ANALYSIS OF DEFAULTS OCCURRED DURING BIAS EXTENSION TESTS ON NON-CRIMP FABRICS

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Keywords: Non-crimp fabric, Bias extension test, Chemical binder system, Shear, Slippage

Abstract
The formability of NCF have been studied in several scientist works [1–4]. However, most of those studies ignore the presence of a chemical binder system (polymer) needed in the industrial applications. This component is usually added on the fabric to stabilized their 3D geometry (inter-ply and intra-ply cohesion).
This communication presents an analysis of mesoscopic deformation modes of a NCF based on an experimental campaign. Two configurations are studied, the first one is focus on a biaxial NCF without binder system, and the second one investigate the influence of a binder system on this NCF. This study permit to show that the slippage effect is the main deformation mode and that, at 20°C, the binder system modify the deformation modes.

1. Introduction

The forming of dry fabrics defines intrinsic parameters of the preform (for example fiber orientations, local density) [5], [6]. Those parameters have a direct influence on the mechanical behavior of the composite material [7]. The project FAST FORM, led by IRT M2P and supported by a consortium of 15 partners aspires to develop methods and technologies required to manufacture preforms for the automotive industry:

- Structural part with a large size and complex geometries
- With an optimization of the material yield
- Reaching a technical-economic optimum
- Having a production rate of 2 min

The project has chosen to investigate, non-crimp fabrics (NCF) because of their high formability combined to their high mechanical properties in composites material. For this project, the simulation of dry fabrics forming is used to optimize the preforming processes, especially the stamping process of dry fabrics. In order to simulate the formability of a NCF, their mechanical behaviors have to be identified. In plane shear is one of the main deformation mode induced during the forming of complex geometries. To identify this behavior, the bias extension test is used. However, the NCF material can have a complex and indesirable deformation modes during this test [1], [2], [4].

This work present an analysis done to investigate the deformation modes and understand the influence of an industrial binder system on the NCF formability.

2. Materials

This work investigates the behavior during bias extension test of a biaxial NCF of glass fiber. This NCF stiching pattern is knitted with a length of 3.3 mm and a gauge of 10 stichs per inch. The NCF is made of 600 TEX glass fibers.
When it is present, the binder is an epoxy power (15 g/m²) added on the face 2, face with the stitching lines.

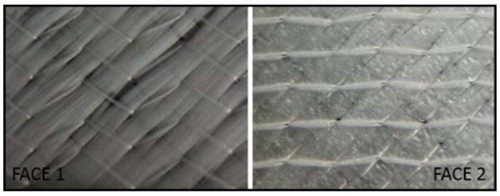

Figure 1. Picture of the NCF studied.

3. In-plane shear and bias extension test

Two definitions can be apply to define the in-plane shear of fabrics. The first one considers that fibers can rotate but they can not slip. This definition is usually used for modeling woven fabrics or NCF material (denoted bi-directional theory). The main assumption is that lenghts along both fiber directions are constant regarding the shear. The second definition is based on the assumption that fibers can slip but they can not rotate. This definition is usually used for modeling unidirectional fabrics (denoted unidirectional theory). The main assumption is that lenghts perpendicular to the main fiber direction are constant regarding the shear [8] (fig. 2).

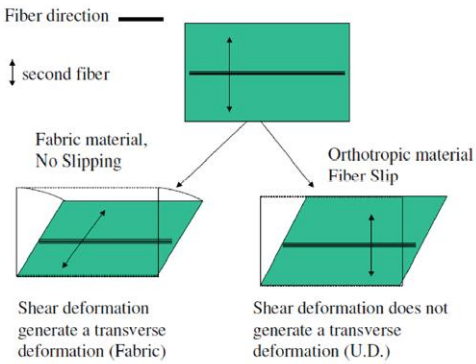

Figure 2. The two shear modes discribing the in-plane fabrics deformations [8]

To determine the shear behavior of a fabric, the bias extension test can be used. This test consists in applying a tension force to a rectangle sample with a length twice longer than its width at least. For an orthogonal bi-axial fabric, at the beginning of the test, fibers have to be at 45°. With the tension, three zones appear on the sample. According to the theory, the zone A corresponds to pure shear, the zones B are half-sheared, and the zones C are not solicitated [9] (fig. 3).
However, for bi-axial NCF, the theory is usually not respected because of undesirable mesoscopic deformation mode, like intra-ply slipping or out of plane ondulation [4], [10].
In this work, the specimens (fig. 3) have a length (L_0 = 140 mm) twice longer than the width (l_0 = 70 mm).

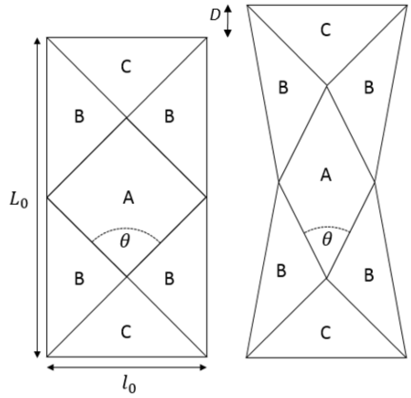

Figure 3. The classic approach describing a bias extension test on a bi-axial fabrics [9]

2. Experimental results

2.1 Configuration without binder

The first presented configuration is without binder. For the configuration, shear and slippage are the mains deformation modes. Thanks to the markers and the sample borders, we can assume that all fibers which are crossing the zone A slip during the test. Also, we have observe that 2 corners of the zone A do not stay horizontaly aligned.

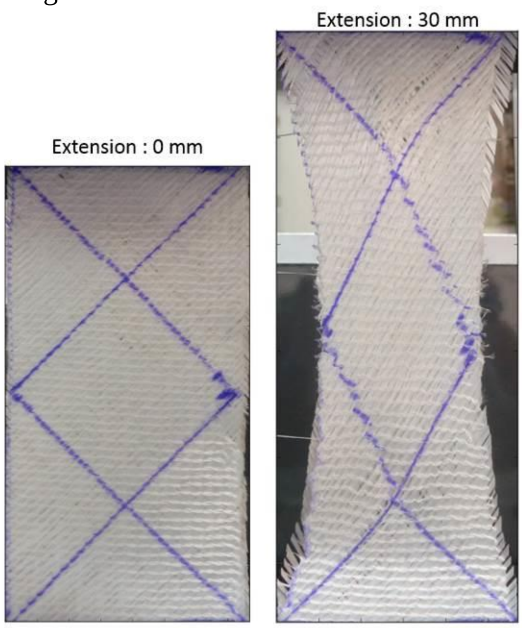

Figure 4. Sample without binder during the bias extension test (left : at 0 mm ; right : at 30 mm)

In regards to those observations, lengths of the borders of the A zone, the angle between the visible fiber direction and the vertical axis have been measured thanks to image analysis. Those measurements are presented in table 1. They have been compared to both shear theories (bi-directional shear and unidirectional shear) for an imposed displacement of 30 mm. For the unidirectional theory, the experimental angle is choosen to calculate the borders lengths of the zone A.
The geometrical description of both theories is given by the schema bellow (fig. 6). In both cases, the border lengths are calculated in function of the initial width of the sample (l_0), the angle between the fiber direction and the vertical axis (w), the displacement imposed during the test (D), and the elongation of a border, noted (Δd, mm).

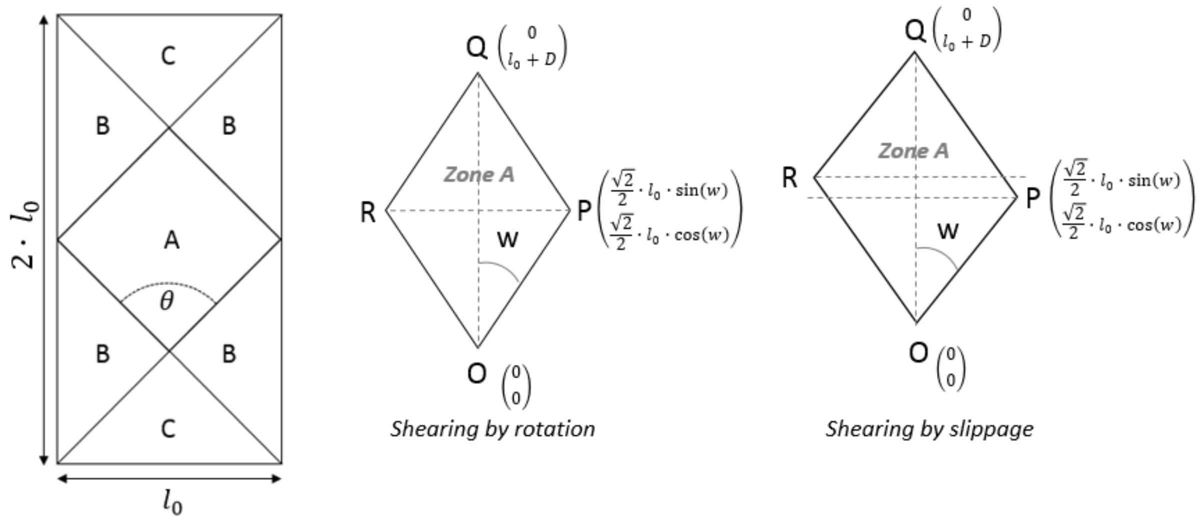

Figure 6. Geometrical approach to describe the deformation during the bias extension test.

Analytical theory for shearing by rotation (bi-directional theory) :

$$\|\vec{OP}\| = \|\vec{RQ}\| = \|\vec{OR}\| = \|\vec{PQ}\| = \frac{\sqrt{2}}{2} \cdot l_0 = \sqrt{\left(\frac{\sqrt{2}}{2} \cdot l_0 \cdot \sin(w)\right)^2 + \left(l_0 + D - \frac{\sqrt{2}}{2} \cdot l_0 \cdot \cos(w)\right)^2} \quad (1)$$

Analytical theory for shearing by slippage (uni-directional theory) :

$$\|\vec{OP}\| = \|\vec{RQ}\| = \frac{\sqrt{2}}{2} \cdot l_0 \quad (2)$$

$$\|\vec{OR}\| = \|\vec{PQ}\| = \frac{\sqrt{2}}{2} \cdot l_0 + \Delta d = \sqrt{\left(\frac{\sqrt{2}}{2} \cdot l_0 \cdot \sin(w)\right)^2 + \left(l_0 + D - \frac{\sqrt{2}}{2} \cdot l_0 \cdot \cos(w)\right)^2} \quad (3)$$

Table 1. Geometrical comparison between both theories and the experimental mesurement

	Border OR (mm)	*Border PQ* (mm)	*Border OP* (mm)	*Border RQ* (mm)	*Angle QOP* (°)	*Angle ROQ* (°)
Experimental	59 ±2	61 ±2	50 ±2	49 ±2	25° ±3	27° ±3
UD shear theory	59,5	59,5	49,5	49,5	26° (choosen)	26° (choosen)
Bi-axial shear theory	49,5	49,5	49,5	49,5	Out of bounds	Out of bounds

The comparison between both theories and the experimental shows that behavior observed is closer to the unidirectional shear theory than to the bi-directional shear theory. In this case, without binder, for this NCF, we can consider that the slippage is the main deformation mode during the bias extension test in the zone A.

2.2 Configuration with binder

The second configuration studied is the NCF with a binder on the face 2 (Figure 1). In this case, we also have noticed the presence of slippage along the fibers directions in the zone B (or C?). However, the sliding occurs through fracture lines, which separate the sample into parts during the test. (fig. 7). For a displacement of 10 mm, six parts were counted (e.g. 5 fracture lines). For a displacement of 20 mm two fracture lines were appeared in addition to the previous ones. And for a displacement of 30 mm one fracture line was appeared in addition to the previous ones, so 8 fractures. Also, we notice a local disorientation of the stiching lines along the fractures.

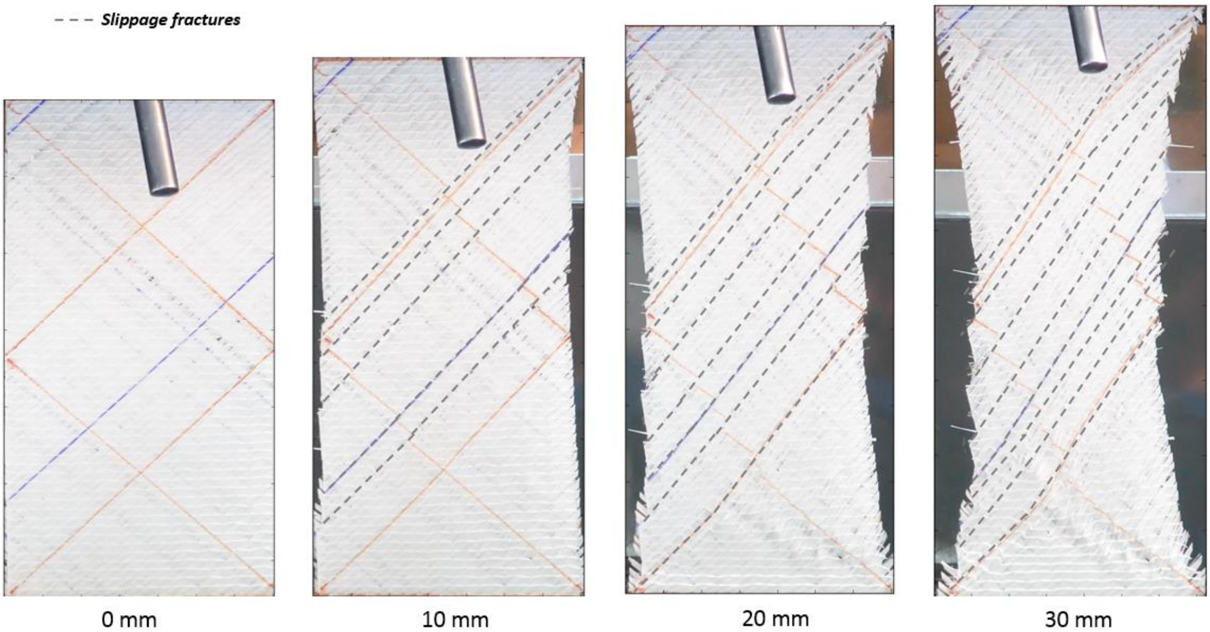

Figure 7. Sample with binder during the bias extension test at several displacements

Thanks to image analysis, the same measurements as the case without binder have been done (Table 2). Same analytical theories are used to describe the deformation of the zone A, and results were compared to experimental results (Table 2).

Table 2. Geometrical comparison between both theories and the experimental mesurement

	Border OR (mm)	*Border PQ* (mm)	*Border OP* (mm)	*Border RQ* (mm)	*Angle QOP* (°)	*Angle ROQ* (°)
Experimental	49 ±5	51 ±5	47 ±5	47 ±5	34° ±4	33° ±4
UD shear theory	64,4	64,4	49,5	49,5	33° (choosen)	33° (choosen)
Bi-axial shear theory	49,5	49,5	49,5	49,5	Out of bounds	Out of bounds

In this case, any of both theories is applicable. Regarding the fiber orientation, the zones B are not clearly identifiable. Except near the zone A, the fibers have approximately the same orientation in zone B as in zone A. Considering that zones B and A (concerned by the same fibres on side 2) are sheared homogeneously, we can apply the UD shear theory on a bigger trapeze (fig 8). However, this assumption involve a discontinuity between the zones C and B.

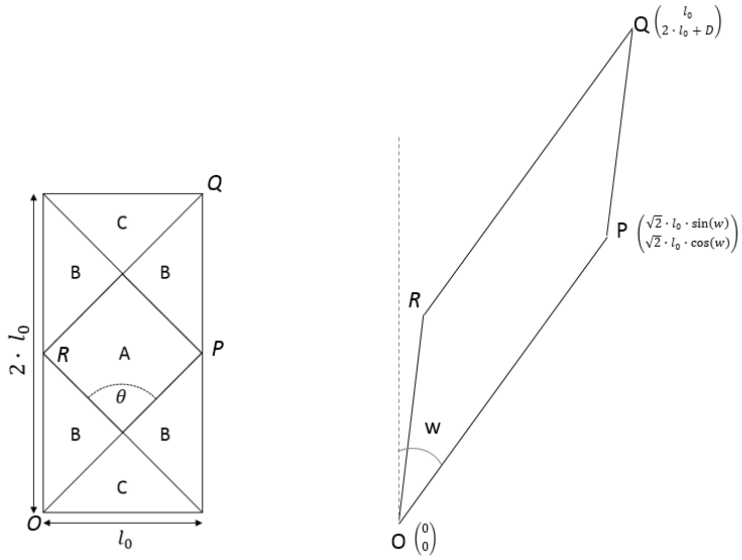

Figure 8. Geometrical description of the deformation mode used for the analytical theory

Analytical theory type UD applying on the larger trapeze :

$$\|\overrightarrow{OP}\| = \|\overrightarrow{RQ}\| = \sqrt{2} \cdot l_0 \quad (4)$$

$$\|\overrightarrow{OR}\| = \|\overrightarrow{PQ}\| = l_0 + \Delta d = \sqrt{\left(l_0 - \sqrt{2} \cdot l_0 \cdot \sin(w)\right)^2 + \left(2 \cdot l_0 + D - \sqrt{2} \cdot l_0 \cdot \cos(w)\right)^2} \quad (5)$$

To verify this hypothesis, we have measured by image analysis the elongation between two points P and Q, and the angle (w, deg) between fibers and the vertical axis.

Table 3. Comparisons between experimental measurements and the new analytical description

	Border PQ (mm)	*Angle of fibers* (°)
Experimental	84 ±5	26° ±5
UD shear theory	85,3	26° (choosen)

The good correlation between this geometrical analysis and the experimental measurements shows that the binder provided rigidity against the rotation and the slippage effect. As the deformation modes seems to be closer to a sheared continuous material with a main reinforcement direction. The hypothesis of the classical approach of the bias extension test are not respected, especially the absence of tensile deformation.

3. Conclusions

This work has permitted to identify deformation modes of a NCF during the bias extension test. As a first step we have identified the main deformation modes occurred during the test. Then, thanks to elementary geometrical analysis, we showed that the observed behavior of the NCF without binder was closer to a unidirectional shear behavior, due to slippage, than a shearing of the fibers between them.
As a second step, the same NCF with binder, used for stabilizing the reinforcement, was tested. The investigations have show the binder modify the deformation mode of the NCF. In this case, any of both shear theories can be applied to describe the observation. A geometrical

description have been proposed and have a great correlation. However this analysis is incompatible with the bias extension test theory. The behavior observed seems to be closer to a bias extension applied on a continuous unidirectional material with fractures along some fibers.

For both case, the slippage is the main deformation mode observes, which lead to have a better description with a unidirectional load. This assumption need to be validated by complementary works, taking in account the complex solicitations (tensil or transverse compression for example).

Acknowledgments

The authors acknowledge the members of the Fast FORM consortium (Arkema, Chomarat, Compose, Coriolis, ESI, Faurecia, Hexion, Hutchinson, Institut de Soudure, IPC, Owens Corning, PEI, PSA, Renault, SISE), the laboratory GEMTEX from the university of Lille and the IRT M2P for the support provided.

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