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EXPERIMENTAL TESTING OF TWO THREE-DIMENSIONAL (3D)-NON CRIMP FABRICS OF COMMINGLED YARNS

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Abstract: *experimental characterization of the mechanical properties of a woven composite reinforcement is an important issue to the better understanding of its behavior during the forming processes. In this paper, results of bias, compaction, bending, friction and forming tests performed in order to characterize the formability of two three dimensional (3D) fabrics of commingled yarns are presented and discussed.*

1. Introduction

In the manufacturing process of a textile reinforced composite part, the behaviour of the textile reinforcement during the forming process is very important since the apparition of defects during this step can affect the mechanical properties of the final part. The experimental investigation of the deformability of fabrics is therefore very important in order to predict and avoid the apparition of such defects. Different tests have been developed in order to characterize the formability of reinforcements such as picture frame test, bias test, uniaxial and biaxial tension test, friction and forming tests. An overview of those tests can be found in [1].

Because they offer better delamination properties, impact and fatigue resistance than conventional composites, interest for 3D textile reinforced composites is growing. Carvelli et al. [2] presented experimental results of tests performed on a 3D E-glass composite reinforcement, the biaxial behavior of the fabric was identified, uniaxial bias extension and picture frame tests have shown results in good agreement with the kinematic theoretical assumptions up to 30° shear angles. Zhang et al. [3] have shown the great influence of fabric density on the in-plane shear properties and analyzed the inter-ply shear deformation and failure mode. But still very few results can be found concerning experimental testing protocols and results of such 3D fabrics.

In this study, 3D fabrics woven with commingled yarns are used. In such yarns a thermoplastic (polypropylene, polyethylene) is mixed by a commingling process with the reinforcement fibers (glass, carbon) in the yarns. The final composite is obtained by a fast and efficient thermoforming process offering the possibility of a low-cost and rapid manufacturing of complex shaped composites [4]. The use of commingled yarns guarantees a good repartition of the matrix that enhances the composite quality.

The aim of this work is to study the experimental behavior of two 3D non-crimp fabrics with different weaving architectures. The behaviors in bias extension, bending, compaction were investigated. The fabric/metal friction which is involved during forming between tools and fabrics was also studied. Finally, a preforming test with one of the fabrics using a tetrahedral punch was realized.

2. Materials and methods

2.1 Description of the 3D-fabrics

The weaving architectures of the two 3D fabrics considered in this study are displayed on Figure 1. Both fabrics have five layers of yarns in the weft direction and four in the warp direction. In fabric A, the position of weft yarns in the different layers is the same, the z-yarns are vertically oriented and interlock just 3 layers of weft yarns. In fabric B, the position of weft yarns is shifted between the layers, the z-yarns are diagonally oriented and interlock the 5 layers of weft yarns. The weaving densities of fabrics are detailed in Table 1. The thickness of the fabrics is a little more than 4 mm (the final thermofomed parts are expected to be approximately 1.6 mm thick). The areal density is close to 2800g/m² for fabric A and 2900g/m² for fabric B. The yarns used to weave the fabrics are 410 tex glass fiber (GF) polypropylene (PP), referred as GFPP yarns.

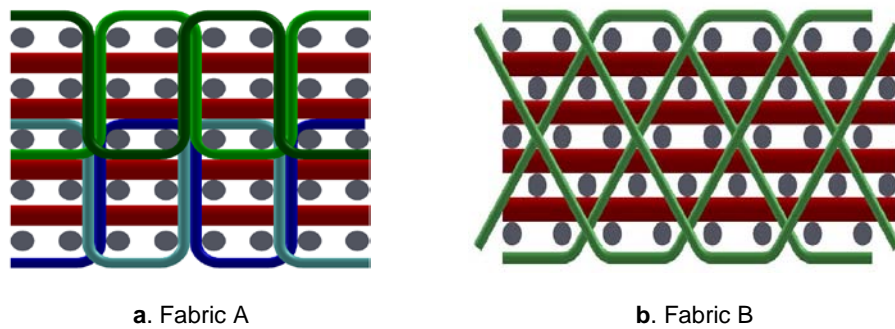


Figure 1. Weaving configuration of the two fabrics

-weft : -240 yarns/10 cm (GFPP) -warp : -200 straight yarns/10 cm (GFPP) -200 Z-yarns/10 cm (orthogonal) (GFPP) +32tex PP binding yarns	-weft : -268 yarns/10 cm (GFPP) -warp : -200 straight yarns/10 cm (GFPP) -200 Z-yarns/10 cm (diagonal) (GFPP) +32tex PP binding yarns
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Table 1. Weaving densities of fabrics

2.2 Devices and experimental methods

-Bias tests

The standards tests to investigate the behaviour of reinforcements have up to now mainly been performed on 2D fabrics. Due to the important thickness of 3D fabrics, the testing protocol had to be adapted and validated especially to ensure good clamping conditions. The resin impregnation or the melting of the PP contained in the hybrid yarns provided good results to guarantee an appropriate fixation of the fabrics in the clamping areas [5]. Uniaxial bias tension tests were performed on a universal tensile testing machine INSTRON 4507, with a 10 kN load cell. Two testing configurations were used: specimen of 80 by 160 mm, testing speed 10 mm/min and specimen of 120 by 240 mm, testing speed 20mm/min. The shear angles were measured by both marker tracking method [6] and digital image correlation (7D software) [7].

-Bending test

Bending tests have been performed on a specific generalized cantilever test with profile identification using an optical measurement. The description of the testing apparatus and of the method to extract bent shapes can be found in [8]. Due to the important rigidity of the fabrics, the use of additional weight is necessary in order to obtain sufficient curvatures. The bending profiles of the fabrics for different bending length were registered and used to rebuild the moment-curvature behaviour of fabrics in warp and weft directions.

-Compaction test

Compaction tests were performed using 2 compaction platens (diameter 150 mm) and a testing speed of 1mm/min up to a 1MPa compaction pressure. A 200kN load cell was utilized; displacements were measured using a LVDT sensor. Results are presented in terms of compaction pressure P as a function of fibre volume fraction Vf. Cyclic compaction tests consisting in 5 cycles of loading and unloading up to the same 1MPa pressure were also performed on the 2 fabrics.

-Friction test

Fabric/metal friction tests were performed using the device described in [9]. Tests were performed with a 1mm/s testing speed. The influence of testing direction (warp/weft/45°) and of the pressure between the fabric and the metal were investigated. At least 5 tests were performed in each testing configuration.

-Forming test

A forming test using a highly double curved punch with a triple point (tetrahedral punch) was performed using fabric B. The process parameters have been determined and optimized based on the fabric behaviours characterized before. The punch speed was 30mm/min. 6 blank holders were utilized: 3 rectangular and 3 square. The exerted pressure was 0.0825 bar on the square blank holders and 0.0252 bar on the rectangular ones. The position of blank holders, the fabric orientation and the position of faces (1, 2, and 3) of the punch can be seen on Figure 2. More details concerning the forming device can be found in [10, 11].

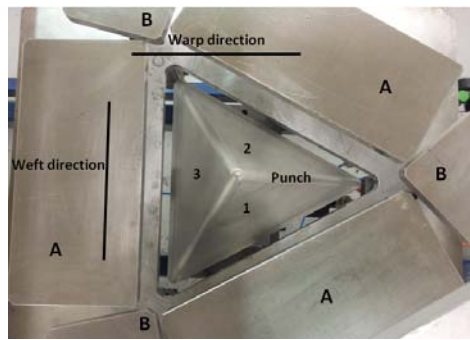


Figure 2. Forming device. A: rectangular blank holders. B: square blank holders. 1, 2, and 3: punch faces

3. Results and discussion

3.1 Bias tests

In figure 3.a, bias test results obtained for fabric A with the two testing configurations are presented (total of 4 tests). Results are very similar in the two configurations showing no significant effect of the testing speed and specimen dimensions. A rapid non linear increase of the shear load after reaching shear angles of more than 20° is observed. Maximum shear loads reached are quite high. The evolution of shear angle can be compared to the theoretical value (Figure 3.b) calculated by a kinematic model assuming no deformation of zone 1 and shear angle in zone 3 twice the shear angle of zone 2 (see the localisation of zones in Figure 3.a.). A good agreement is highlighted for shear angles less than 20° (30° in [2]) but values diverge for more important angles. In the 3D fabric, the shear behavior is influenced by the fabric density [3] and by the binding yarns which introduce an obstacle to the rotation of in-plane yarns [3], the important densities of fabrics studied here and the important number of binding yarns can explain the rapid divergence between theoretical and experimental angles. The deformation of the supposed undeformable zones in the fabric (see in the circles of Figure 4.b) can be observed. No wrinkles appeared during the testing, even at high shear angles. This tends to confirm that the apparition of wrinkles is not only conditioned by the shear angle but also by yarn tension and bending behaviour of the fabrics [12-13]. Maximum shear angles (approximately 48°) and shear forces reached for the 2 fabrics are quite similar.

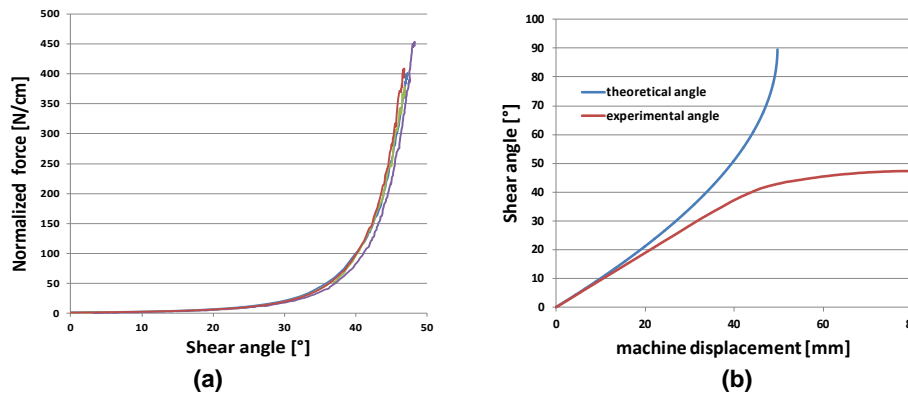


Figure 3. (a) Bias tests results: normalized force as a function of shear angle. (b) Comparison of the theoretical and experimental shear angle (configuration 120 by 240 mm)

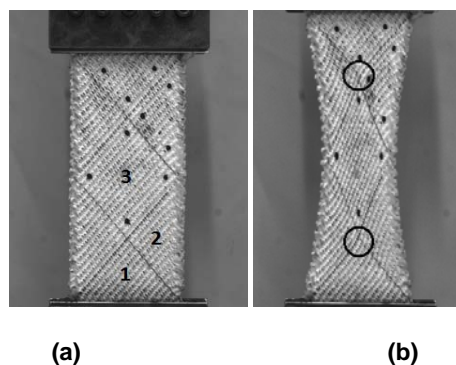


Figure 4. (a) Position of the different zones in a sample before testing. (b) Localization of the deformation of zones 1 during testing

3.2 Bending test

As mentioned in section 2.2, bending tests were carried out on a specific generalized cantilever test with profile identification using an optical measurement. An example of captured bending profile is shown in Figure 5.a. The tests were realized at different bending lengths and the extracted bending profiles are presented Figure 5.b. Then, the moment-curvature curves along the profiles were reconstructed; the obtained results for the 2 fabrics in the weft directions are shown (Figure 5.c). Compared to 2D fabrics, higher moments for lower curvatures are highlighted, especially in the weft direction and for fabric A. This can be an explanation why wrinkles, that are an out of plane fabric bending, do not appear during bias extension tests. Indeed, the appearance of wrinkles is strongly related to the locking angle, yarn tension but also to the bending stiffness of the fabric [12, 13].

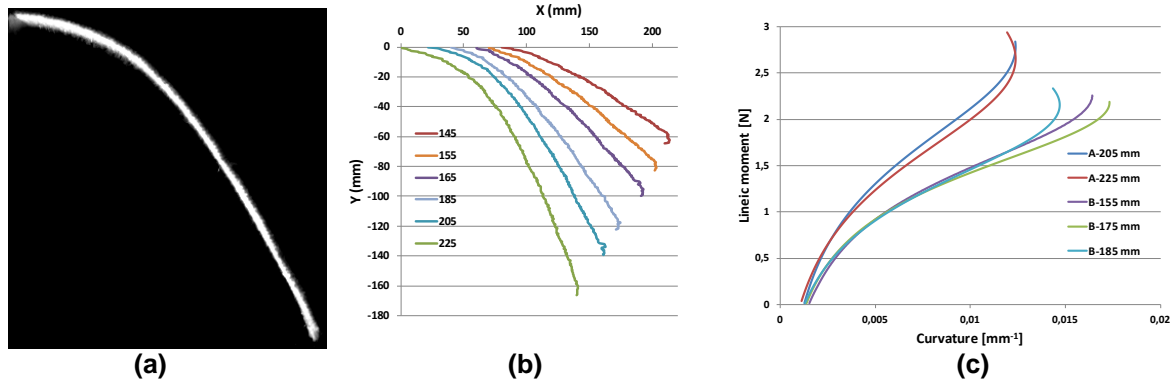


Figure 5. (a) Bending profile image (Fabric A, weft direction, bending length 215mm, additional weight 152 g). (b) Extracted bending profiles for different bending length (Fabric A, weft direction, additional weight 152 g). (c) Reconstructed moment-curvature curve of the 2 fabrics in the weft direction.

3.3 Compaction test

Example of compaction results for fabric B are shown on figure 6. Classical non linear stiffening is highlighted. The initial fibre volume fraction is approximately 35% and increases up to 57% when the maximum pressure of 1MPa is applied. A good repeatability of results is observed with little differences at the beginning of the loading. Results of cyclic tests show, especially after the first cycle, an important permanent deformation that can be attributed to the reorganization of the fibre network. After some cycles, a repeatable loading/unloading cycle is obtained.

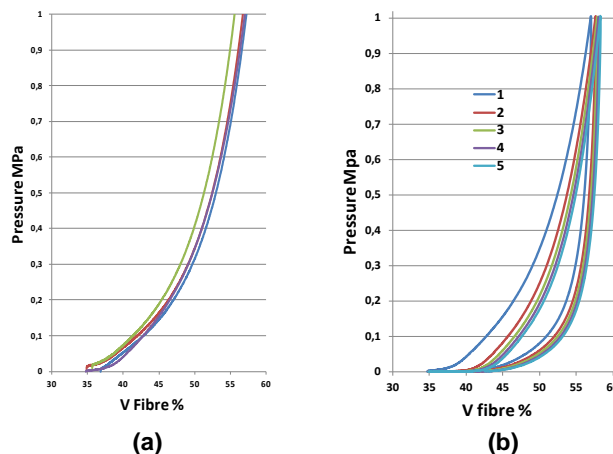


Figure 6. (a). Repeatability of simple compaction tests (b). Result of cyclic compaction

3.4 Friction test

Results of fabric/metal Coulomb friction coefficient are presented in Table 2. Note that the pressure used for these tests are determined on the base of the values that can be reached during an industrial forming

process. Results highlight that, depending on the fabric direction and pressure, quite important variations of the friction coefficients can be observed. The Coulomb friction coefficient decreases with the increasing of the applied normal pressure. This is in good correlation with the results obtained previously in a friction benchmark on Twintex fabric [14]. For fabric A, the minimum value (0.15) is obtained in the weft direction for the 20 kPa pressure, the maximum one is obtained in the warp direction for the 5kPa pressure (0.26). For fabric B the same kind of results is obtained but the variation of the friction coefficient is less important (minimum 0.17, maximum 0.24). Those quite important variations should be taken into account in the forming simulations.

		5 kPa			10 kPa			20 kPa		
		weft	45°	warp	weft	45°	warp	weft	45°	warp
Fabric A	Average friction coefficient	0,209	0,220	0,261	0,168	0,181	0,228	0,150	0,152	0,191
	Standard deviation	0,011	0,010	0,011	0,003	0,001	0,002	0,002	0,002	0,003
Fabric B	Average friction coefficient	0,202	0,200	0,246	0,180	0,184	0,210	0,173	0,175	0,210
	Standard deviation	0,005	0,007	0,005	0,002	0,006	0,007	0,006	0,007	0,004

Table 2. Measured metal/friction coefficients in the different testing configurations for both fabrics

3.5 Forming test

In order to highlight the potentialities of the 3D fabric for composite parts manufacturing, a forming test of highly double curved shape was carried out on fabric B. The configuration used is described in the previous section. Note that the blanks holder pressures were fixed on the basis on the results of the friction tests and tensile tests [5] and also on previous shaping tests conducted on other fabrics in our lab. Figure 7 shows the faces 1 and 3 of the obtained shape at the macroscopic level. Measured shear angles are similar to those observed on other fabrics with this forming punch [12]. The final shape is quite good since no wrinkles appeared on the useful part of the tetrahedral perform. Some little wrinkles are observable in the lower portion of the shape especially on face 3. Nevertheless, the area of occurrence is not a useful part of the final composite piece, and therefore it will be cut after the thermoforming step. Finer optimization of the blank holder pressures may however hide this defect.

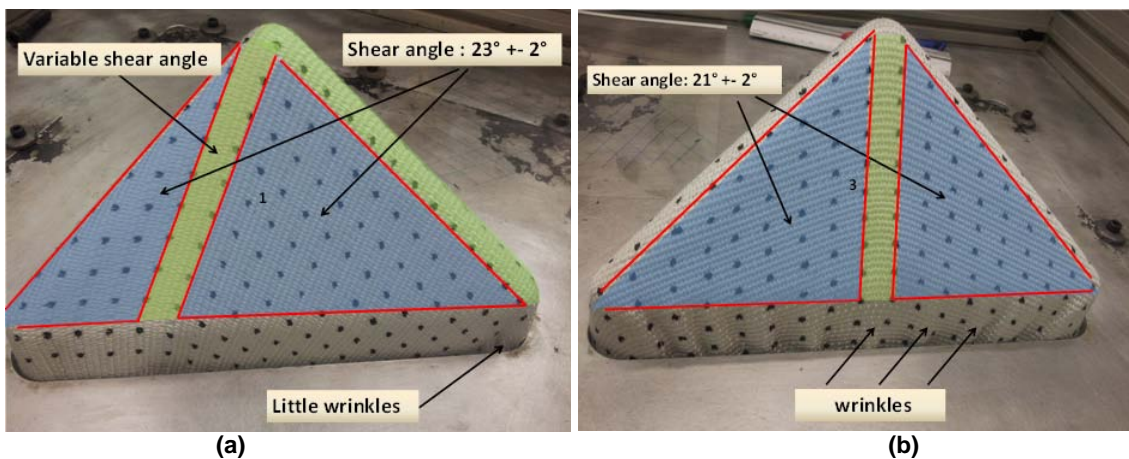


Figure 7. Forming results on the tetrahedral shape (a). Face 1 (b). Face 3

4. Conclusion

In this study, results of experimental tests performed on two 3D non-crimp fabrics with different weaving architectures were presented. Testing protocols were successfully adapted for the testing of the thick 3D fabrics.

The behaviour of fabrics in bias extension was investigated. No wrinkling was observed on the specimens even at high shear angles, the high bending rigidity of the fabrics highlighted in this study and the high shear loads reached during the tests can be an explanation. Results have shown that measured shear angles are

in agreement with the kinematical model only for small shear angles (less than 20°). A maximum shear angle close to 48° was observed for the 2 fabrics.

A non-linear behaviour and the importance of plastic deformation have been observed in compaction, significant variations in the measured metal/friction coefficient depending on the testing direction and pressure have been highlighted.

Those results can be used as data input for forming simulations. They were also used to determine the testing parameters for a forming test performed on one of the two fabrics. The feasibility of a complex double-curved shape has been demonstrated by obtaining a final preform without defects on the useful part.

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