EXPERIMENTS ON LAMINATED PLATE WITH EXTENSION/TWIST COUPLING

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Abstract

Structural shape modification can be useful in many industrial applications. This paper deals with experiments and results on a rectangular laminated plate. This plate presents a strong extension/twist coupling due to an high anisotropic composite material and a lays-up sequence optimization. A large number of mechanical experiments has been done to compare the result to the prediction of the classical laminate theory. 3-dimensioned shape acquisition and optical microscopic observations of the plate have been performed, they allow the behavior of this plate to be better understood.

1 Introduction

Armanios E.A. [1] (1996) studied the extension/twist effect with laminate composites plate in order to use it in aeronautical structure. The aim of this paper is to understand how this kind of effect works before taking advantage of such technology in larger structure. This effect is interesting because it results in a great displacement due to a solicitation in another direction, this strange phenomenon is the expression of a well chosen stacking sequence.

1.1 Extension/twist phenomenon

This effect is possible to occur with laminate manufactured with composite materials. Actually, the anisotropy ratio E_L/E_T (Longitudinal and Transversal Young modulus) of a material, in addition to its orientation in the plies can drive the extension twist phenomenon.

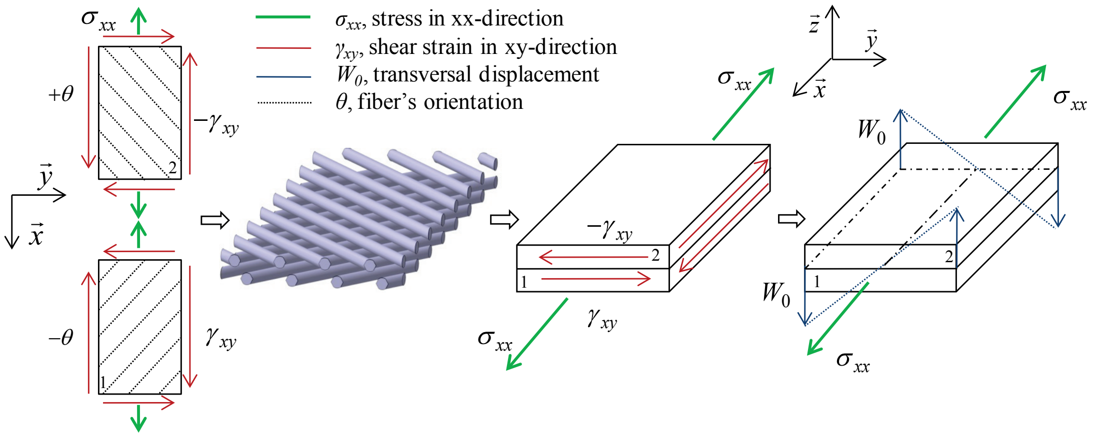

Figure 1. Explanations of the extension/twist phenomenon

In our case, an antisymmetrized angle repartition (Fig 1) has been chosen, in order to expose the extension/twist coupling. Each ply responds to the extension by an opposite shear, these two shear strains bringing about a rotation of the laminate. This kind of stacking with this symmetry zeroes some terms of the coupling matrix and allows an expected behavior of the shell by avoiding extension/bending coupling.

$$\begin{pmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{pmatrix} = \begin{pmatrix} A & B \\ B & D \end{pmatrix} \cdot \begin{pmatrix} \varepsilon^0 \\ k \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} & 0 & 0 & 0 & B_{16} \\ A_{12} & A_{22} & 0 & 0 & 0 & B_{26} \\ 0 & 0 & A_{66} & B_{16} & B_{26} & 0 \\ 0 & 0 & B_{16} & D_{11} & D_{12} & 0 \\ 0 & 0 & B_{26} & D_{12} & D_{22} & 0 \\ B_{16} & B_{26} & 0 & 0 & 0 & D_{66} \end{pmatrix} \cdot \begin{pmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \\ k_x \\ k_y \\ k_{xy} \end{pmatrix} \tag{1}$$

Eq. 1 comes from the Classical Laminate Theory [2] and links loads with strains. Where A_{ij} represent the in-plane behavior of the plate, the D_{ij} control the out of plane bending behavior and the B_{ij} matrix is the coupling between the two kinds of displacements.

Actually, one of the goal of the design with composite materials is to cancel this B_{ij} matrix because it often implies unwanted behaviors. In this paper, explanations to retrieve information about the stiffness matrix with different trials will be given.

The main idea was to follow the lifetime of a sample from the stripping to the destruction. A first part of this paper will expose how to estimate initial distortions coming from the curing step. Secondly, three mechanical experiments will be shown to estimate different items of the stiffness matrix and also to expose the extension/twist coupling. A short conclusion will be given to synthesize different outcomes. Several replicates were used to confirm the results we present and to estimate the scattering of the data.

2 3D-shape measurements using non-destructive technique

Laminates with structural coupling often exhibit great displacements due to the curing process. Acquisitions of scatter plots representing the surface of samples have been done with a scanner measuring arm (Fusion FaroArm, 0.05mm repeatability). The greatest displacements are in z-direction due to the specific stacking sequence. Besides, as in the CLT [2], the following relation is assumed:

$$W_0(x,y) = -\frac{k_{xy}}{2}xy - \frac{k_x}{2}x^2 - \frac{k_y}{2}y^2 \tag{2}$$

A deterministic algorithm has been develop using the least square method to fit the scatter plot on a virtual deformed plate which is defined by Eq. (2). It allows to rotate and displace the frame with the assumption that the scanned geometry is close to a bended-twisted shell. This program retrieve curvature coefficients of the out of plane displacements.

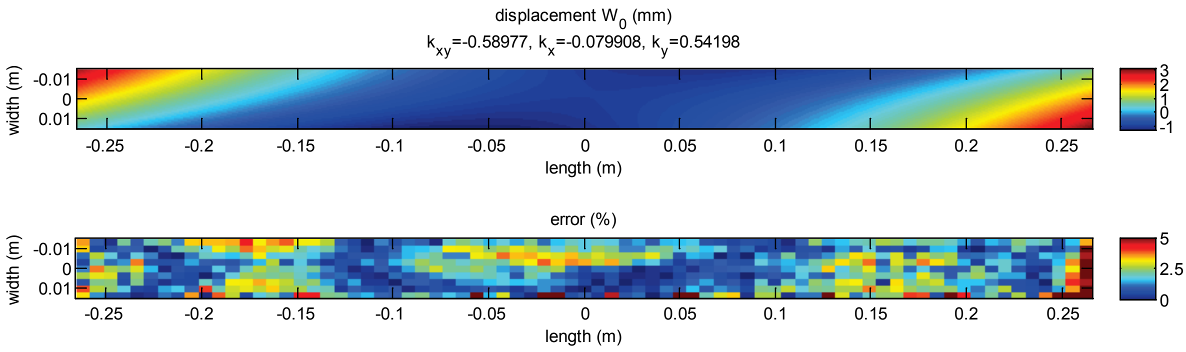

Figure 2. Out of plane displacement repartition and error of an unsolicited twist plate

Figure (2) shows that an accurate regression is possible from a scatter plot. Such data permit to define a best stacking sequence in order to reduce residual stresses. From now on, a large amount of information about the shape of the unloaded plate is available, and mechanical trials can be done.

3 Mechanical experiments

3.1 Experimental set-up and precautions

During tests, data from many sensors (torque, load, displacement, angle, strain gages) are gathered. In the figure (3), a snapshot shows a Schenck tensile/torque machine (65kN, 1000N.m) used to test samples, a synthetic overview of the experiment points out apparatus of the sample (sensors, actuators, mechanical junctions).

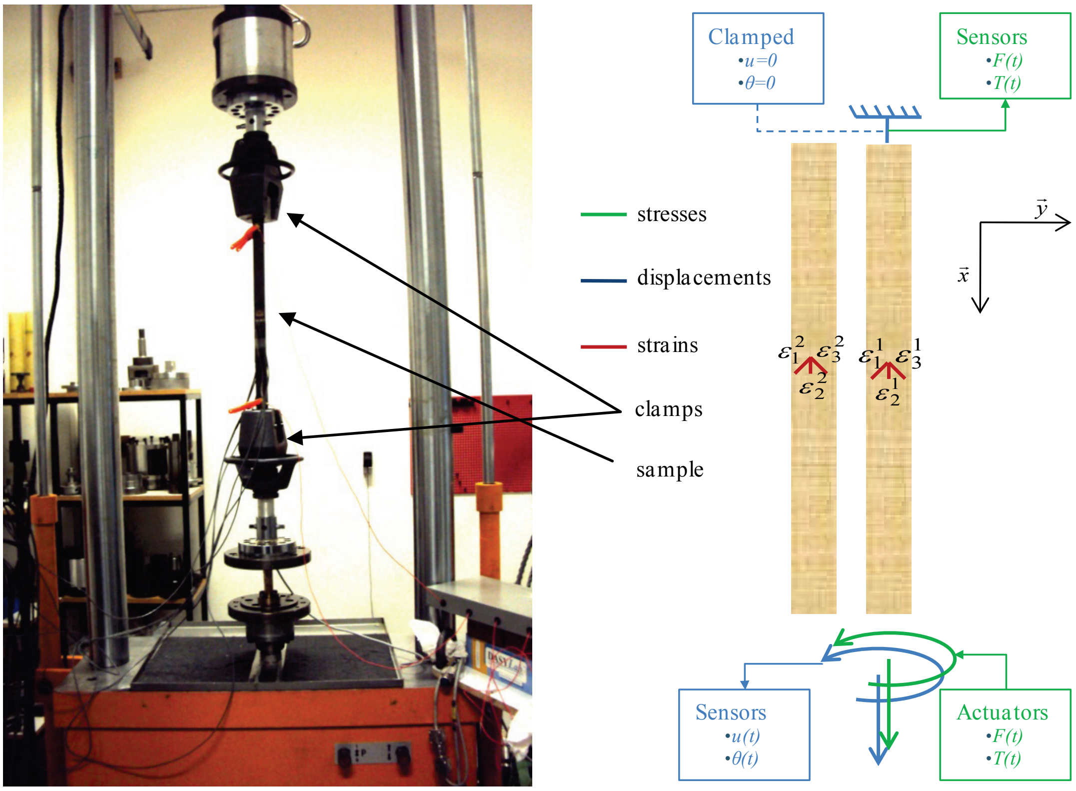

Figure 3. Apparatus of tensile test

Determination of the strain tensor is an important step. Strain gage rosettes in delta configuration give strains in three specific directions, a frame transformation is needed to retrieve the surface strain tensor in structural axis Eq. (3).

$$\begin{pmatrix}\varepsilon_{xx}\\ \varepsilon_{yy}\\ \gamma_{xy}\end{pmatrix}_k = \begin{pmatrix}0 & 1 & 0\\ 1 & -1 & 1\\ -1 & 0 & 1\end{pmatrix}\cdot\begin{pmatrix}\varepsilon_1\\ \varepsilon_2\\ \varepsilon_3\end{pmatrix}_k \tag{3}$$

Assumptions of the CLT allow to express strain and curvatures as in the double Eqs. (4).

$$\begin{pmatrix}\varepsilon_x^0\\ \varepsilon_y^0\\ \gamma_{xy}^0\end{pmatrix} = \frac{1}{2}\left(\begin{pmatrix}\varepsilon_x\\ \varepsilon_y\\ \gamma_{xy}\end{pmatrix}_{z_{up}} + \begin{pmatrix}\varepsilon_x\\ \varepsilon_y\\ \gamma_{xy}\end{pmatrix}_{z_{bot}}\right) \qquad \begin{pmatrix}k_x\\ k_y\\ k_{xy}\end{pmatrix} = \frac{1}{(z_{up}-z_{bot})}\left(\begin{pmatrix}\varepsilon_x\\ \varepsilon_y\\ \gamma_{xy}\end{pmatrix}_{z_{up}} - \begin{pmatrix}\varepsilon_x\\ \varepsilon_y\\ \gamma_{xy}\end{pmatrix}_{z_{bot}}\right) \tag{4}$$

So, the complete strain tensor at one point of the plate can be experimentally obtained and compared to numerical simulations.

The balance of the quarter-bridge strain gage circuits is made before the clamping of the sample, the effect of this latter can be pointed out. Actually, the misalignment producing bending in several axis, or torsion can be underlined. We can see in figures 4a and 4b longitudinal strain gages signal during the clamping.

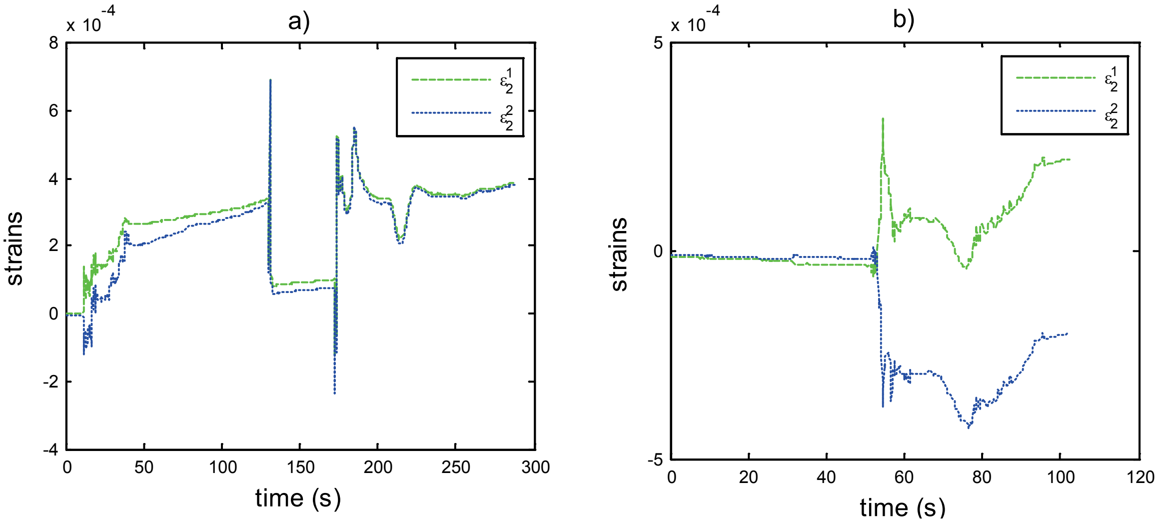

Figure 4. Strains in xx-direction induced by clamping, a) suitable, b) unsuitable

Difference in extension between ε^1_2 and ε^2_2 implies a bending around axe y of the plate. As a result, the left clamping induced more bending than the right one, even if the strain is more important in the first case (due to the self closing wedge clamp). A possible extend to other directions will produce other kinds of shape and other difficulties.

3.2 Zero-torque tensile test

This is the main goal of the study. The torque is controlled by a Proportional Integral Derivative controller device to be equal to 0 when a linearly time dependent force is imposed. This experiment is useful to monitor rotation induced by the extension/twist coupling.

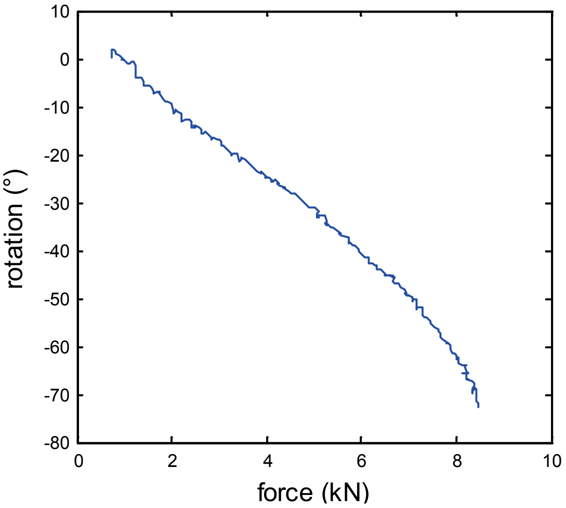

Figure 5. Relation between force and rotation without torque

The figure (5) points out the extension/twist effect. Henceforth, with a null torque, the plate is naturally rotating up to 70°. With these kinds of displacements, non-linear geometry effects appear because a tensile force in a global frame is a combination of in plane and out of plane force in a local frame. This can be predicted with an analytical formulation [1] or a finite element method [3].

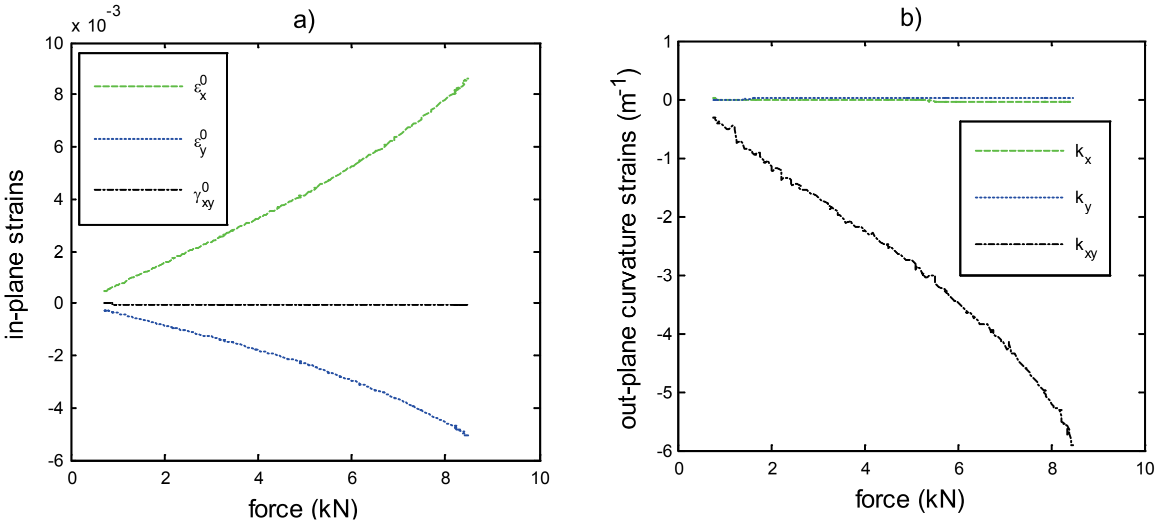

Figure 6. Variation of different a) strains and b) curvature with force

Figure 6b shows the link between two terms N_x and k_{xy}. The sample is not bending because of the low values of k_x and k_y. Figure 6a shows no occurrence of shear strain in the neutral plane and simultaneously linearity of ε_x^0 and ε_y^0 with the force.

3.3 No-rotation tensile test

This experiment allows us to link the torque with tensile force resulting of the extension twist coupling. Even if the plate remains flat, the out-plane behavior is expressed. The advantage of this trial is that there is no geometrical non-linearity from the great displacement shape of the twist plate because the plate remains flat.

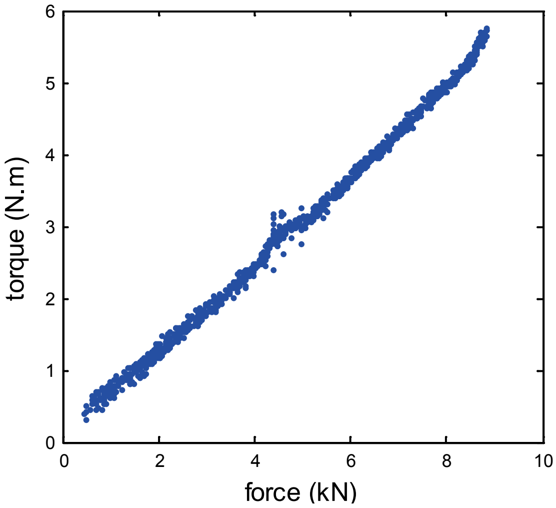

Figure 7. Relation between force without rotation

When a fixation is done, the extension/twist effect is prevented, but it nevertheless appears through a large torque resultant seen by the sensor. The torque and force can be expressed with Eq (5), allowing to retrieve matrix coefficients A_{11}, A_{12}, B_{16}, B_{26}.

$$\begin{pmatrix} N_x \\ M_{xy} \end{pmatrix} = \begin{pmatrix} A_{11} & A_{12} \\ B_{16} & B_{26} \end{pmatrix} \cdot \begin{pmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \end{pmatrix} \tag{5}$$

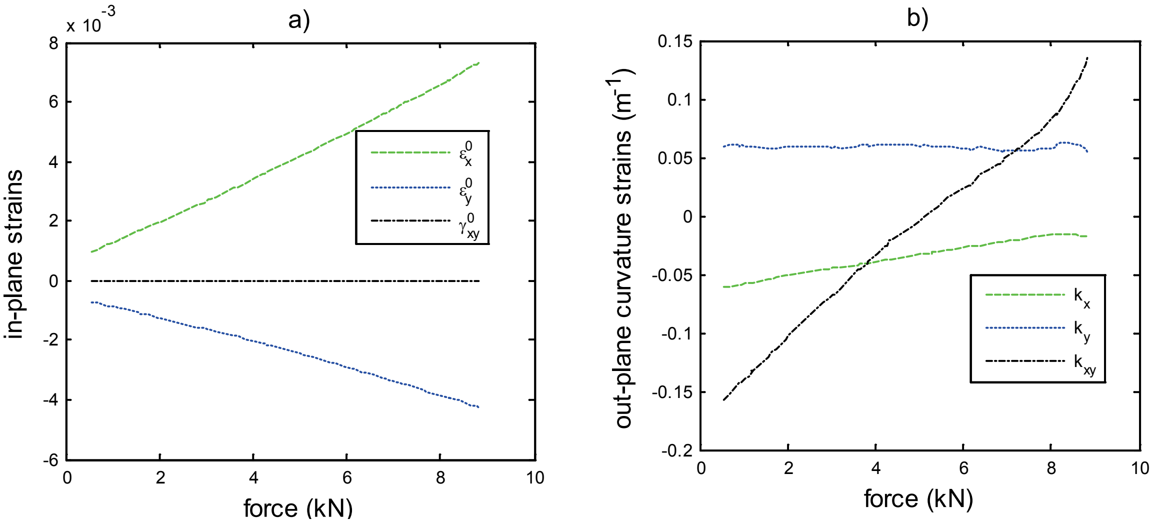

Figure 8. Variation of different a) strains and b) curvature without rotation

This experiment points out a low variation of k_{xy}, because the plate is twisted without solicitation. Applying a tensile force with a null rotation makes the shell become plane. k_{xy} doesn't approach 0 because bridges of the gauge are equilibrated on a deformed shape.

3.4 Torque test without displacements

This last trial exhibits the reverse extension/twist coupling. Actually, the out of plane displacement is used to see this reverse effect happening on the extension behavior.

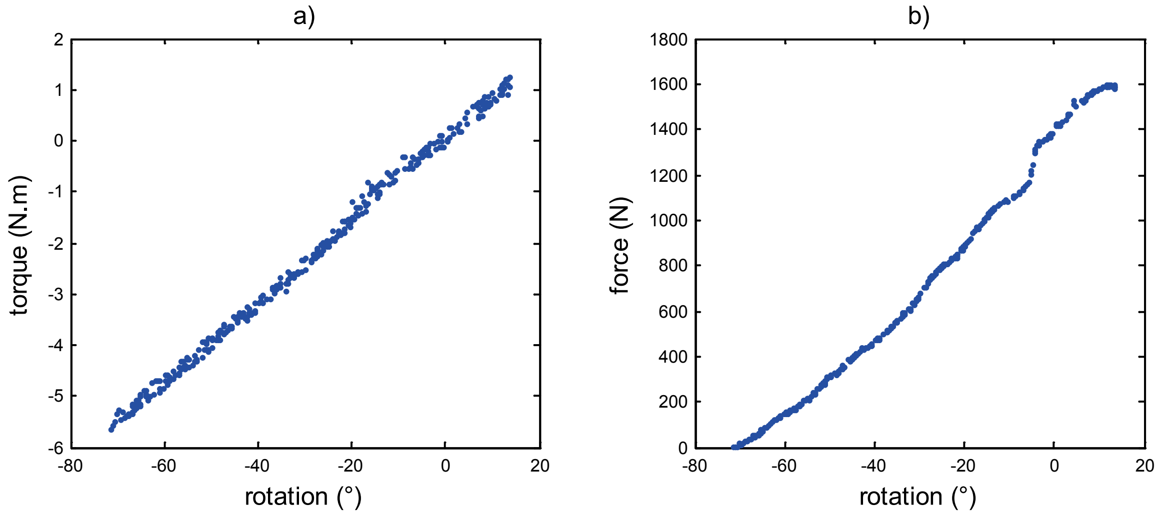

Figure 9. relation of a) torque and b) force with rotation without displacement

It's also a simple experiment used to estimate the D_{66} (torsional stiffness) which is the link between rotation and torque Eq. (6). The reverse coupling is seen in the second figure 9b, by applying a torque on the plate. But this is not the best method to estimate B_{16}, because the sample is very stiff in the longitudinal sense. This two figures (10) support that only k_{xy} is variable.

$$M_{xy} = D_{66} k_{xy} \qquad N_x = B_{16} k_{xy} \tag{6}$$

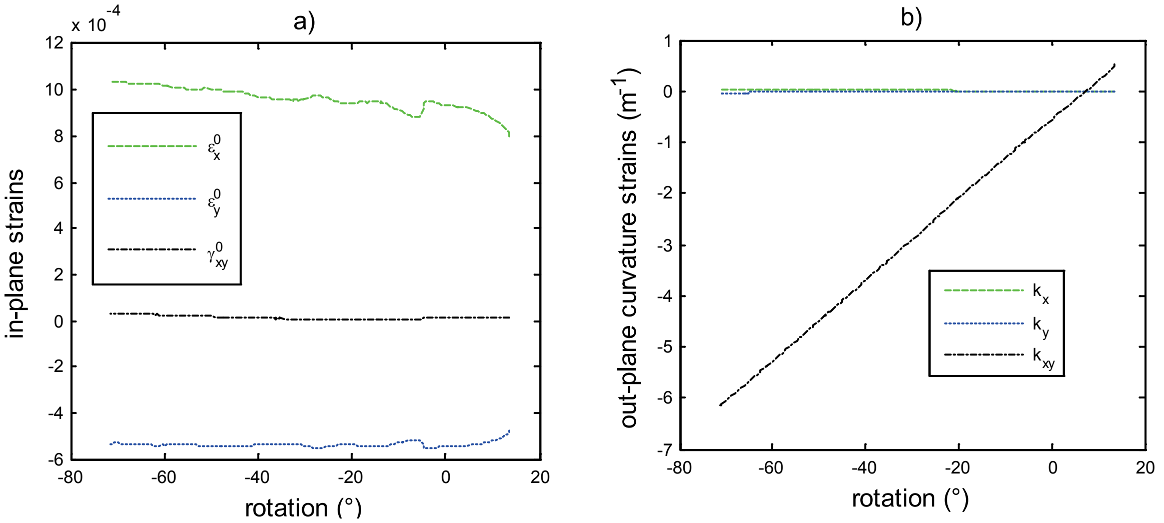

Figure 10. Variation of different a) strains and b) curvature without displacement

4 Destructive experiments

Mechanical experiments can eventually lead to the destruction of the sample. There are several ways of monitoring it. Figure (11) represents three fields of temperature measured with a Cedip infrared camera at an acquisition rate of 150Hz. An increase of heat emission is seen about 100 ms before the sample breaks.

The shape of this sudden increase follows the orientation of a specific ply of the stacking sequence of the laminate. This kind of failure has been observed on all extensions/twist samples and matches with transversal crack. In that case, the transversal direction stress (in the ply frame) is larger than the yield strength in this particular ply, in other words, this is a matrix damage.

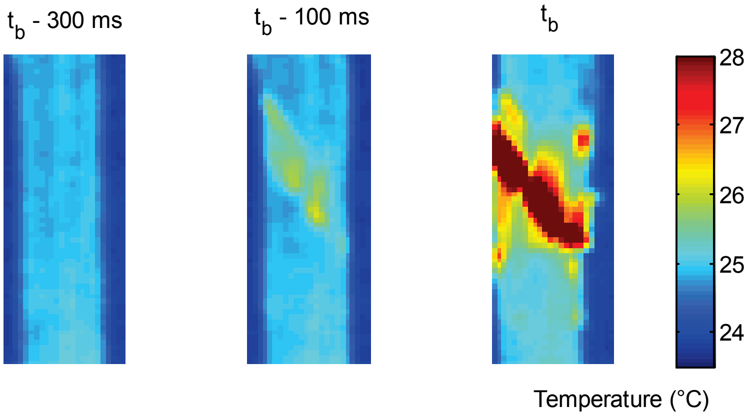

Figure 11. Temperature fields at different time before and after the sample break

Optical microscopy remains an useful tool when it's needed to optimize the fabrication of a laminate. In our case, a slice of the plate was polished to be seen with a microscope, these observations allows to monitor thickness, fiber repartition, damage growth, delaminations, etc...

5 Conclusion

All experiments of this paper have shown the capability of a plate with such a large extension/twist coupling. This is now easy to compare with analytical calculations of finite elements results. We have proved that such a plate is sustainable and respond well to loads in terms of rotation (about 70°). The next step of such a technology is the application on a larger structure.

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