Failure stresses of plain weave glass/epoxy under different in-plane biaxial loading ratios

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Résumé

Les matériaux composites sont largement utilisés dans les applications d'ingénierie. Dans le cadre de la caractérisation mécanique de ces matériaux, l'essai biaxial sur éprouvette plane peut s'avérer intéressant par rapport à l'essai conventionnel de traction uniaxiale réalisé selon différentes directions. Cependant, la définition de la géométrie de l'éprouvette cruciforme constitue une difficulté majeure pour cet essai. Dans ce contexte, l'objectif de cette étude est de caractériser le comportement à la rupture d'un matériau composite dans une large gamme d'états de contraintes. L'éprouvette proposée est composée des deux talons d'aluminium collés de chaque côté du matériau composite d'épaisseur constante. Les essais de traction biaxiale sont réalisés pour différents chemins de déformation allant de la traction uniaxiale jusqu'à la traction équi-biaxiale. Les déformations majeures et mineures dans la zone centrale (calculées par la méthode de corrélation d'images) et les efforts mesurés selon les deux axes de l'éprouvette constituent la base expérimentale. En se basant sur l'ensemble des chemins de déformation testés, une enveloppe de rupture du matériau étudié peut être obtenue à partir des contraintes (ou déformations) majeures et mineures déterminées au moment de la rupture de l'éprouvette.

Abstract

Composite materials are widely used in engineering applications. The mechanical characterization of these materials is of major importance and the in-plane biaxial tensile test can be an interesting alternative to conventional uniaxial tensile tests along multiple directions. The major problem related to this test is the design of the cruciform specimen. In this study, the objective lies in the failure characterization of composite materials under a wide range of stress state. The proposed specimen is composed of two aluminum tabs glued on each side of a constant thickness composite sample. Experimental biaxial tensile tests are led for several displacement loading ratios from uniaxial to equibiaxial stretching. Major and minor strains in the central zone (calculated by DIC technic) and measured tensile forces along the two specimen axes constitute the experimental database. According to the loading ratios, the minor and major stresses (or strains) at the onset of failure will define a failure envelop for the material.

Keywords: Biaxial test, cruciform specimen, strain path, composites, digital image correlation

1   Introduction

Due to their high specific mechanical properties, composite materials have been largely used in engineering applications such as aerospace, automotive or civil structures. The anisotropic mechanical behavior of the composites makes their characterization not straightforward [1]. Over the past years, different approaches have been proposed for the characterization of composite materials. Uniaxial test is the mostly used method by researchers due to its low cost and simplicity. However, since most of the materials are subjected to multi-axial stress state in real life applications, the multi-axiality of the biaxial test methods is suitable for their characterization. The two most used biaxial methods are (i) test on tubular specimens and (ii) in-plane biaxial test on cruciform specimens. The biaxial test on tubular specimens was the earliest method and it was used by various researchers since it solves the problem of the edge effect problem found in the coupon-like specimens [2]. Different researchers show that the biaxial test on tubular specimens produces a dominant effect of through thickness stresses which limits the characterization of composite materials for tubular applications [3,4]. However, since most of the engineering applications require the use of flat composites, the in-plane biaxial test is a well adapted characterization method. Another advantage of the in-plane biaxial test is the ease with which it allows to vary the biaxial stress ratio since that is directly related to displacements imposed on the two axes of the cruciform specimen.

One of the major problems for the in-plane biaxial test is the design of the specimen. Different cruciform shapes have been proposed in the literature for metal and composite material. All these shapes are defined based on the same requirements [5–8]: (i) strain localization or failure, depending on the mechanical behavior to be identified, must occurs in the central zone, (ii) a homogeneous stress state is sought in the central area, (iii) the two previous prerequisites must be verified for different biaxial stress ratios. In order to reach a high strain concentration and then failure in the central zone of the cruciform specimen, the thickness of the central area must be reduced. Two different types of composite cruciform specimens were defined in the literature. The first one was defined with straight boundaries between the arms (Figure 1). For this shape, the thickness reduction in the central zone was made by "cladding". The composite is prepared by curing some composite plies (with a circular hole in the center) on both sides of the tested composite plate. This specimen was rarely used because of the high loads required to reach the failure [9,10]. The second type of shape, which is the mostly used, is a specimen with curved shape between the four specimen arms. The thickness reduction in this type of specimens is generally performed by milling (Figure 1) [5,6,11]. However, for this type of cruciform specimen, the milling of the composite can affect its mechanical properties. Thus, authors have used a new concept by gluing aluminum tabs with a multi-material epoxy adhesive on both sides of a constant thickness composite plate in order to reduce the central zone thickness of the cruciform specimen without affecting the mechanical properties of the composite [12]. Based on several loading ratios between the two specimen axes, the minor and major strains in the central zone are obtained experimentally in order to construct the failure envelop of a glass/epoxy composite.
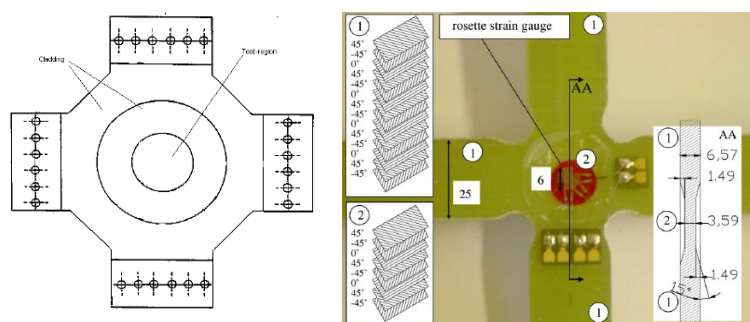
Figure 1. Biaxial cruciform specimens with straight boundaries [10] (left) and curved boundaries [6] (right)

2 Experimental procedures

2.1 Composite materials

The composite used in this study is a four plies (of ply thickness 0.25 mm) plain-weave composite. The in-plane elastic properties of the 1mm sheet are given in Table 1.

Material	$E_x = E_y$ (GPa)	G_{xy} (GPa)	υ_{xy}
Glass/Epoxy	22.8	4.1	0.14

Table 1. Glass/Epoxy material properties

2.2 Cruciform specimen

As explained before, aluminum tabs are used to make the cruciform specimens. The tabs are made from aluminum alloy AA2017 with an initial thickness of 3 mm. The thickness is gradually reduced to 1 mm near the central zone, as shown in Figure 3. The AA2017 has an elastic Young modulus of 70 GPa, a Poisson ratio of 0.3 and a yield stress of 230 MPa. The most important factor for the achievement of the tests is the quality of the bonding between the aluminum tabs and the composite. The composite must reach the failure in the central zone before a failure in the adhesive. The best performances of the adhesive are reached when (i) the aluminum surface is treated by shot peening and (ii) the thickness of the adhesive is controlled in order to have a homogeneous adhesive spreading (the thickness is controlled by adding an amount of 1% of microbeads of 0.1 mm diameter to the adhesive). Figure 3 shows the cruciform specimen assembled with dimensions.
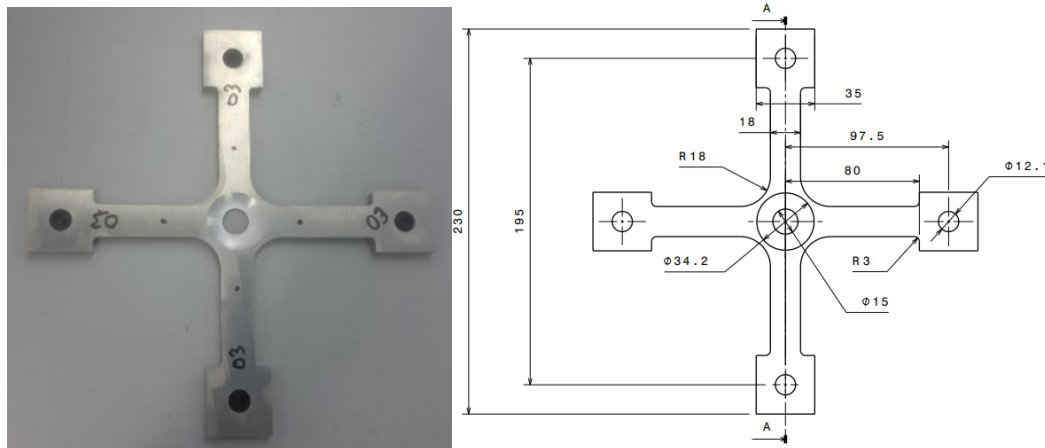
Figure 3. Cruciform specimen dimensions

2.3 Biaxial test procedure

Considering the biaxial testing setup, the biaxial machine (Figure 4) has a capacity of 50kN for each actuator. The central zone of the cruciform specimen is painted with white paint and then sprayed by some tiny black points (Figure 5). A high-speed camera of maximum frequency 3000 Hz is set above the specimen in order to film the test. The extracted images are used to calculate the experimental strains in the central area using digital image correlation technic (DIC).
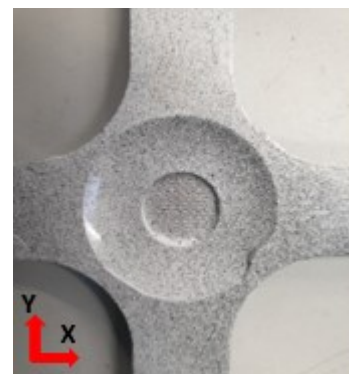

Figure 4. Biaxial testing machine

Figure 5. Painted specimen for the DIC

Different cruciform specimens have been loaded under different biaxial tensile ratios by imposing different displacement ratios along the two arms. For the correlation method, GOM Correlate software has been used for the calculation of the strains. Similar DIC parameters have been used for all the tests (facet size 32x32 pixels and a distance of 32 pixels between the facets). The experimental stresses have been calculated according to the experimental strains and the material properties using constitutive laws (Equation 1). During the test, the forces in each arm are measured using strain gauge sensors.

$$\sigma_{x,exp} = \frac{(\varepsilon_x + \vartheta_{xy}\varepsilon_y)E_x}{1 - \vartheta_{xy}\vartheta_{yx}} \quad \sigma_{y,exp} = \frac{(\varepsilon_y + \vartheta_{yx}\varepsilon_x)E_y}{1 - \vartheta_{xy}\vartheta_{yx}} \qquad \text{Eq.1}$$

3   Results and discussion

In order to construct the failure envelop of the composite material, Table 2 shows the three different biaxial ratios applied in this study with their corresponding velocities in X and Y directions (tests are made in quasi-static conditions). The biaxial tensile ratio is defined as the ratio of displacement applied on the cruciform arms in X and Y directions (Ux/Uy). For example, a biaxial tensile ratio of 1/2 means that the displacement applied in y-direction arm is twice that of the displacement in x-direction. The loads in arms, strains and stresses at the onset of failure of the composite are presented for each test. Figure 6 shows an example of a failed specimen under uniaxial stretching on cruciform specimen.

Test number	Test01	Test02	Test03
Biaxial tensile ratio	1/ free	1/2	1/1
Velocity applied (V_x (mm/min)/V_y (mm/min)	1 / -	0.1/ 0.2	1/1

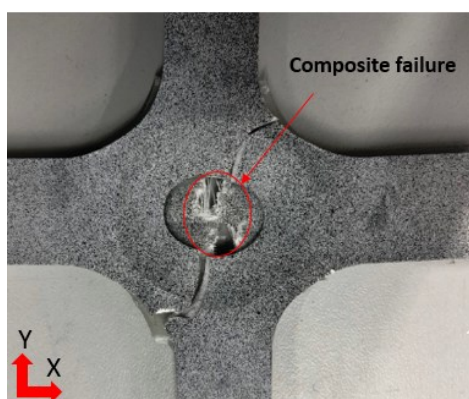Table 2. Biaxial testing ratios studied

Figure 6. Cruciform specimen failure under 1/free biaxial ratio

First, Test01 (uniaxial test) has been performed on the cruciform specimen. Figure 7 shows the force applied on the specimen until the failure with respect to time. The composite fails at a load of 35kN.
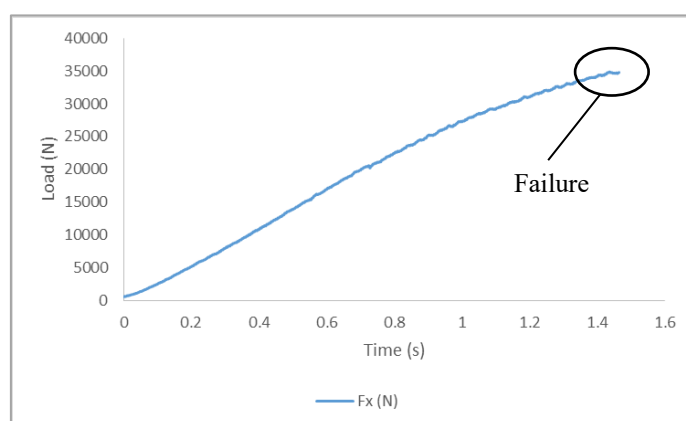

Figure 7. Load vs time in Test01

The variation of strains and stresses along x and y directions with respect to time are shown in Figure 8. The composite fails at a major strain level ε_x of 3 % which is equivalent to a stress level σ_x of 680 MPa.

Moreover, the negative value of the minor strain ε_y (- 0.9%) at the failure shows the compression behavior of the material due to Poisson effect.
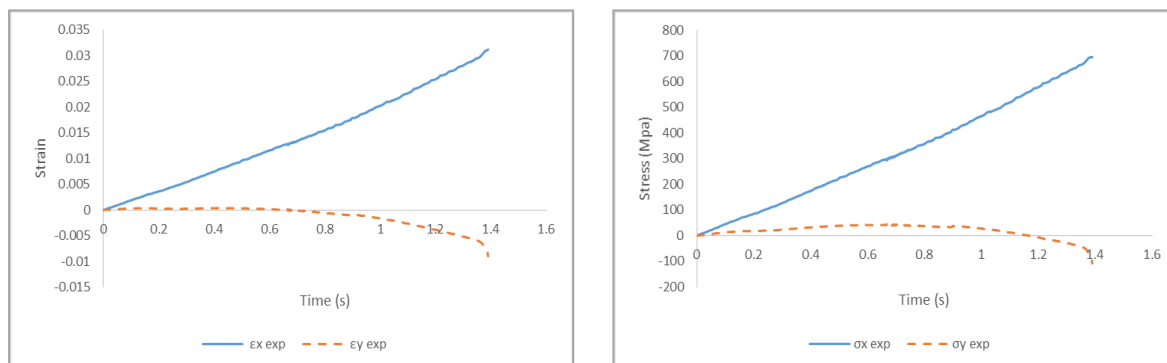

Figure 8. Strain (left) and stress (right) variation in central zone for Test01

For Test02, Figure 9 shows the loading in both x and y directions with respect to time. The figure shows that the specimen fails at a load Fy = 40 kN and Fx= 31 kN. Compared to the uniaxial test, the load reached at the failure of the specimen is higher in the biaxial test. This is called biaxial strengthening of the material which was noticed by many other researchers [13].
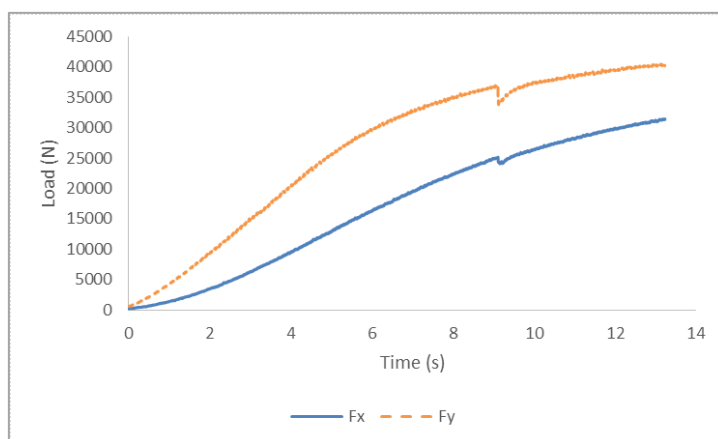

Figure 9. Load vs time for Test02

The experimental strains and stresses are presented in Figure 10; the specimen fails at a deformation of 1.4% and 3.1% in x and y directions, respectively. The calculated stresses at failure are 440 MPa and 750 MPa in x and y directions, respectively.
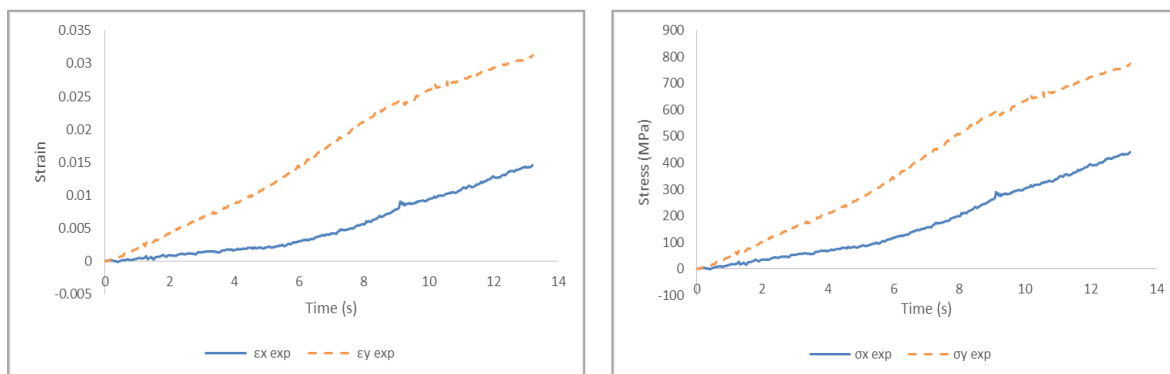
Figure 10. Strain (left) and stress (right) in the central zone for Test02

The last test presented in this paper is the equibiaxial test, an equal displacement has been applied on both arms in order to determine the failure strain on the composite. Figure 11 shows the variation of Fx and Fy with respect to time for the equibiaxial test. The failure occurred at a load Fx of 42 kN and Fy of 40 kN. A small desynchronization is noticed in the loading curves which is related to the machine. The displacements at the extremities of the x and y arms at the failure are 1.08 and 1.16 mm, respectively, which shows the equibiaxial state in this test and prove that this desynchronization can be neglected.
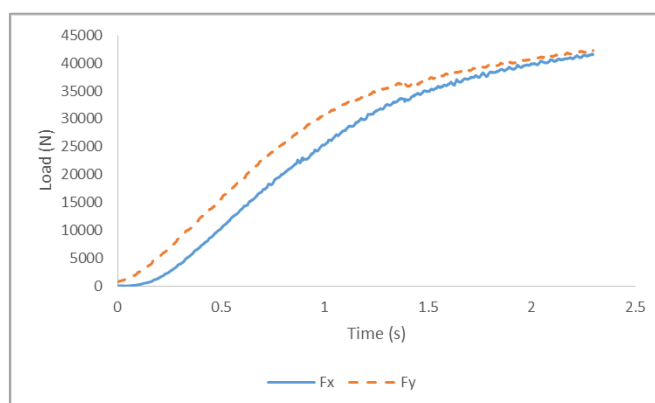

Figure 11. Load vs time in Test03

The strains and stresses with respect to time for the equibiaxial test are shown in Figure 12. The results show a strain (stress) level of 3.2% (830 MPa) in x-direction and 2.7% (740 MPa) in y-direction. The results are close in both directions which again shows the equibiaxiality of the test.
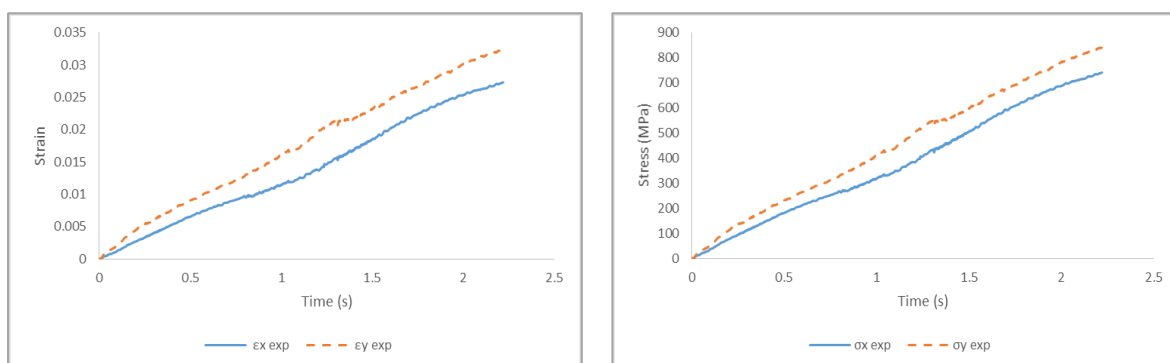

Figure 12. Strain (left) and stress (right) in the central zone for Test03

According to the results presented, the strain path under different loading conditions can be shown. The strain path is defined as the variation of the major strain with respect to the minor strain. The end of each strain path defines the failure of the material. Figure 13 shows the strain paths for the three different tests. Moreover, the first quadrant of the failure envelop according to the calculated stresses is presented in Figure 14. The failure envelop is symmetric. A comparison between the experimental failure envelop and the envelop generated by the well known Maximum Stress criterion is shown in Figure 14.

The Maximum Stress criterion is a non-interactive criterion that defines the failure of the material when either stress in x or y directions reach the ultimate strength of the material. The shape of the failure envelop according to this criterion is a rectangle (square if the strength of the material is equal in both x and y directions). This criterion (along with Maximum Strain criterion) was one of the most used by many authors [14]. However, according to the experimental results, it is clear that the Maximum Stress criterion under-estimates the failure stresses of this material in the biaxial loading conditions. The maximum deviation between the experimental results and the Maximum Stress criterion is for the equi-biaxial test where the major stress reaches 830 MPa experimentally leading to a difference of 18% with the Maximum Stress criterion (640 MPa).
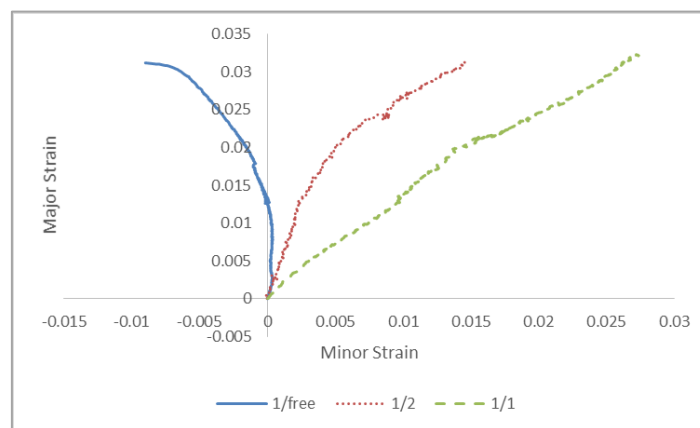

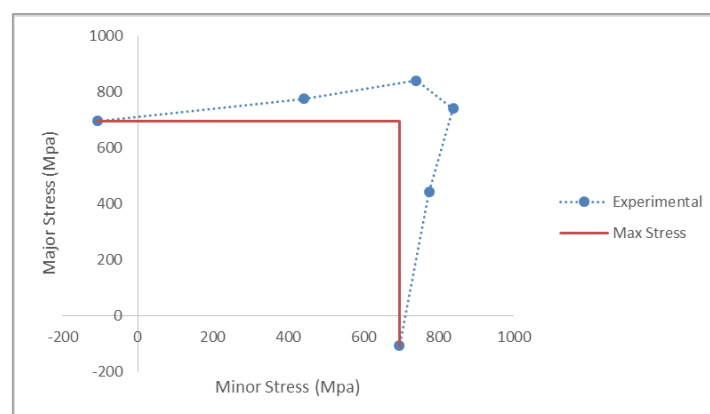Figure 13. Strain path of glass/epoxy composite under three loading conditions

Figure 14. Failure envelop of the glass/epoxy composite compared with Max stress criterion

4   Conclusion

In this study, a dedicated cruciform specimen (composed of aluminum AA2017 tabs glued on composite plate) is validated successfully for the characterization of composite materials under different biaxial

stress states. The experimental strains at the onset of failure of glass/epoxy composite are determined by digital image correlation technic for three different biaxial tensile ratios. The stresses are calculated based on the strain results using the constitutive law equation. The failure envelop was obtained and compared with the maximum stress criterion. The results show that the maximum stress criterion under-estimates the stresses at the onset of failure under biaxial loading conditions.

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