

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 ϵ_L , transverse strain ϵ_T and shearing ϵ_{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.

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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).

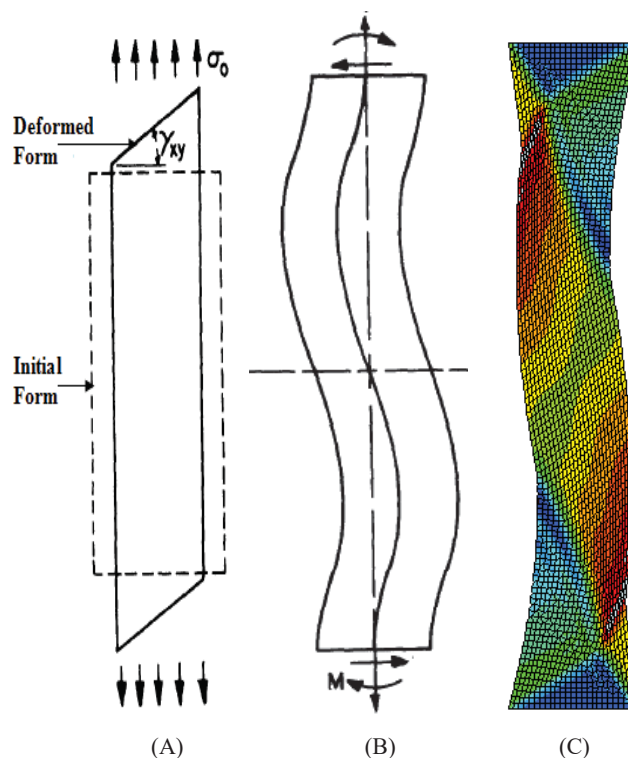


Fig. 1 Off-axis tensile test, (A) uniform state stress, (B) non-uniform state stress and (C) numerical simulation of non-uniform state stress [2]

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.

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	Fabric 2	Fabric 3	Fabric
		T	S4	ST	S3
Fabric Structure		Plain	Twill 3/1	Satin 4 (SatinTurk)	Twill 2/1
Warp direction	Yarn fibers	52% PES 48% C	52% PES 48% C	52% PES 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 48% C	52% PES 48% C	52% PES 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:

$$r(\%) = \frac{\sqrt{\sum_j \left(\frac{\sum_i (F_i - \bar{F}_j)^2}{5} \right)}}{\sum_j \bar{F}_j} \quad (1)$$

$$Vr(\%) = (r_{FJ} - r_{AJ}) / \left(\frac{r_{FJ} + r_{AJ}}{2} \right) \quad (2)$$

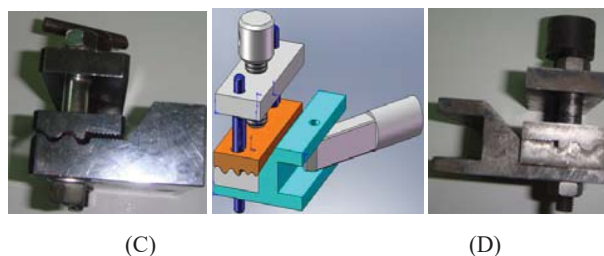
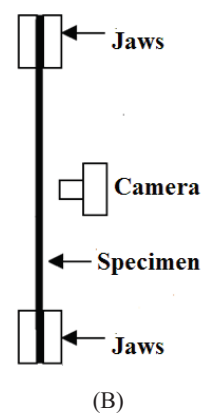
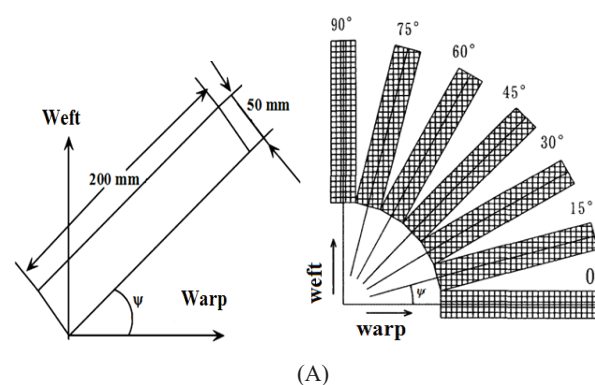


Fig. 2 Experimental Procedure (A) Test specimen (B) Camera position (C) Fixed jaws (D) Articulated jaws

TABLE II
 INDEX OF REPEATABILITY AND VARIATION OF THE DISPERSION

		r (%) AJ	r (%) FJ	Both	V_r
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:

$$WT = \int_0^{AL_{rup}} F dAL \text{ and } LT(\%) = \frac{2 WT}{EMT \cdot F_{rup}} \quad (3)$$

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.

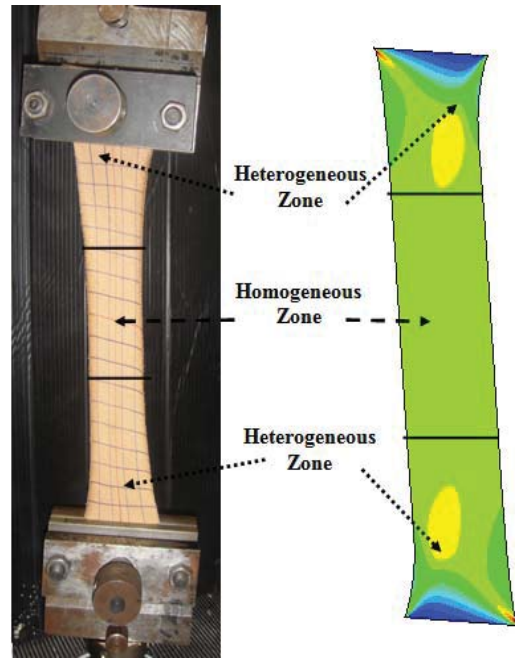
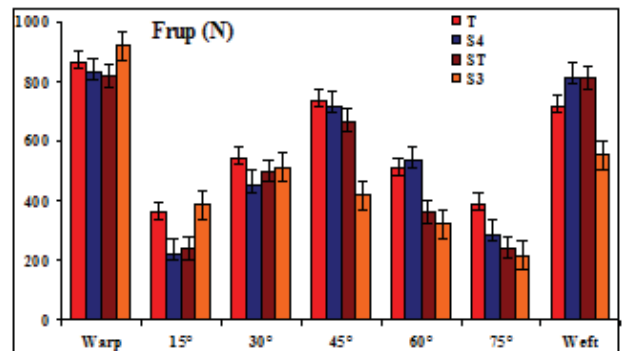
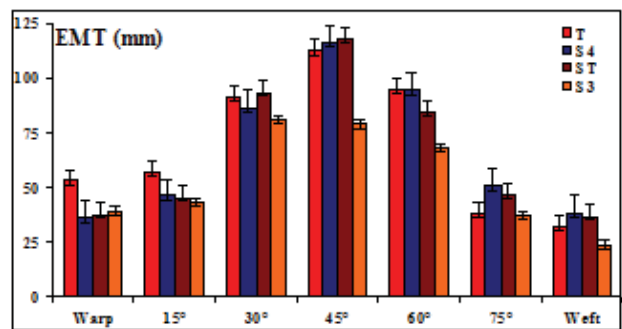


Fig. 3 Off-axis tensile test oriented 60° S3

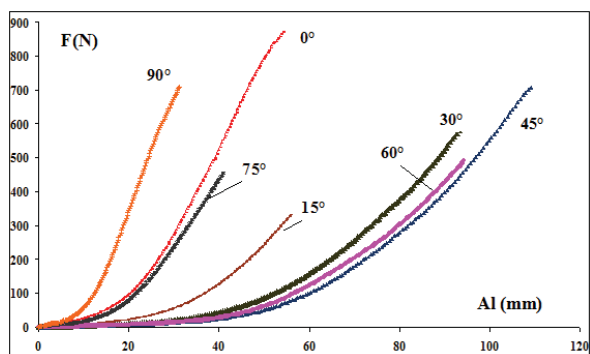


(A)

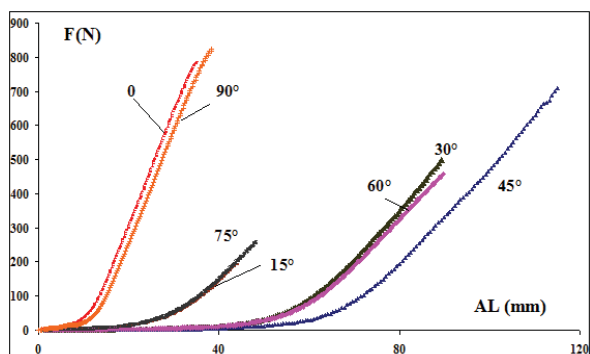


(B)

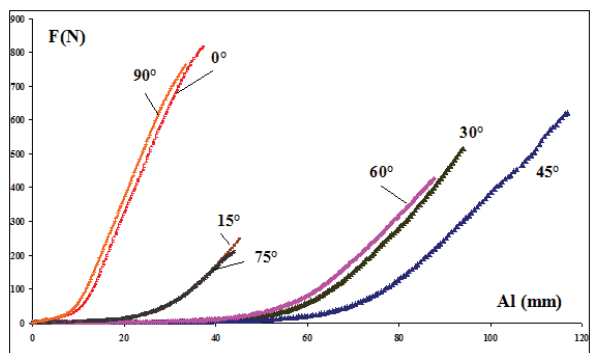
Fig. 4 (A) Breaking load (Frup) and (B) Tensile elongation (EMT) fabric 1, 2, 3 and 4



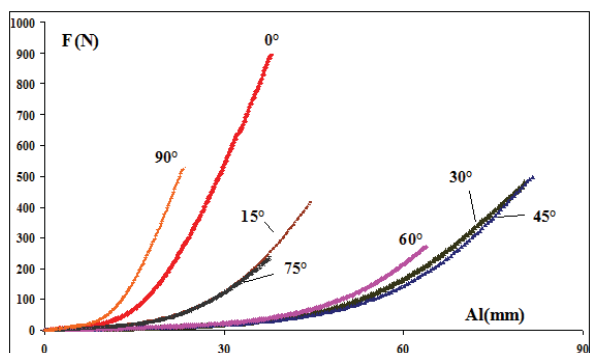
(A)



(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 ϵ_L , transverse strain ϵ_T and shear ϵ_{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 ϵ_L curves for fabric 4 along 45° and 15° oriented directions and Load /transverse strain ϵ_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 than 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		Fabric 4	
		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

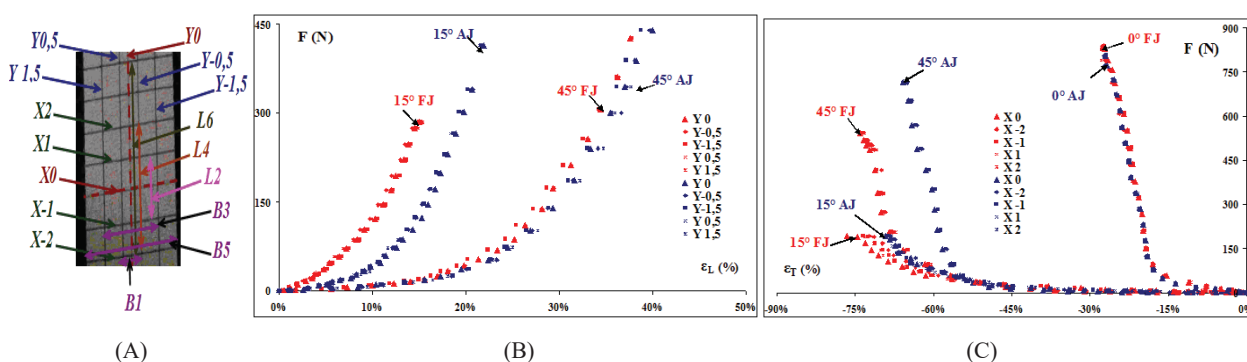
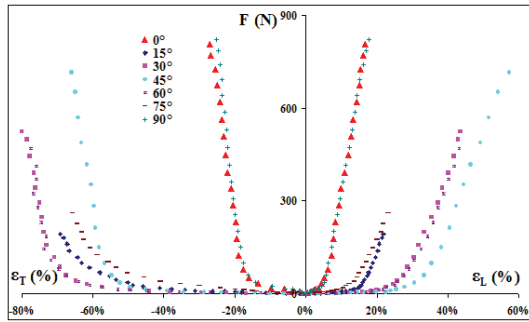
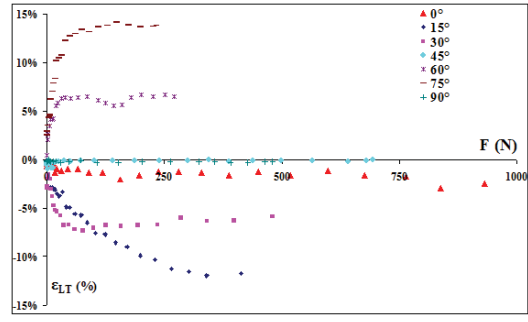


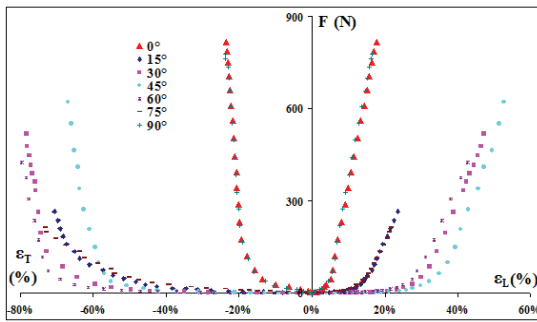
Fig. 6 Measuring position (A), Load (longitudinal strain ϵ_L) for fabric 4 (B) and Load (transverse strain ϵ_T) for fabric 2(C)



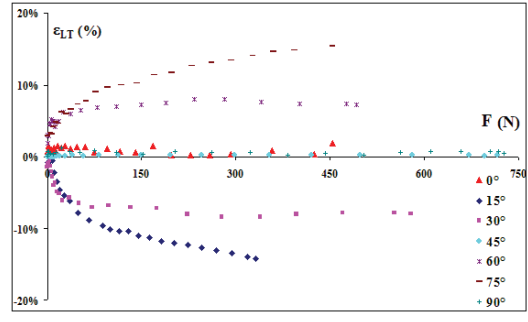
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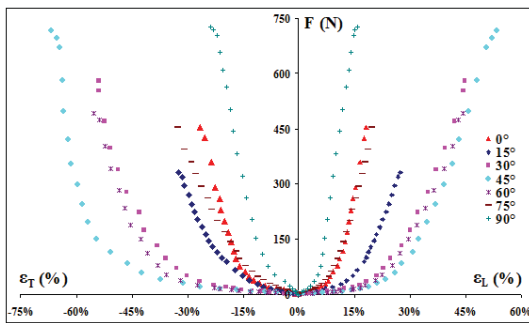
(A)



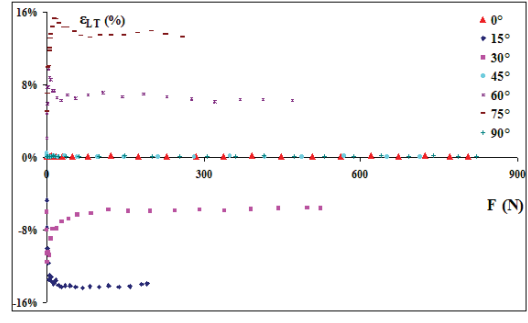
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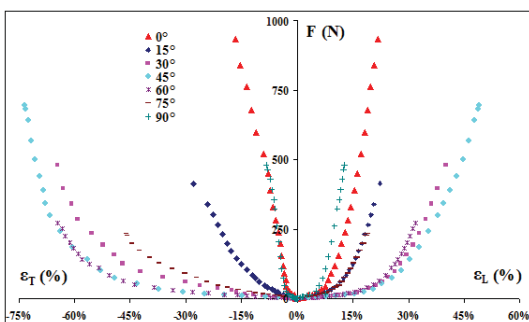
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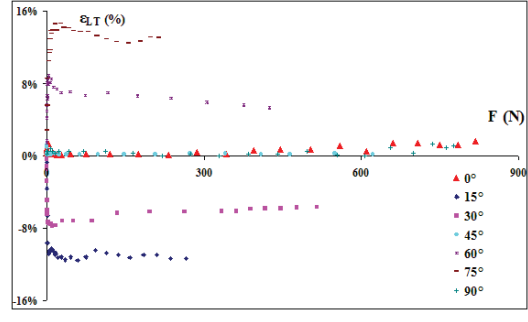
(C)



(C)



(D)



(D)

Fig. 7 Load (longitudinal strain ϵ_{11} , transverse strain ϵ_{22}) for fabrics 1 (A), 2 (B), 3 (C) and 4 (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 ϵ_L , transverse strain ϵ_T and shear ϵ_{LT} as a function of Load.

REFERENCES

- [1] M.P. Nemeth, C.T. Herakovich, D. Post, "On the off-axis tensile test for unidirectional composites. *Interim rept. no. 28*, Apr. 1982.
- [2] R. Zouari, "Analyse du comportement mécanique d'un tissu en traction off-axis," *Editions universitaires européennes*, 2014.
- [3] N.J. Pagano, J.C. Halpin, "Influence of End Constraint in the Testing of Anisotropic Bodies," *Composites materials*, 1968, V2, N4, page 18-31.
- [4] M.P. Nemeth, C.T. Herakovich, D. Post, "On the off-axis tensile test for unidirectional composites". 1982. *Virginia Polytechnic Institute and State University Engineering Science and Mechanics Blacksburg, National Aeronautics and Space Administration Hampton*. privet publication.
- [5] F. Pierron, E. Alloba, Y. Surrel, A. Vauran, "whole-field assessment of the effect of boundary conditions on the strain field in off-axis tensile testing of unidirectional composite," *Compos Sci Technol*, 1998, V 58, pp 1939-1947,
- [6] G. Ping, K. Greenwood, "The Scope for Fabric Engineering by Means of the Weave," *J. Text I*, 1986 V 77, N2, pp 88-103,
- [7] P. Ning, M.Y. Yoon, "Structural anisotropy, Failure criterion and shear strength of woven fabrics," *Text Res J*, 1996, V66, N4, pp 238-244.
- [8] S.P. Ng, R. Ng, W. Yu, "Bilinear approximation of anisotropic Stress-Strain properties of woven fabrics." *RJTA*, 2005, V9, pp1-15.
- [9] R. Zouari, S. Ben Amar, A. Dogui, "Experimental and numerical analyses of fabric off-axes tensile test," *J Text I*, Jan 2010, V. 101, N 1, pp 58-68.
- [10] C.Y. Ho, "A new end tab design for off-axis tensile test of composites materials," *HTMIAC Report 5*, 1987.
- [11] A. Dogui, "Two-Dimensional large-strain kinematics: application to tensional and off-axis tensile tests," *J M T A*, 1988, V. 7, N 1, pp 43-64.



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