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DEVELOPMENT OF AN INTRALAMINAR SHEAR FIXTURE FOR THE TESTING OF COMPOSITE SPECIMENS OUT OF THEIR ORTHOTROPY AXES

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Abstract

The design of innovative ceramic matrix composites parts requires a precise characterization of the materials to avoid oversizing costs. Several methods already exist to characterize the shear properties of composite laminates, classically the tensile tests on $\pm 45^\circ$ balanced specimens (EN 6031), known for their effectiveness. However, sampling specimens directly from parts or structures restricts the ability to select ply stacking sequences.

Out-of-orthotropy-axes tests on unidirectional composite specimens allow for shear properties determination, but the stress state in the specimens is highly heterogeneous [1] [3], affecting measurements quality, especially for shear fracture stresses. Rotating fixtures have been developed to mitigate edge effects due to clamped jaws [2] [3] and homogenize the stress state in the specimens, but cannot reach high levels of stress.

A double ball-jointed fixture for intralaminar shear testing of composite unidirectional specimens is hereby introduced. The in-plane rotations allow to limit the stresses heterogeneity one can observe in out-of-orthotropy-axes testings with clamped jaws. A comparison between a clamped-jawed tensile test on $(\pm 45^\circ)_{ns}$ stackings, and tests performed on the developed fixture with off-axis UD specimens is proposed to validate the method.

1. Introduction

Industrialists designing Ceramic Matrix Composite (CMC) parts need an extensive knowledge of their materials properties in order to minimize the manufacturing costs. They can consider both macro-properties and meso-properties (at the laminate ply scale) knowledge of their materials for instance, the latter giving more freedom when a change of the ply stack is chosen for a specific part. For CMCs however, the high cost of the materials and –more often than not- the impossibility to produce specimens identical to the structure without manufacturing a part lead the industrialists towards the testing of coupons taken directly from these parts and structures, with no control of the ply stacking for a specific test, granting then rather macroscopic properties.

1.1. Intralaminar shear tests on anisotropic specimens

Several methods exist to measure the intralaminar shear properties of composites. The most classical one is the tensile test on $(\pm 45^\circ)_{ns}$ coupons (EN 6031 or NF EN ISO 14129 standards). These tests are easy to perform, one only needing a tensile test machine and specimens with a symmetrical and balanced

stacking. These tests grant the shear modulus, strength, but can also be used to monitor the evolution of damage in the plies.

Another very popular method is the Iosipescu test [4] [5] [6], performed on a wide variety of specimens (either unidirectional composites or more complex structures like 2.5D Carbon / Carbon specimens for instance). Many improvements on the so-called “Wyoming fixture” and specimens shapes, or even on the interpretation of the measurements, have been introduced to get finer results for both the shear moduli and strength [5] [7], while damage evolution have been assessed in [6] and [8] (with a Ladevèze damage model [9] for the latter). Nevertheless, the area in which the shear strain is measured is fairly thin in such test, which does not guarantee the presence of a sufficient amount of Representative Volume Elements (RVEs), necessary to the characterization of highly architected structures.

Off-axis tensile tests on unidirectional coupons were also deeply investigated for the shear properties characterization of composites, initially with a 10° angle in [10], in order to minimize the transverse stress while optimizing the shear one. However, when performed with clamped jaws, such test leads to high heterogeneities in the stress fields in the specimen, as an in-plane bending is induced on the coupon, generating the so-called “S-shape” [1]. A solution to this issue is to use oblique tabs instead of rectangular ones, with the angle computed using compliance matrix coefficients [11]. This however requires at least an idea of the coefficients before the test, and is compromised by the evolution of damage during the test, as the shear modulus are affected by damage as presented in [9] for instance. Furthermore, [12] shows that despite using oblique tabs, the 10° off-axis tensile tests underestimates the shear strength in comparison to Iosipescu tests.

Another solution to the in-plane bending is to free the rotations of the specimens. This requires a new design of the jaws to allow the needed in-plane rotation. [2] [3] [13] propose different fixtures with varying designs of the revolute joints between the specimens and the crosshead / frame of the tensile test machine. However, the fixtures in [2] and [3] cannot withstand high levels of stress as their revolute joints are rather fragile. [13] finally shows that changing the off-axis angle to 45° leads to an error on the shear modulus close to 0. This makes the 45° off-axis tensile test an effective way of measuring the shear moduli of unidirectional composites, but not the shear strength. It also guarantees a wider area with homogeneous shear strain and stress fields in the coupons when compared to the Iosipescu test.

1.2. Framework

The material studied in the framework of this paper is an orthotropic Carbon / Carbon composite reinforced in its third direction, the intralaminar shear properties of which are being investigated (modulus, shear stress, damage evolution with a Ladevèze *a priori* model [9]). Nevertheless, the specimens that were provided are directly derived from mechanical parts, which does not allow one to perform classical tensile test on ($\pm 45^\circ$)_{ns} coupons to get the shear properties. Fortunately, the structure of the C/C composite is so that it can be assimilated to a unidirectional plate, as one of the two in-plane orthotropic direction shows a way higher fiber density than the second.

The 3D structure and manufacturing process of the composite induce a highly architecture profile which requires a certain amount of RVEs for its behavior to be captured. This excludes the Iosipescu test as a candidate for the characterization of the shear properties. The off-axis tensile test, on the other hand, appears as a both simple and fine method for this purpose, however requiring the design of a fixture allowing the in-plane rotation of the specimen at high levels of applied forces, and considering the off-axis angle as a function of the property that is sought (shear modulus or shear strength).

This paper introduces the design of such fixture and the experimental campaign on a unidirectional Carbon / Epoxy composite to validate it for the shear modulus measurement.

2. Off-axis tensile test

2.1. End-constraints effect on anisotropic specimens loaded out of their main axes

As explained in [1], performing a tensile test on an anisotropic material out of its main axes leads to in-plane bending and very heterogeneous stress and strain fields in the specimen if the boundary conditions at the edges of the specimen do not allow rotation, thus not guaranteeing the desired failure mechanisms. Furthermore, heterogeneous strains and stresses fields are an issue if one needs to consider a large enough number of RVEs under the same mechanical solicitation for behavior homogenization. A solution to such issue is to allow the specimen to rotate during the tensile test. With the center of rotation located at the center of the border separating the tab of the useful area of the specimen, *i.e.* at the edges of the jaws, the kinematic and static fields are way more homogeneous. The off-axis specimen then takes the shape of a shear parallelogram instead of the infamous S-shape. The interest of freeing the rotation at the tab level is then clearly established.

2.2. Rotating jaws constraints

Fixtures freeing the in-plane rotation to homogenize the strains and stresses fields through the width and length of anisotropic specimens loaded off-their-axes are presented in [2][3][13]. All of them rely on revolute joints, ensured by different methods. For [2] and [3], the joints design does not allow the specimen to reach high levels of stresses, and would then only permit the measurement of the shear modulus, but not the damage evolution nor the fracture stress of certain materials. The fixture of [13] seems to be designable to reach higher loadings, though no clear information about it is provided by the authors. However, this fixture hides the rotation centers of the specimen because of its design, not allowing the user to observe the boundary conditions with Digital Image Correlation techniques for instance, thus not ensuring the full validity of the kinematic fields.

The purpose of the hereby presented work is drawn by the need to characterize a CMC material. The specimens provided for this study are quite thick and high levels of loadings are reached, which implies that the design of a rotating fixture should meet the needs of such constraint. The solutions of [2] and [3] are then dismissed.

A finer control of the loading axis can be provided by the use of spherical joints rather than revolute ones. Indeed, if the jaws were ball-jointed, the loading axis would pass through the centers of both joints. Aligning the specimens neutral axes with the loading would then be easier and would allow for finer measurements, as no momentum would be induced by a misalignment of the different parts in the tensile test machine. This solution is then investigated, but comes at the cost of visibility on the specimen, as using ball-joints to allow for the rotation of the jaws while being able to sustain heavy loads is space-consuming and would conceal an area around the jaws. A loss on the boundary conditions visibility would be induced by such design, whereas checking on their validity is absolutely necessary to ensure the strains and stresses fields homogeneity. A solution to such issue is to shift the ball-joints from the actual rotation centers of the specimen, that are sought to be at the border between the jaws and the rest of the specimen.

These constraints require a precise design to both shift the rotation center from the ball-joints and maintain a high level of possible loadings.

2.3. Fixture design

The chosen solution is to ensure the rotation of the jaws with spherical roller bearings that can be selected to withstand different levels of loadings, and to bring the centers of rotations at the jaws level by using a shear parallelogram system, with revolute joints at its vertex to allow the required rotations. The revolute joints could be ensured by pins or bearings, but such solution requires a very fine machining of the components so that every axis is well positioned, otherwise risking the fixture to be hyperstatic. The solution that was figured out to allow all the rotations for the shear parallelogram is to use the bending of thin tailored composite blades that are linked to the rest of the fixture. Figure 1 shows the whole

fixture with a composite specimen locked into the jaws. The 4 composite blades are visible on the sides of the crosspieces.

The blade are manufactured with several layers of different natures. Carbon UD plies at the center allow for the blade to transfer the loading applied during the test to the specimen, whereas satin aramide plies on the outer layers permit the bending of the blade to accommodate to the shear angle during the test, thus acting as the needed revolute joints.

Each pair of jaws is located between two inner crosspieces (with speckle pattern painting in Figure 1) that are tied to the bending blades, and are then allowed to rotate during the test. The center of rotation is by design displaced at the center of the border between the tabbed area and the rest of the specimen, which corresponds to the boundary conditions that are sought.

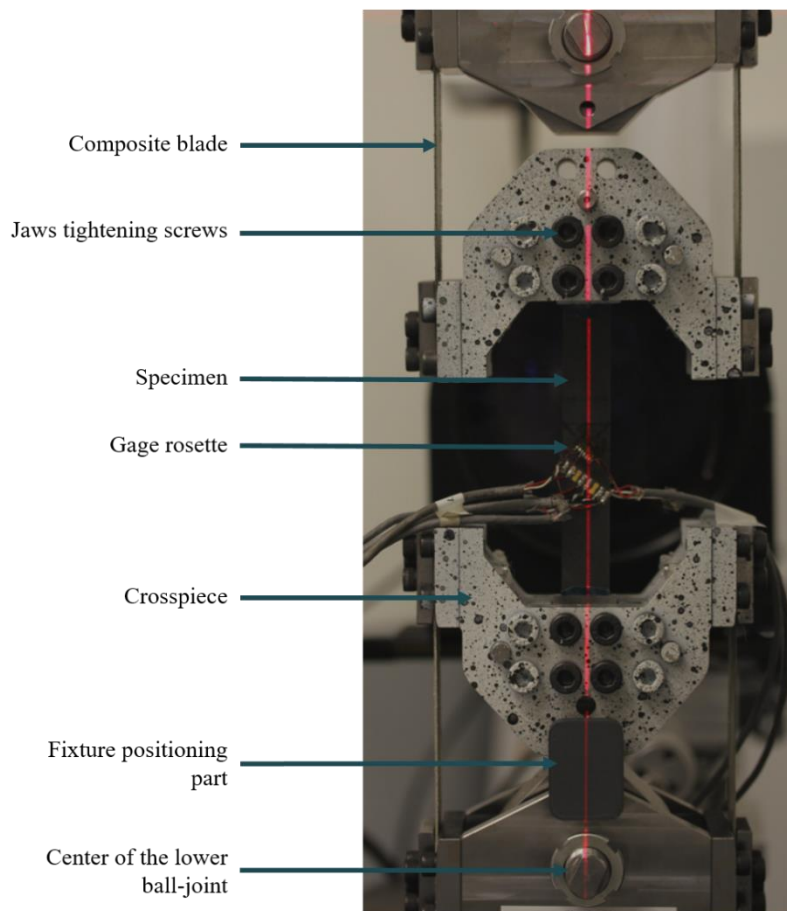


Figure 1. Photograph of the whole fixture. The fixture positioning part is removed during the test to allow the rotation of the crosspieces, following the bending of the composite blades.

3. Experimental validation of the design

3.1. Choice of the specimens and experimental setup

The composite that is chosen for the tests is a Carbon / Epoxy, whose plies are made out of HexPly[®] M79 prepreg. The plates are manufactured in the laboratory, and a characterization campaign has been performed to determine the plies longitudinal, transverse and shear moduli using the ISO 527-5 (longitudinal and transverse properties) and EN 14129 (shear properties) standards procedures, on 4-ply laminates (3 specimens per test configuration). The expected (provided by the manufacturer) and measured parameters are presented in Table 1. The ij indexes correspond to the in-plane orthotropic direction in the py : 11 is the fiber direction, 22 is the transverse direction, and 12 the shear one.

Table 1. Expected and measured parameters of the Carbon / Epoxy HexPly[®] M79.

Mechanical parameter	E ₁₁ (GPa)	E ₂₂ (GPa)	ν ₁₂	G ₁₂ (GPa)
Expected (s/m = 15%)	132	7.6	N/A	N/A
Measured	112.63	7.88	0.33	4.24

For a rotating fixture, a 45° between the loading axis and the fibers direction of the UD composite allows to directly compute the shear modulus in the ply using the transverse and longitudinal strains in the specimen frame (directly measured by the gages) as follows :

$$\varepsilon_{xx} - \varepsilon_{yy} = \frac{\sigma_{xx}}{2G_{12}} \quad (2)$$

, where xx and yy correspond to the test frame longitudinal and transverse direction, *i.e.* the loading and transverse axes of the specimen. The shear modulus is directly read in shear stress / shear strain curves (presented in Figure 3), and its evolution after damage can also be assessed. A 45° is then ideal for the measurement of the shear damage variable.

Nevertheless, the 45° test is not enough to obtain the damage evolution law. Indeed, damage is driven by both the transverse and shear contributions of the strain energy density. Using the ply mechanical properties, its four in-plane strain energy density contributions when submitted to a uniaxial σ_{xx} as a function of the angle of solicitation of the ply θ can be computed. Such solicitation is only possible for UD composites if the fixture is rotating, which is the case in the hereby presented design. The expression of the elastic strain energy density e is reminded here :

$$e = \frac{1}{2} \left(\frac{\sigma_{11}^2}{E_{11}} + \frac{\sigma_{22}^2}{E_{22}} + \frac{\tau_{12}^2}{G_{12}} - 2 \cdot \frac{\sigma_{11} \cdot \sigma_{22} \cdot \nu_{12}}{E_{11}} \right) \quad (1)$$

, where σ_{11} , σ_{22} and τ_{12} are the stresses in the ply frame. Each contribution is presented in Figure 2 as a function of the angle θ between the applied stress direction and the orthotropic axes.

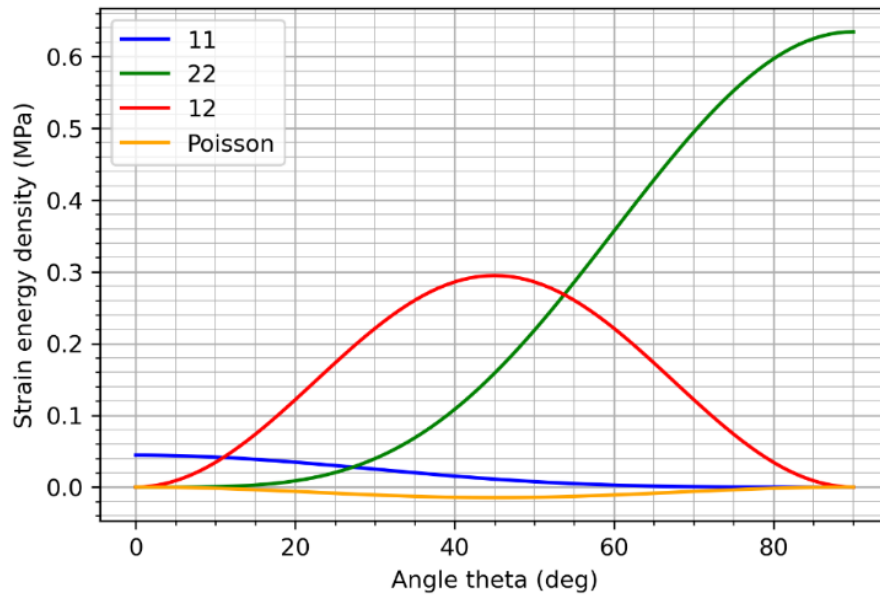


Figure 2. Elastic strain energy densities along the orthotropic axes of a composite ply as a function of the angle of rotation of a Carbon / Epoxy composite ply under a 100 MPa uniaxial solicitation.

Figure 2 shows that a 45° angle maximizes the strain energy density of the shear contribution (12), while maintaining a level for the transverse (22) one equivalent to half the shear. The damage driving variable is defined by the contribution of both the shear and transverse strain energy density contributions, balanced by a coupling parameter. For a 45° angle, the transverse one is not neglectable and must be taken into account. A second test must be performed, usually a 67.5° off-axis tensile test, to determine this coupling parameter and express the damage law. Tests with other angles to identify the coupling in the damage law can also be performed with the hereby introduced fixture.

Thus, 45° Carbon / Epoxy UD plates were manufactured, with satin glass-epoxy tabs glued to the plates using a prepreg resin and a heating press. The specimens are then cut in the plates using a digitally controlled waterjet machine. The approximate dimensions of the coupons are 200mm long for 20mm wide, with a thickness of around 1.3mm, and the tabs are 40mm long, leaving an effective length of 120mm. The precisely measured widths (w) and thicknesses (t) of the specimens are reported in Table 2 :

Table 2. Dimensions of the tested specimens.

Ref.	w (mm)	t (mm)
UD45-1	19.27	1.3
UD45-2	19.33	1.31
UD45-3	19.60	1.25

3.2. Experimental setup

The strains in the specimens are locally measured with two gage rosettes, symmetrically glued on each face of the coupons, bringing the xx, yy and 45° strains (where xx refers to the loading, yy the transverse and 45 the 45° direction) on both side of the specimens. These measurements on both sides allow one to acknowledge the effect of out-of-plane bending and quantify it, which is especially important for thicker specimens. Furthermore, a fine speckle pattern is painted on one side of the specimen in order to use Digital Image Correlation to measure the displacement and strain fields, particularly in the boundary condition area, which would validate the fixture design if these fields are similar to the digitally computed ones. A coarser speckle pattern is painted on the crosspieces holding the jaws, as their angle of rotation during the test is directly linked to the shear strain.

The specimens neutral axes are aligned with the loading one by using a laser as shown in Figure 1. The jaws are hereby manually tightened on the tabs of the specimens using screws.

A first coupon was tested without gages to determine the shape of the Load-Displacement curve and help design the load-unload cycles pattern of the tensile test machine.

3.3. Results

Out of the three tested specimens, two reached a shear failure while one did not. Indeed, the jaws were badly tightened on the second specimen, and as the load increased, a lot of friction occurred in the jaws, dissipating energy (visible via the hysteresis on the load-displacement curve) while the coupons slipped out of the jaws at the end of the test. Nevertheless, the strains measured by the gages remain correct for this test. The shear moduli were measured in the linear parts of the three shear stress / shear strain curves. The computed moduli and measured shear failure stresses are referenced in Table 3 :

Table 3. Measured mechanical properties.

Ref.	G ₁₂ (GPa)	τ ₁₂ (MPa)
UD45-1	3.82	29.3
UD45-2	4.015	N/A
UD45-3	4.226	30.5

The average shear modulus is of 4.02 GPa, which is 5.2% less than those measured on ($\pm 45^\circ$) EN 14129 specimens, and the standard deviation is of 4.8%, which is fairly satisfactory.

Figure 3 shows the $\tau_{12} = 2 \cdot G_{12} \cdot \varepsilon_{12}$ curves of the three tests. The results of the tests can be exploited to measure the damage evolution of the shear contribution, though the UD45-2 specimen did not reach failure and did not damage as much as the others because of the slipping of the coupon in the jaws.

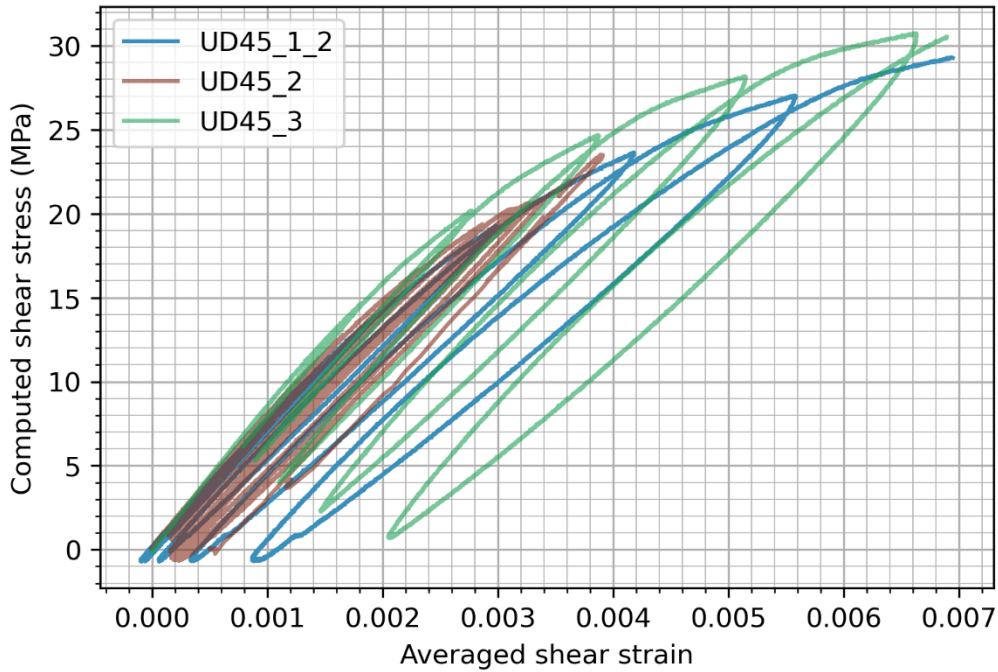


Figure 3. Load-unload cycles for each specimens.

Finally, the displacement fields computed by the Digital Image Correlation have not been studied yet, but their comparison to the simulated fields should bring a validation of the boundary conditions that are supposedly imposed during the test. This analysis will be presented in further works.

4. Conclusions and perspectives

To put it in a nutshell, the designed rotating fixture appears to be working quite well for the characterization of shear mechanical properties using 45° off-axis UD specimens. A few more tests need to be performed to ensure that the measurements of the properties are representative, especially for the fracture stress, that could be compared to failure stresses measured on a classical 10° specimen under rotating boundary conditions for instance. Moreover, DIC results are yet to be processed in order to validate the boundary conditions during the test.

One could argue that certain angles minimize the transverse strain energy density contribution to the point of neglect, and that the damage law could be directly measured with a test at such angles (*confer* Figure 2). While the thermodynamic force driving damage could be more easily identified by neglecting one contribution out of the two, the precise computation of the shear modulus and then its evolution is not guaranteed for such configuration. This remains an academically interesting track that might be explored in further works.

To conclude, tests on composite stacks simulating the quasi-UD structure of the Carbon / Carbon composite that is the actual framework will be performed to verify if the shear properties and damage evolution of the ply can be identified on quasi-UD composites.

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