^\circ/90^\circ/0_2^\circ]$ perforated plates with 2 holes or 4 holes and the splitting crack detected through DIC on the upper face. The onset, the location, the orientation and the evolution of these splitting cracks until the final failure are well predicted by the proposed damage and failure approach. Further works should consist in using more advanced post-processing of the DIC information, as proposed in [15], in order to identify precisely the crack locations (positions and lengths) for the different load levels to perform quantitative comparisons with the present damage model.

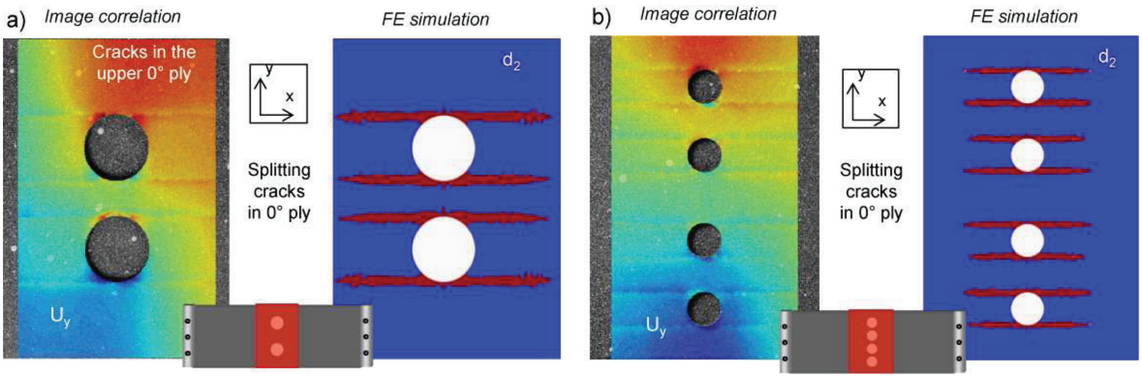

Fig. 8. Comparison of the observed damage detected by DIC in the upper 0° ply with FE predicted matrix damage for [0_2°/90°/0_2°] perforated plates with (a) 2 holes; (b) 4 holes.

7. Conclusions

In order to design composite structures for civil aircrafts, it is necessary to understand the damage and failure mechanisms occurring in these components through experimental test campaigns and associated numerical simulations. The full-field measurements through Digital Image Correlation are used as a help for the analysis of tests on composite structures and it has been illustrated through analysis of three test campaigns performed at Onera dealing with the damage and failure of multi-perforated plates subjected to tensile loading, impacted plates with initial delamination subjected to compressive loading, and L-shaped angle specimens subjected to four-point bending loading.

These tests have been analyzed using different classical measurement techniques (LVDT sensor, strain gauges, acoustic emission…) and through stereo digital image correlation (DIC).

The additional information provided by DIC has permitted to:

- Validate the boundary conditions of the tests, such as detection of initial misalignment of the specimen in the experimental device, for instance,
- Cross-check the measurements obtained with other more classical techniques in order to improve the confidence into these methods,
- Improve the understanding of the damage and failure mechanisms and permit to distinguish a global from a local buckling, or to detect intra-ply damage or delamination...
- Validate the (behavior, buckling, damage and failure) predictions of the Finite Element simulations.

To go further, some works dealing with the inverse identification of the 3D properties of the constitutive UD plies of the composite structures representative of aeronautical components using full-field measurements through DIC are currently under investigation. Different existing approaches presented during the IUTAM symposium, such as Virtual fields method [13] or DIC method assisted by solid mechanics using FE simulations [14], will be considered and applied to different composite structures subjected to 3D multiaxial loadings.

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