# Experimental Characterization of Anisotropic Mechanical Properties of Textile Woven Fabric

Rym Zouari, Sami Ben Amar, Abdelwaheb Dogui

***Abstract*****—**This paper presents an experimental characterization of the anisotropic mechanical behavior of 4 textile woven fabrics with different weaves (Twill 3, Plain, Twill4 and Satin 4) by off-axis tensile testing. These tests are applied according seven directions oriented by 15° increment with respect to the warp direction. Fixed and articulated jaws are used. Analysis of experimental results is done through global (Effort/Elongation curves) and local scales. Global anisotropy was studied from the Effort/Elongation curves: shape, breaking load (Frup), tensile elongation (EMT), tensile energy (WT) and linearity index (LT). Local anisotropy was studied from the measurement of strain tensor components in the central area of the specimen as a function of testing orientation and effort: longitudinal strain $\varepsilon_L$, transverse strain $\varepsilon_T$ and shearing $\varepsilon_{LT}$. The effect of used jaws is also analyzed.

***Keywords*****—**Anisotropy, Off-axis tensile test, strain fields, Textile woven fabric.

## I. INTRODUCTION

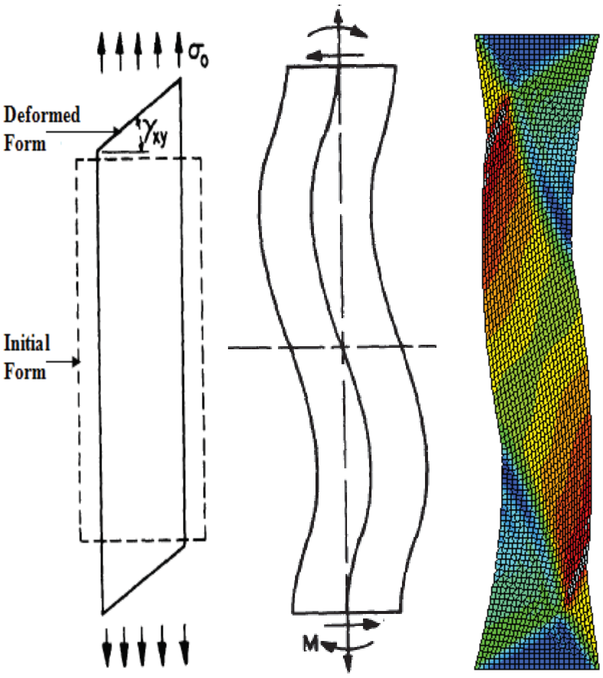
OFF-axis tensile test was considered as the basic test to characterize material anisotropic behavior essentially for composite materials. It is a tensile test along a direction other than the orthotropic material directions.

An homogeneous off-axis tensile test of orthotropic material in an orthotropic plane transforms the specimen as illustrated in Fig. 1 (A) [1]-[11].

Pagano et al. have shown experimentally and theoretically for composite materials effect of fixed and rigid jaws. When ends specimens were clamping they were deprived of natural rotation of the material [3]. The bending moment generated by off-axis tensile test, cause torsion and an increase flexion in the center of specimen. It engendered also an inhomogeneous deformation.

Since 1968, Pagano et al. have tried to solve the problems. They studied the jaw influence and its effect on the stress distribution in the specimen [4]. Wu et al. discussed the design of a rotary and articulated jaw for composite materials. This assembly allows the formation of a planar constraint by only changing the boundary conditions by allowing the rotation of the jaws [10]. The results of Halpin and Pagano were verified and extended by Richards et al and Rizzo et al. [5].

Pindera et al. [6] studied the effect of coupling extension/shearing in the anisotropic material behavior. Indeed, with fixed jaws the ends of the oriented specimens are fixed and when the coupling is applied [10], it generates a state of non-uniform stress. The specimen evaluated in S form. This result is verified experimentally and numerically and it is illustrated in Figs. 1 (B) and (C).



(A) (B) (C)

Fig. 1 Off-axis tensile test, (A) uniform state stress, (B) non-uniform state stress and (C) numerical simulation of non-uniform state stress [2]

Nin is the first who studied the evaluation of mechanical behavior of textile fabrics during the off-axis tensile test followed by Ng et al. [7], [8]. But they are only interested in effort and elongation at breaking.

Since 2006, Zouari et al. started off-axis tensile test analysis for textile clothing fabrics to characterize their anisotropic behavior in analogy with composite materials [2]-[9].

In this study, an experimental investigation was conducted to study the mechanical properties anisotropy of textile woven fabrics during an off-axis tensile test. We performed analysis of the global response of Effort/Elongation curves and local response in the center by image correlation using the grid method of textile woven behavior. Jaws influences are also analyzed.

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## II. MATERIALS AND METHODS

### A. Off-Axis Tensile Test

Off-axis tensile test will be carried for 4 textile woven fabrics shown in Table I where CF is the cover factor and VSF is the fabric specific volume.

A new design and fabrication of articulated jaws is used to allow specimen a free rotation in the normal direction and to improve off-axis tensile test.

Off-axis tensile test is performed with a constant displacement rate of 100mm / min. For each direction and each fabric, the test is repeated 5 times. A video camera was used to observe deformation in the central zone of the specimen during the test. 25 frames per test are used to analyze the deformation before breaking.

### B. Specimen

Fig. 2 presents respectively test specimen (A), camera position during off-axis tensile test (B) and fixed (C) and articulated jaws (D) used for testing. The specimen is cut out according to a direction forming an angle ψ with the warp direction (0°(warp), 15°, 30°, 45°, 60°, 75° and 90°(weft)).

Off-axis tensile test is performed according to warp, weft, oriented 15°, 30°, 45°, 60° and 75° directions with articulated jaws (AJ) and according to warp, weft, oriented 15° and 45° with fixed jaws (FJ).

TABLE I
FABRIC DESCRIPTION

| | | Fabric 1<br>T | Fabric 2<br>S4 | Fabric 3<br>ST | Fabric<br>S3 |
|---|---|---|---|---|---|
| | Fabric Structure | Plain | Twill 3/1 | Satin 4 (SatinTurk) | Twill 2/1 |
| Warp direction | Yarn fibers | 52% PES<br>48% C | 52% PES<br>48% C | 52% PES<br>48% C | 100% C |
| | Yarn Type | Twisted | Twisted | Twisted | Twisted |
| | Finesse (Nm) | 36/2 | 36/2 | 36/2 | 34/2 |
| | Count (Yarn/cm) | 26 | 24 | 24 | 29 |
| | Crimp (%) | 5,6 | 5,6 | 5,6 | 8,5 |
| Weft direction | Yarn fibers | 52% PES<br>48% C | 52% PES<br>48% C | 52% PES<br>48% C | 100% C |
| | Yarn type | Twisted | Twisted | Twisted | Simple |
| | Finesse (Nm) | 36/2 | 36/2 | 36/2 | 17 |
| | Count (Yarn/cm) | 24 | 24 | 24 | 17 |
| | Crimp (%) | 5,3 | 5,3 | 5,3 | 5,8 |
| | Area fabric (g/m$^2$) | 182 | 178 | 175 | 357 |
| | Thickness (mm) | 0,41 | 0,51 | 0,5 | 0,6 |
| | CF Fabric | 20,16 | 19,58 | 19,58 | 148 |
| | VSF (cm$^3$/g) | 2,25 | 2,87 | 2,86 | 21,44 |

## III. GLOBAL BEHAVIOR

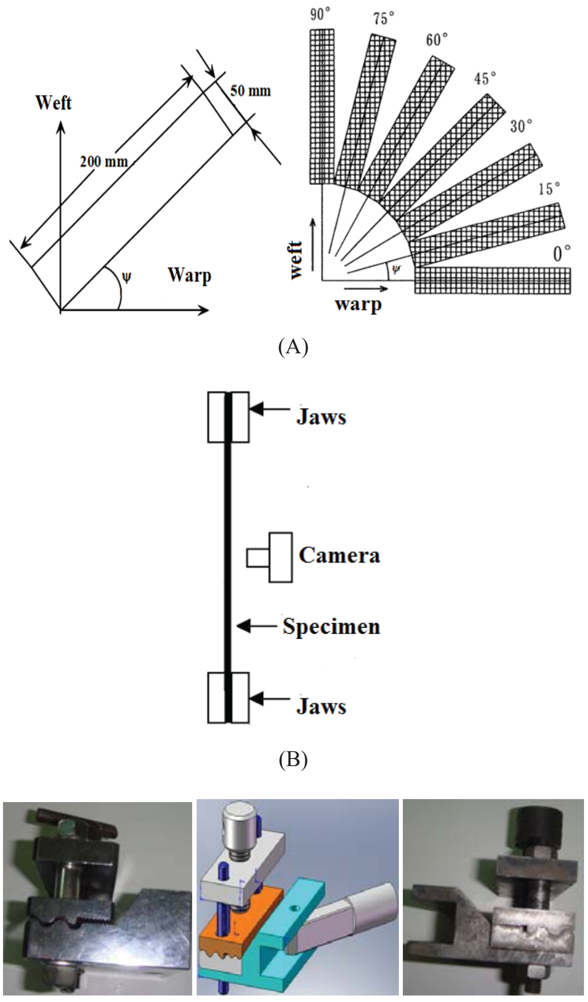
For global behavior, we studied jaws influence, breaking load (Frup), tensile elongation (EMT), tensile energy (WT) and linearity index (LT) along different direction for four textile woven fabrics.

### A. Jaws Effect

Comparing global experimental results obtained with FJ and AJ, we note a good repeatability for test specimens along warp, weft and oriented 45° directions. The dispersion was observed along 15° oriented direction. Table II presents the index of repeatability *r*(%) [2] and the variation of dispersion *Vr*(%) for four fabric where:

$$\boldsymbol{r}(\%) = \frac{\sqrt{\sum_{j}^{N}\left(\sum_{i}^{5}\frac{\left(\boldsymbol{F}_i - \bar{\boldsymbol{F}}_j\right)^2}{5}\right)}}{\sum_{j}^{N}\bar{\boldsymbol{F}}_j} \tag{1}$$

$$\boldsymbol{Vr}(\%) = \left(\boldsymbol{r}_{\mathrm{FJ}} - \boldsymbol{r}_{\mathrm{AJ}}\right) / \left(\frac{\boldsymbol{r}_{\mathrm{FJ}} + \boldsymbol{r}_{\mathrm{AJ}}}{2}\right) \tag{2}$$



(A)

(B)

(C) (D)

Fig. 2 Experimental Procedure (A) Test specimen (B) Camera position (C) Fixed jaws (D) Articulated jaws

TABLE II
INDEX OF REPEATABILITY AND VARIATION OF THE DISPERSION

| | | *r (%)* AJ | *r (%)* FJ | Both | *Vr* |
|---|---|---|---|---|---|
| T | 0° | 0,42 | 0,69 | 0,66 | 0,49 |
| | 90° | 0,88 | 0,78 | 1 | -0,12 |
| | 15° | 1,06 | 0,87 | 1,23 | -0,20 |
| | 45° | 0,79 | 0,48 | 0,72 | -0,49 |
| S4 | 0° | 0,62 | 0,47 | 0,68 | -0,28 |
| | 90° | 1,03 | 0,95 | 1,7 | -0,08 |
| | 15° | 1,60 | 1,40 | 9,5 | -0,13 |
| | 45° | 1,09 | 0,89 | 1,1 | -0,20 |
| ST | 0° | 0,75 | 0,50 | 1,03 | -0,40 |
| | 90° | 0,49 | 0,97 | 1,29 | 0,66 |
| | 15° | 1,41 | 2,05 | 5,36 | 0,37 |
| | 45° | 1,11 | 0,72 | 1,76 | -0,43 |
| S3 | 0° | 0,60 | 1,16 | 1,42 | 0,64 |
| | 90° | 1,27 | 1,12 | 4,77 | -0,13 |
| | 15° | 0,88 | 1,62 | 10,55 | 0,59 |
| | 45° | 0,56 | 1,07 | 1,21 | 0,63 |

### *B. Load/Strain Behavior*

We have a uniform deformation in the centers of specimens during off-axis tensile testing and non near jaws extremities. Fig. 3 presents experimental and numerical off-axis tensile test along 60° oriented direction. Articulated jaws minimize the folds in the center of specimen and their extremities.

Fig. 4 illustrates the breaking load (Frup) and tensile elongation (EMT) for four textile woven fabrics. The breaking load is relatively high and the tensile elongation is greater along warp, weft and 45° oriented directions. The influence of anisotropy on textile woven fabric breaking load and tensile elongation is shown in Fig. 4.

Table III presents the tensile energy (WT) and linearity index (LT) along all directions for four textile woven fabric defined as:

$$WT=\int_{0}^{AL_{rup}} F\,dAL \text{ and } LT(\%)=\frac{2\,WT}{EMT.\,F_{rup}} \quad (3)$$

The tensile energy is relatively high along of 45° oriented direction and the linearity index is superior along of warp and weft direction for four textile Woven fabric.

Fig. 5 gives load–extension average curves off-axis tensile test before buckling respectively for four fabrics in various directions. It illustrates the anisotropic behavior of the textile fabric with different angles from loading to the warp direction. We observe more extensibility along of the direction oriented 45 ° to the other directions. As can be seen in Table III and in Fig. 5 high anisotropy in Load-Extension behavior is a characteristic of most of the studied fabrics. Most textile woven fabric are not balanced, even for twill and satin, but we notice in global behavior for S4, ST and S3 a symmetry in the mechanical behavior with respect to the diagonal 45° oriented direction. The textile woven fabric mechanical behavior depends on the loading direction.

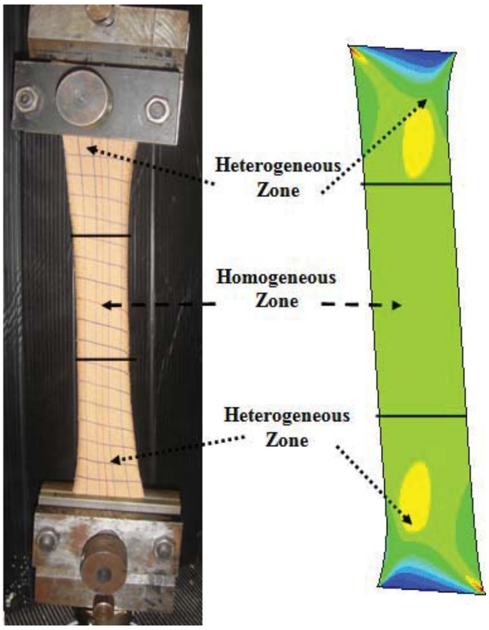
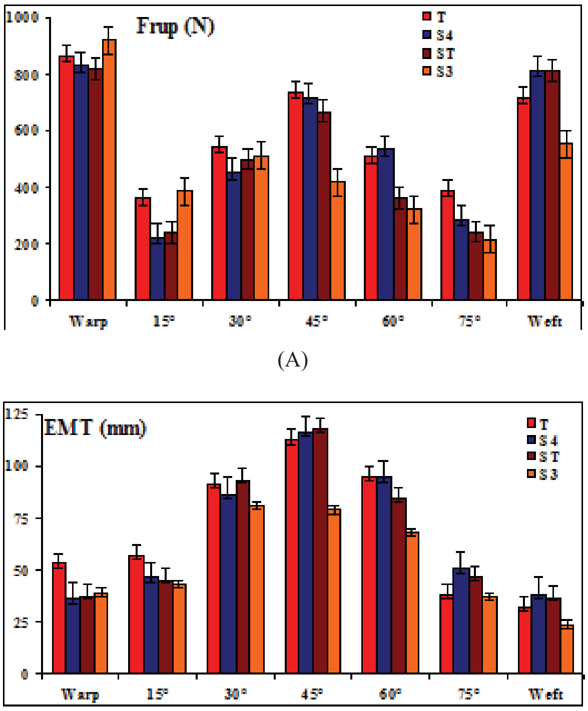


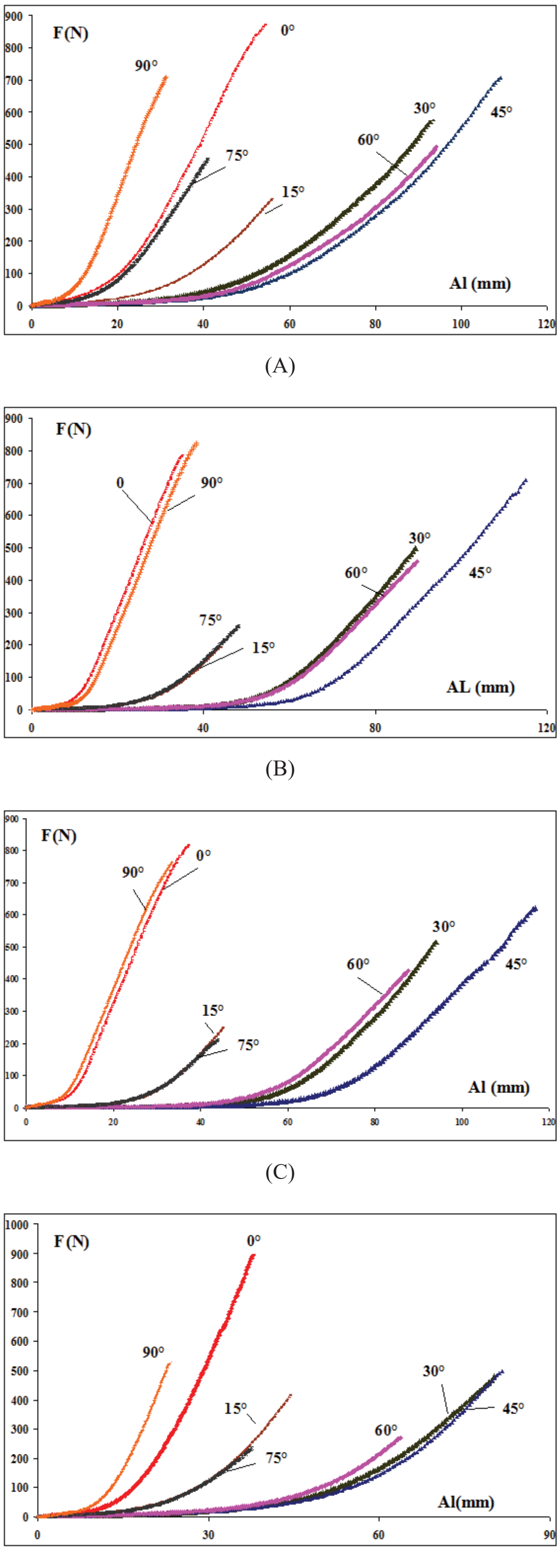
Fig. 3 Off-axis tensile test oriented 60° S3



(A)

(B)

Fig. 4 (A) Breaking load (Frup) and (B) Tensile elongation (EMT) fabric 1, 2, 3 and 4



(A)

(B)

(C)

(D)

Fig. 5 Off-axis Load–extension curves before buckling, (A) T, (B) S4, (C) ST, (D) S3

## IV. Local Behavior

An image correlation by the grid method [2] is used for the measurement of strain tensor components in the central area of the specimen. Only the test near the average for each direction and each textile woven fabric is studied.

For local behavior, we studied jaws influence, longitudinal strain $\varepsilon_L$, transverse strain $\varepsilon_T$ and shear $\varepsilon_{LT}$ as along of different direction for four textile woven fabrics. We analyze the jaws influence on the evaluation of the longitudinal strain and transversal strain along warp, weft and 45° and 15° oriented directions.

Fig. 6 presents measuring position, Load/longitudinal strain $\varepsilon_L$ curves for fabric 4 along 45° and 15° oriented directions and Load /transverse strain $\varepsilon_T$ curves for fabric 2 along warp and 15° and 45° oriented directions.

When tensile stress is applied along loading direction, compression induces in the width. The grid allows transverse strain analysis.

### *A. Longitudinal and Transversal Strain*

Jaws have no influence on longitudinal strain along warp, weft and 45° oriented directions. It's effect transverse strain results essentially along 45° and 15° oriented directions

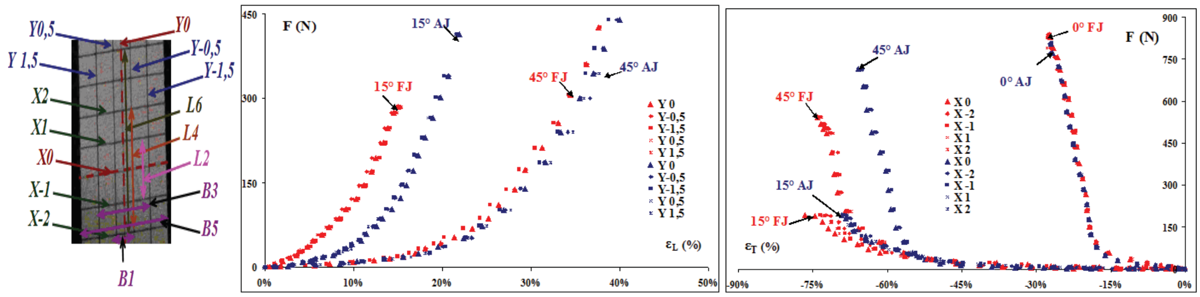
For 15° oriented direction, local longitudinal strain obtained with AJ is more important than this obtained with FJ Inversely, transverse strain obtained with AJ is less than this obtained with FJ. Experimental results test with AJ have less dispersion and have more repetitiveness than this with FJ. This experimental observation is valid for four tested textile woven fabrics.

Longitudinal strain and transverse strain evolution were not linear as a function of the effort. Then textile woven fabric has a non-linear mechanical behavior

Load/(longitudinal strain and transverse strain) curves obtained with different angles of loading the warp is illustrated in Fig. 7 for four textile woven fabrics. Extensibility is more great along longitudinal and transversal for oriented directions then warp and weft directions. It is due to shearing component behavior.

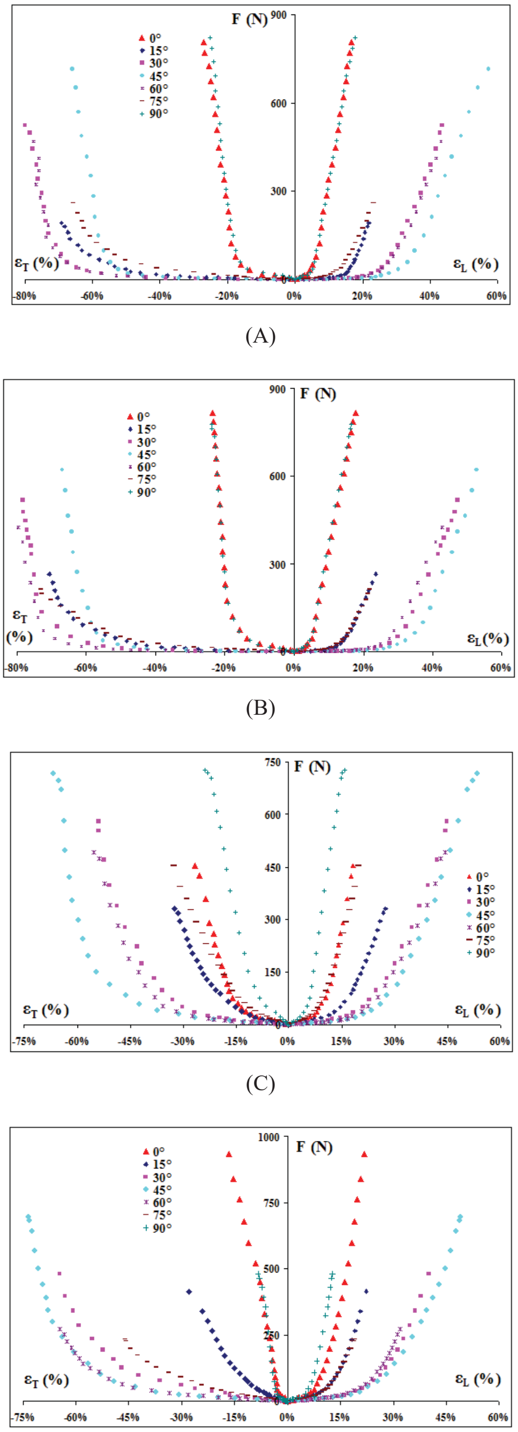
TABLE III
TENSILE ENERGY (WT) AND LINEARITY INDEX (LT)

| | | Fabric 1 | | Fabric 2 | | Fabric 3 | | Fabric4 | |
|---|---|---|---|---|---|---|---|---|---|
| | | WT (Nmm) | LT (%) | WT (Nmm) | LT (%) | WT (Nmm) | LT (%) | WT (Nmm) | LT (%) |
| 0° | E1 | 16094 | 69 | 11701 | 77 | 11808 | 80 | 9743 | 53 |
| | E2 | 16526 | 70 | 12553 | 81 | 12668 | 81 | 9205 | 54 |
| | E3 | 14540 | 66 | 12281 | 81 | 12093 | 80 | 9091 | 51 |
| | E4 | 16330 | 68 | 10969 | 76 | 11823 | 81 | 9498 | 53 |
| | E5 | 14377 | 66 | 10829 | 75 | 11167 | 77 | 9303 | 53 |
| | Moy | 15574 | 68 | 11667 | 78 | 11912 | 80 | 9368 | 53 |
| 90° | E1 | 9050 | 71 | 9517 | 61 | 12559 | 93 | 3300 | 46 |
| | E2 | 7151 | 72 | 9138 | 58 | 13693 | 92 | 3025 | 46 |
| | E3 | 7772 | 70 | 9375 | 59 | 13910 | 92 | 3160 | 49 |
| | E4 | 8438 | 74 | 9871 | 63 | 12685 | 89 | 2832 | 45 |
| | E5 | 9347 | 76 | 10465 | 76 | 12408 | 87 | 2797 | 45 |
| | Moy | 8352 | 72 | 9673 | 63 | 13051 | 91 | 3023 | 46 |
| 45° | E1 | 25253 | 58 | 19328 | 45 | 15383 | 40 | 5512 | 40 |
| | E2 | 19305 | 45 | 14469 | 41 | 17393 | 42 | 6194 | 34 |
| | E3 | 18485 | 47 | 18365 | 44 | 14291 | 39 | 5432 | 37 |
| | E4 | 26588 | 74 | 17014 | 40 | 14838 | 38 | 5877 | 38 |
| | E5 | 24634 | 56 | 17762 | 40 | 15132 | 38 | 6049 | 30 |
| | Moy | 22853 | 56 | 17388 | 42 | 15408 | 39 | 5813 | 36 |
| 15° | E1 | 5083 | 49 | 1752 | 42 | 2702 | 44 | 3722 | 48 |
| | E2 | 4744 | 51 | 1946 | 40 | 2378 | 44 | 3711 | 41 |
| | E3 | 4491 | 37 | 2075 | 41 | 2836 | 43 | 3201 | 47 |
| | E4 | 5131 | 51 | 2031 | 41 | 2643 | 55 | 3732 | 44 |
| | E5 | 4987 | 52 | 2226 | 31 | 1947 | 40 | 4193 | 46 |
| | Moy | 4887 | 48 | 2006 | 39 | 2501 | 45 | 3712 | 45 |
| 30° | E1 | 11277 | 45 | 5598 | 29 | 9668 | 35 | 7851 | 39 |
| | E2 | 10454 | 46 | 5384 | 33 | 7366 | 35 | 8403 | 41 |
| | E3 | 11875 | 48 | 6177 | 26 | 7838 | 34 | 9664 | 40 |
| | E4 | 13158 | 49 | 5330 | 28 | 8710 | 36 | 7989 | 42 |
| | E5 | 11478 | 47 | 5854 | 32 | 6529 | 34 | 8385 | 42 |
| | Moy | 11648 | 47 | 5669 | 29 | 8022 | 35 | 8458 | 41 |
| 60° | E1 | 13433 | 47 | 5838 | 35 | 5432 | 36 | 3317 | 38 |
| | E2 | 10302 | 46 | 10802 | 41 | 3513 | 33 | 3270 | 43 |
| | E3 | 9437 | 45 | 13607 | 42 | 4291 | 36 | 6992 | 43 |
| | E4 | 10790 | 46 | 8117 | 38 | 6716 | 36 | 3573 | 40 |
| | E5 | 11769 | 44 | 12230 | 42 | 7435 | 37 | 6075 | 42 |
| | Moy | 11146 | 46 | 10119 | 40 | 5478 | 36 | 4646 | 41 |
| 75° | E1 | 2968 | 53 | 2764 | 44 | 1994 | 40 | 1982 | 45 |
| | E2 | 3253 | 51 | 3349 | 46 | 3808 | 52 | 1349 | 48 |
| | E3 | 3844 | 55 | 3796 | 47 | 2208 | 44 | 2090 | 49 |
| | E4 | 4990 | 54 | 3518 | 44 | 1996 | 43 | 1185 | 48 |
| | E5 | 4793 | 56 | 3110 | 49 | 2559 | 44 | 2825 | 46 |
| | Moy | 3970 | 54 | 3307 | 46 | 2513 | 44 | 1886 | 47 |



(A) (B) (C)

Fig. 6 Measuring position (A), Load (longitudinal strain $\varepsilon_L$) for fabric 4 (B) and Load (transverse strain $\varepsilon_T$) for fabric 2(C)



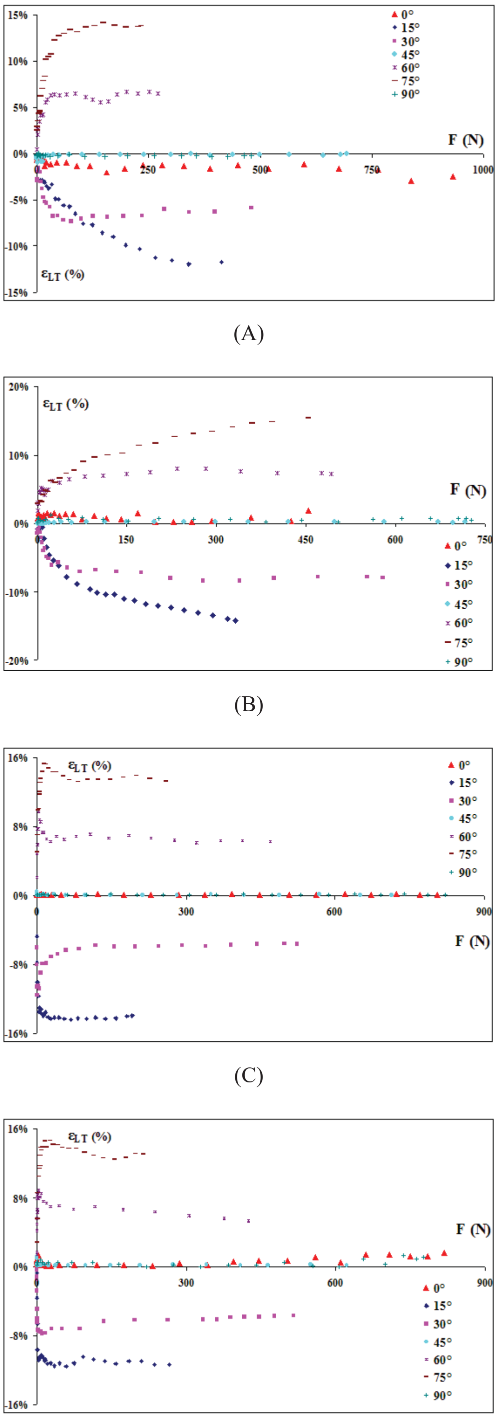
(A)

(B)

(C)

(D)

Fig. 7 Load (longitudinal strain $\varepsilon_{11}$, transverse strain $\varepsilon_{22}$) for fabrics 1 (A), 2 (B), 3 (C) and 4 (D)



(A)

(B)

(C)

(D)

Fig. 8 Shear (Load) for fabrics 1 (A), 2 (B), 3 (C) and 4 (D)

### *B. Shear*

Contrary to uniaxial and classical tensile test, off-axis tensile test generates a shear compound. Articulated jaws MA allow specimen rotation consequently a greater freedom of yarns slip and permit this shearing.

Shear/Load curves obtained with different angles of loading to the warp is illustrated in Fig. 8 for four textile woven fabrics with MA.

The shear evolution is not linear as a function of the effort. Shearing is approximately zero along warp, weft and 45° oriented directions. It is negative along 15° and 30° oriented directions and it is positive along 75° and 60° oriented directions.

## V.CONCLUSION

The ability of textile fabric to support effort and stress at an angle other than two principal directions is important in structures used in breaking load technical applications. In this work, a new experimental method of off-axis tensile testing has been developed to characterize textile woven fabric anisotropy behavior. Jaws effects on the mechanical behavior of textile woven fabrics have been studied for four fabrics with different structure. Anisotropy is naturally connected with the anisotropy of the woven fabric structure. Experimental process has revealed that the fixed jaws influence the off-axis tensile response. To perform homogeneous test, articulated jaws were used to make shear component behavior possible.

Anisotropy of textile woven fabric behavior has been represented in global and local behavior:

- Global anisotropy was illustrated in breaking load (Frup), tensile elongation (EMT), tensile energy (WT) and linearity index (LT).
- Local anisotropy was observed on longitudinal strain $\varepsilon_L$, transverse strain $\varepsilon_T$ and shear $\varepsilon_{LT}$ as a function of Load.

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