Development of the 3D multiaxis weaving technology and geometrical characterization of the produced performs

A. R. Labanieh[a*], X. Legrand[a], V. Koncar[a], D. Soulat[a]

[a] *GEMTEX, ENSAIT, Université de Lille 1, 2 Allée Louise et Victor Champier 59100 Roubaix*
**e-mail : ahmad.labanieh@ensait.fr*

Keywords: textile reinforcement, 3D multiaxis weaving, geometric characterization.

Abstract
Novel technique to produce 3D multiaxis woven preform has been developed and presented in this paper. Geometric characterization for the produced samples using the advanced machine prototype has been carried out based on analyzing the captured micrographs for the cross section of the impregnated samples. The geometry of the yarns within the structure (yarns cross section shape and area and the yarns path) was investigated in addition to measurement of geometric parameters of the yarns and the unit cell. The acquired geometric data serve also in construction of a geometric model for this structure and better understanding the effect of the structure geometry on its mechanical performances.

1. Introduction

The laminate composite material, made by stacking several layers of 2D fiber reinforcement without fibers through thickness link, has high sensibility to delamination fracture and low impact resistance [1,2]. Therefore, many studies focus on evolving the 3D fiber reinforced composite structure by working on insertion of fiber reinforcement in the through thickness direction using different textile technologies. The 3D weaving technology appeared as good solution, where it allows the fabrication of continuous woven preforms composed of several in-plane yarns layers (warp in 0° and filler in 90°) linked together by yarns passing in the through thickness direction of the fabric called binder yarns or weaver yarns. The 3D woven composite showed high fracture toughness and high delamination resistance compared to equivalent laminates composites [3,4]. However, the abrasion of the yarns on loom machineries and the waviness of the in-plane yarns in the through thickness of preform cause degradation of the in-plane properties [5,6,7], in addition to the impossibility to align in-plane yarn other than 0° and 90°. Therefore, the 3D multiaxis weaving technology has been developed to enable insertion of in-plane fiber reinforcement in a direction +/-θ° in addition to 0° and 90° [8,9]. To assess the effect of the biases yarns on the elastic properties of composite, numerical mechanical analyses for the 3D multiaxis woven composite has been earlier executed [10] after construction of predictive geometric model [11]. A significant improvement regarding the in-plane out-of-axis performance and the shear properties were noticed for the 3D multiaxis woven composite when compared to equivalent 3D orthogonal woven composite. That encouraged to developing this weaving technology. Several patents [12] have been published dealing with this technology, but they are still under development and require more optimization. In this paper, the principle of the developed prototype of multiaxis weaving loom is presented with identification of the geometric properties of fabricated samples.

2. Multiaxis 3D weaving machine

2.1. Description of the multiaxis 3D woven preform

The multiaxis 3D woven preform is derived from the 3D orthogonal woven preform, in which several layers of in-plane no-interlaced yarns (oriented in 0° or 90°) are linked together only by binder yarns passing through whole the thickness of the fabric for each column of weft yarns. The multiaxis architecture possesses additionally in-plane biases yarns oriented in +θ° and –θ°. Thus, this preform was defined as "5-axis" denoting the axis of the constitutive yarns of the preform, Figure 1.

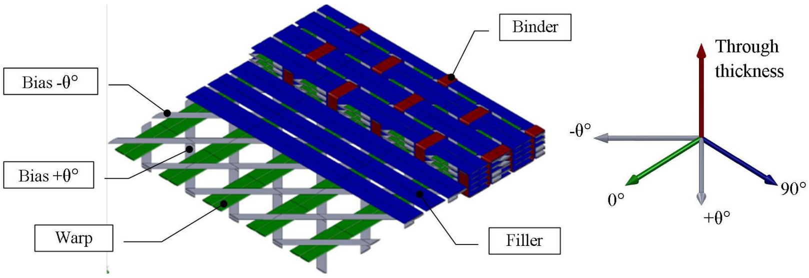

Figure 1: Schematic for the multiaxis 3D woven preform illustrates the 5 axial yarns structure.

2.2. Developed techniques in the multiaxis 3D weaving machine

As the 3D orthogonal interlock weaving technology in which multiple filler yarns are inserted simultaneously in each weaving cycle, the multiaxis 3D weaving technology requires, additionally, assuring the +/-θ° orientation of the biases yarns within the structure. Therefore, the biases yarns are translated transversally to the longitudinal axis of the loom one step for each weaving cycle, as shown in figure 2. This transversal translation movement should be with respect to creating a proper gap through which the binder yarns could be inserted at each weaving cycle without crossing the other in-plane yarns to avoid abrasion and rupture of these yarns. That implies the necessity of exact controlling the position of biases yarns and warp yarns in the weaving zone to create the proper gaps. All the patents published in this domain focus on realizing this transversal translation of the biases yarns. The proposed mechanisms produce prefoms containing two successive layers of biases yarns in opposite orientation +/-θ° without the possibility to insert warp layer between them and they are limited concerning the possible number of layers. The importance of introducing warp layer between two opposite successive layers of biases yarns is referred to decrease the delamination stresses that could appear between them at the free edge of preform, according to mechanics of laminate composite [13,14], in the case of high angle between two successive layers.
In this project, the guide blocks technique has been used to control the movement of biases yarns. In this technique, each individual bias yarn pass through one guide block. The total of guide blocks displace together in closed cycle, when guide block arrives to extreme position in the row, it move up/down to the next level, so, the associated yarn changes its orientation from +θ° to -θ°. A warp yarns layer is inserted between the two successive opposite biases layers by passing through the holes of fixed bar and all the guide blocks move around it thanks to the special shape of the guide blocks and the bar. Otherwise, the transversal translation of biases yarns on the weaving machine implies adapting the other mechanisms required for weaving process.

Five samples of multiaxis 3D woven architecture have been fabricated using this developed prototype with variation of the linear density (denoted μ) of the used yarns and their number (denoted n^{uc}) in the preform. All samples have the same number and order of layers as following: 90°/ 0°/ -θ°/ 0°/ +θ°/ 90°/ +θ°/ 0°/ -θ°/ 90°, and the detailed manufacture and weaver parameters are listed in table 1.

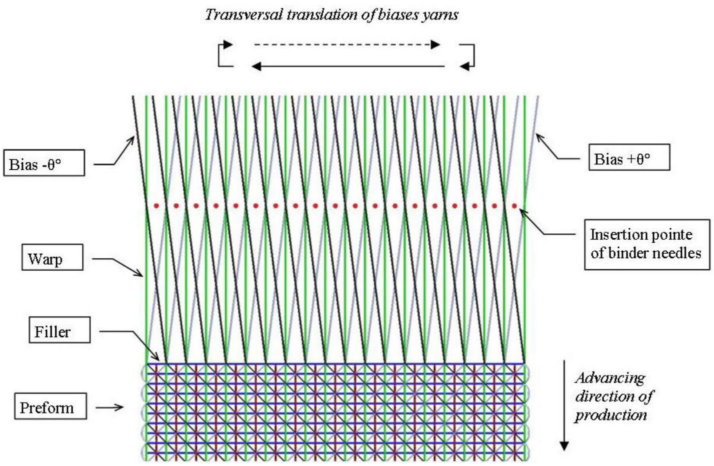

Figure 2: trajectory of yarns in the weaving zone.

3. Geometrical characterization

The geometrical characterization of the fabricated samples is necessarily required to identify the geometry of the component yarns within the structure and evaluate their geometrical parameters. This evaluation will help, in the next work, on the first side to assess the effect of the architecture, the manufacture parameters and the weaving parameters on the preform geometry and on another side to evaluate their influence on the mechanical perormance. Furthermore, this characterization aids to re-evaluate the earlier predictive geometric model towards construct a more accurate RVE, serving in the mechanical modeling, as well to improve the weaving process.

The geometrical characterization involves the microscopic observation of the component yarns inside the structure and measuring the characterizing geometric parameters of the unit cell (fiber volume fraction, proportion of each yarn sets, preform thickness, repeat dimensions) and of the yarns (cross section dimensions and area, crimp of yarns).

3.1. Microscopic observation

The optical method could be used to observe paths and cross sections of the yarns inside the preform by capturing images for the preform cross sections. But, cutting and manipulating the dry preform lead to distortions of shapes and positions of yarns because of the poor cohesion between fibers within the yarn. Therefore, the samples have been impregnated using a transparent resin allowing the distinction between the yarns cross sections. Then, they have been cut in four specific planes. These cut planes have been specified depending on the position of the binder yarn and the crossing point between the two opposite biases yarns. Two cut planes are in warp direction, one is through a binder yarn (denoted warp-a) and the other is at the middle between two binder yarns (denoted warp-b). The other two planes are in filler direction, one is when the crossing point of the two opposite biases yarns (+θ° and –θ°) is in the plane of binder yarn (filler-a) and the other is when this crossing point is between two binder yarns (filler-b).

	yarns	Fiber material	Unit	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
$\mu\, x\, n^{uc}$	Warp	E-Glass	g/Km	900 x 3	900 x 3	900 x 3	2400 x 2	2400 x 3
	Filler	E-Glass	g/Km	900 x 2	900 x 2	900 x 2	2400 x 2	2400 x 2
	Biases	E-Glass	g/Km	900 x 1	900 x 2	900 x 1	2400 x 1	2400 x 2
	Binder	Aramid	g/Km	172	172	172	172	172
binder per cm	λ_b^s		1/cm	1,628	1	1	1	1
	λ_b^f		1/cm	2	1	1	1	1

Table 1: manufacture and weaver parameters of five produced samples.

3.2. Fiber volume fraction measurement

Two experimental methods could be followed [15]: density measurement method and resin removal method. We followed the density measurement method involving the measurement of the density of the produced composite, in addition to know the density of the component yarns and that of the used resin. Then, the equation (1) could be applied to evaluate the fiber volume fraction. Where, ρ_c (g/cm^3) is the density of composite sample, ρ_f is the density of used fiber, ρ_m is the density of used resin and FVF is fiber volume fraction (%).

$$FVF(\%) = \frac{\rho_c - \rho_m}{\rho_f - \rho_m} . 100 \tag{1}$$

3.3. Crimp measurement

The yarns are undulated into the through thickness of the fabric due to the interlacement between the warp and filler yarns as in the 2D fabric or between warp and filler yarns from different layers of fabric as in the 3D angle interlock. Further, the in-plane yarns could be also misaligned in the fabric plane due to inappropriate weaving setting. Crimp percentage term is used to express the measure of this waviness in yarns [16].

The crimp of in-plans yarns into the through thickness of fabric could be arisen even when no-interlacement between in-plane yarns as for 3D orthogonal fabric by binder yarn pushing filler yarns into through thickness also when compacting the preform through consolidation.

The waviness in the through thickness direction of the yarns affects strength, ductility and fatigue life of woven composite [6]. Further, the misalignment of in-plane yarns from load direction contributes to the formation of the kink band when compression of composite structure [6]. Therefore, it is important to quantify the crimp of in-plane yarns in the composite architectures. Further, this quantification aids to define the path of the yarns within the structure through construction the geometric model.

Here, the crimp percentage for warp yarns, in through thickness direction of preform, is measured on the captured micrographs. On the cut plane “warp-b” for all produced samples, the length of center line of the warp yarns (*L'*) is measured on a known straight distance (*L*). The centre line is defined by spline passing through the midpoint of vertical segments defining the thickness of the yarn, as illustrated in Figure 3. Then from the ratio of the difference between the two lengths to the length (*L*) the crimp percentage is computed. In the same manner, the crimp of filler yarns was measured on the two cut plane “filler-a” and “filler-b”.

3.4. Packing factor

The packing factor (pf) of the filaments inside the constitutive yarns indicates the contact pressure applied by the surrounding yarns. That varies depending on interlacement architecture of yarns and the fiber density in the unit cell. The higher value corresponds to higher pressure on the perimeter of the yarn so smaller cross section area. Otherwise, the packing factor parameter is essential to assigning the material properties of yarns in the mechanical modeling since the yarn is considered as a composite material of fiber and matrix. This parameter could be calculated by computation method consisting of implementing the following equation based on the measured area of the yarns cross section (S [mm²]) in addition to the linear density of the yarns (μ [g/Km]) and the fiber density (ρ [g/cm^3]).

$$pf = \frac{\mu 10^{-3}}{S\,\rho} \tag{2}$$

4. Results and Observations

4.1. Measured parameters

On each micrograph, the yarns cross section is outlined and its area is measured using image-j software tools, Figure 3. Also, the two dimensions; width (l) and height (h) of each yarn cross section are measured then the aspect ratio (AR) between these two dimensions is computed. In the same manner, the dimensions of the unit cell (Lw, Lf, H) for each sample are measured. The fiber volume fractions of the five preforms were measured by “the density measurement method”, and the results are reported in the table 2, where, the density of the E-glass fiber and aramid fiber was 2.58gr/cm^3 and 1.44gr/cm^3 respectively, from the provided data sheet, while the density of the used matrix was 1.142gr/cm^3. The mean of the packing factor for the yarns in the five samples is computed by equation (2) after measurement of the yarns cross section area, Table 3.
A variation in order of 3.5% to 7% was noted for the total thickness values between the four micrographs of each sample. The higher thickness is at “filler-a” and “warp-a” planes where the binder yarn pass over the crossing of the two biases yarns (-θ° and +θ°), whereas the lower thickness is at filler-b and warp-b where the crossing of the two biases yarns is between two binder yarns.

4.2. Crimp percentage of in plane yarns

The mean and the standard deviation of the crimp percentage for warp yarns and weft yarns are listed in Table 4.
As explained earlier, in the multiaxis 3D woven architecture, there is no interlacement between the in-plane yarns that is why the measured crimp percentage for warp and middle (inner) filler yarn is low whereas the extreme (outer) filler yarn shows higher crimp resulting from the binder yarn, passing over it. With less yarns gap, the extreme filler yarn experiences higher waviness at filler-b plane where the biases yarns crossing is not on binder yarn plane, so binder is more able to push the outer filler yarns toward the preform centre. That is corresponding to the thickness measurement results where lower thickness value is obtained on filler-b plane. In the 2D plain fabric, the crimp percentage of the warp and filler yarns is around 3-5%. Thus, the crimp of inner in-plane yarns, in through-thickness direction of preform, could be negligible for this architecture.

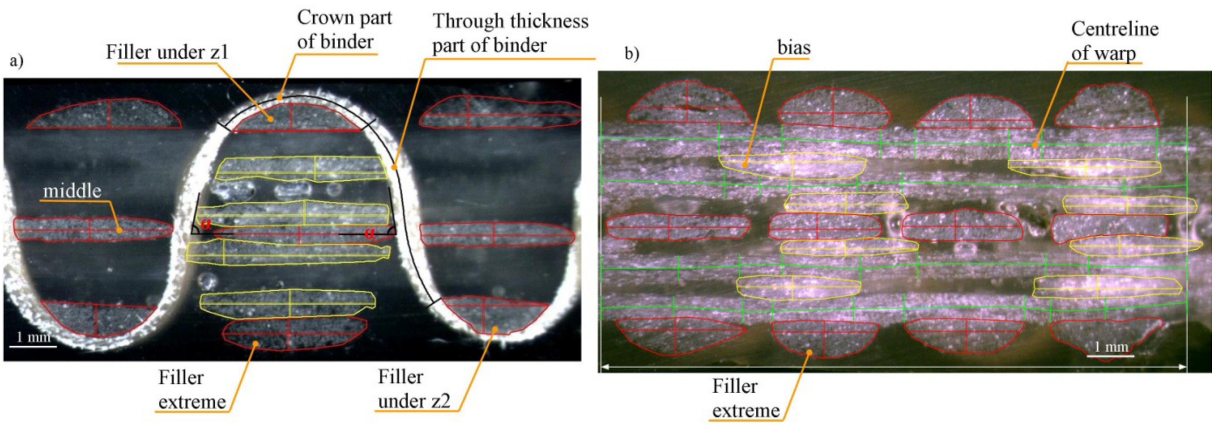

Figure 3: micrographs of cross sections of sample-1, a) at cut plane warp-a, b) at cut-plane warp-b. Green line for the centre line of warp yarn, red outline for filler yarn and yellow outline for biases yarns.

	sample-1	sample-2	sample-3	sample-4	sample-5
FVF [%]	31,12	25,02	26,35	33,13	34,95

Table 2: Fiber Volume Fraction percentage of the five samples.

Yarns	**Sample-1**	**Sample-2**	**Sample-3**	**Sample-4**	**Sample-5**
Warp	0,51	0,43	0,44	0,51	0,47
Filler-middle	0,54	0,48	0,53	0,52	0,52
Filler- extreme	0,41	0,39	0,42	0,44	0,39
Filler- under z	0,56	0,55	0,77	0,67	0,65
Bias	0,48	0,46	0,45	0,52	0,55
Binder	0,40	0,39	0,34	0,34	0,38

Table 3: the mean of the computed packing factor for the yarns in the five produced samples.

	cut plane		**sample-1**	**sample-2**	**sample-3**	**sample-4**	**sample-5**
Warp yarn	warp-a		0,04	0,14	0,19	0,10	0,07
Filler yarn	filler-a	outer	0,02	0,23	0,08	0,13	0,08
		inner	0,01	0,16	0,05	0,13	0,07
	filler-b	outer	0,21	0,05	0,03	0,29	0,28
		inner	0,04	0,04	0,01	0,01	0,00

Table 4: Crimp percentage of warp yarns in the five samples.

4.3. Cross section of filler yarns

The shape and the area of the filler yarns cross sections, on the same cut-plane, vary in function of its location through the thickness inside the preform due to the interaction and the contact with surrounding yarns. At the cut plane “warp-a“, we can distinguish three sections for filler yarns, figure 3-a. At mid-plane of preform, the filler yarn section, denoted “middle”, has lateral contact with binder yarn, which has vertical trajectory at mid-plane, and contact on upper and lower surfaces of its section with two adjacent bias layers. So, it has more tend to rectangular cross section shape. Otherwise, the filler yarn at the two extreme surfaces of preform has two different sections both of them have one contact surface with the next warp yarn layer. However, the first section, denoted “filler- under z”, when binder yarn passes over filler yarn it takes semi-elliptical cross section shape with less cross section area (higher packing factor) comparing to “middle”, table 3. Contrariwise, the second section, denoted

"extreme" no binder yarn passing over it so less contact pressure resulting in higher cross section area (lower packing factor) with more elliptical shape. At the cut plane "warp-b", Figure 3-b, as this plane is between two binder yarns just the two cross sections "middle" and "extreme" are noted.
Furthermore, concerning the regularity of the area of the filler_ middle section across the cut-planes, a low variation is observed whereas a more important variation regarding the AR.

4.4. Cross section of Warp and biases yarns

The variation of the bias and warp yarns cross section area between the cut planes is less than 7.12% and 9.48% respectively. Otherwise, the variation of AR, signify the variation of the shape, is more important and more dispersed; further, it could be related oppositely to yarns counts per unit cell. However, the variation of AR for warp yarns cross section is less important than in bias yarns and it is more stable between the two planes. That is attributed to the variation of the contact with surrounding yarns along its trajectory inside the structure due to the passage under binder yarns. Where, as shown in cut plane type "a", the bias yarns pass between two through thickness plane of binder yarns so higher lateral pressure resulting in lower AR. However, as no binder yarn is in cut plane type "b", less lateral pressure resulting in higher AR and elliptical cross section shape are noticed.
Concerning the repeatability at the same cut-plane and between the unit cells, the variation of the area for the bias and warp yarns is approximately about 10%, while the variation of the AR is more important and more dispersed. That is could be referred to the yarns gap parameters, where the variation is less important with poor yarn gap. Also that is related to the weaving process because of the manual functioning of the mechanisms.

4.5. Path and cross section of binder yarn

As illustrated in Figure 3-a, the binder yarn could be divided into two parts; through thickness part and crown part (passing over filler yarn and appears on the top and bottom surfaces of preform). The inclination angle (α) of the through thickness part of binder yarn relative to horizontal mid-plane of preform was measured as shown in Figure 3-a. This angle α is varied between 90°-93° for samples (1, 4, 5) and 65°-80° for samples (2, 3). It is affected essentially by count per unit length and linear mass density of the filler and biases yarns in a unit cell of the structure and the preform thickness. For higher fiber content it tends to 90° whereas it decreases with less fiber content. Otherwise, the shape of the binder yarn cross section varies along its path. This variation may be noticed through monitoring its thickness. The thickness of through-thickness part is more important than at crown part (flatten or semi elliptic cross section) and that is attributed to the contact conditions with the surrounding yarns.

Conclusion

The prototype has been developed showing the possibility of fabrication of a 3D multiaxis woven preform with biases in-plane yarns oriented around + and – 45° with separation the two successive layers of biases yarns by a warp yarns layers. In the realized geometric characterization for the produced samples, the component yarns geometric parameters (cross sections dimensions, area and filament packing factor) as well the unit cell parameters (unit cell dimensions, preform thickness, FVF) are measured.
The binder yarns have not an exact vertical path in the preform through thickness, but it depends on the count per unit length and the linear density of filler and bias yarns and the preform thickness. It could be accepted a uniform and constant cross section area for warp

yarns also for bias yarns whereas for filler yarns its cross section shape and area vary depending on its position within the structure. Low crimp percentage was noticed for in-plane yarns in the though thickness direction of the preform but the outer filler yarns shows more important crimp at the crossing over by binder yarns. Otherwise, the crimp should be re-evaluated also after the consolidation of the preform with compaction as in the case of RTM process. The in-plane yarns in the closed-packed preform keep their initial arrangement and show less crimp percentage than the more opened-packed one.

Reference

[1] Chou T. W. Microstructural design of fiber composites. *UK. Cambridge University Press*, 382-390, 1992.

[2] Sih G. C., Skudra A. M. *Failure mechanics of composites*. New York, USA. Elsevier Science Publishers B. V., 1986.

[3] Lomov S., Verpoest I., Robitaille F., Manufacturing and internal geometry of textiles chapter of *Design and manufacture of textile composites* Edited by Long A.C., Woodhead Publishing Limited and CRC Press LLC, 2005,.

[4] Guenon V.A., T.-W. Chou and J.W. Gillespie, Toughness properties of a three dimensional carbon-epoxy composite, *Journal of Material Science*, 24, 4168-4175, 1989.

[5] Rudov-Clark S, Mouritz a. P, Lee L, Bannister MK., Fiber damage in the manufacture of advanced three-dimensional woven composites. *Composite Part A, Applied Science Manufacture*, 34(10), 963–70, 2003.

[6] Cox B. N., Dadkhah M. S., Morris W. L., Flintoff J. G., Failure mechanisms of 3D woven composites in tension, compression, and bending, *Acta Materialla Material*, 42(12), 3967-84, 1994.

[7] Callus PJ, Mouritz a. P, Bannister MK, Leong KH., Tensile properties and failure mechanisms of 3D woven GRP composites, Composite Part A, 30(11), 1277–87, 1999.

[8] Bilisik K., Multiaxis three-dimensional weaving for composites: A review. *Textile Research Journal*; 87(7): 725-743, 2012

[9] Bilisik K., Multiaxis 3D Weaving: Comparison of Developed Two Weaving Methods (Tube-Rapier Weaving versus Tube-Carrier Weaving) and Effects of Bias Yarn Path to the Preform Properties. *Fibers and Polymers*; Vol(11), 104-111, 2010.

[10] Labanieh A. R., Legrand X., Koncar V., Soulat D., Evaluation of the elastic behavior of multiaxis 3D-woven performs by numerical approach. *Journal of composite material*, first published on line: 18 december 2013 as DOI 10.1007/s10443-013-9369-9.

[11] Labanieh, a. R., Legrand, X., Koncar, V., Soulat, D. Novel optimization method to estimate the geometrical properties of a multiaxial 3D woven preforms». *Journal of Reinforced Plastics and Composites.* 32 (10), 700-712, 2013.

[12] Kamiya, R. et al., Some recent advances in the fabrication and design of three-dimensional textile preforms : a review. *Knowledge Creation Diffusion Utilization*, 60, 33-47, 2000.

[13] P. K. Mallick, *Fiber-reinforced composites materials manufacturing and design*. Taylor and Francis Group, LLC, 2008.

[14] Hallal A, Younes R, Fardoun F, S. Nehme. Improved analytical model to predict the effective elastic properties of 2.5 D interlock woven composites. *Composite Structures*, 94, 3009-3028, 2012.

[15] Curtis P. T., Crag, test methods for the measurement of the engineering properties of fibre reinforced plastics, *technical report*, *Controller HSMO London*, 15(4), 259-265, 1984.

[16] Booth J. E., *Principle of textile testing*, 3rd edition, Butterworths, England, 1968.