

# Experimental Investigation About Stamping Behaviour of 3D Warp Interlock Composite Preforms

Clément Dufour · Peng Wang · François Boussu · Damien Soulat

Received: 17 November 2013 / Accepted: 3 December 2013 / Published online: 18 December 2013  
© Springer Science+Business Media Dordrecht 2013

**Abstract** Forming of continuous fibre reinforcements and thermoplastic resin commingled preregs can be performed at room temperature due to its similar textile structure. The “cool” forming stage is better controlled and more economical. The increase of temperature and the resin consolidation phases after the forming can be carried out under the isothermal condition thanks to a closed system. It can avoid the manufacturing defects easily experienced in the non-isothermal thermoforming, in particular the wrinkling [1]. Glass/Polypropylene commingled yarns have been woven inside different three-dimensional (3D) warp interlock fabrics and then formed using a double-curved shape stamping tool. The present study investigates the in-plane and through-thickness behaviour of the 3D warp interlock fibrous reinforcements during forming with a hemispherical punch. Experimental data allow analysing the forming behaviour in the warp and weft directions and on the influence of warp interlock architectures. The results point out that the layer to layer warp interlock preform has a better stamping behaviour, in particular no forming defects and good homogeneity in thickness.

**Keywords** Textile composites · Fabric-reinforced thermoplastic · 3D warp interlock structure · Forming · Double-curved shape

## 1 Introduction

For several advantages such as high fracture toughness and elongation, short processing time, easy storage of prepreg, easy to recycle, and impact properties compared to thermoset composites [2], thermoplastic composites have widely caught the attention of researchers [3–6]. The mixing between matrix resin and the reinforcement can be classified into several techniques [7]. The thermoplastic resin can be superposed on the textile reinforcement as powder or as a thin layer, by film stacking; or by co-weaving to obtain hybrid fabrics structures woven from Glass or Carbon yarns (in weft or warp directions) and Peek or polyester (in weft or warp directions) [8]. Another solution consists in using commingled yarns technique where the reinforcing fibres and the matrix, in the form of spun thermoplastic fibres, are blended

---

C. Dufour · P. Wang (✉) · F. Boussu · D. Soulat  
University of Lille, ENSAIT, GEMTEX, 2 allée Louise et Victor Champier, 59056 Roubaix, France  
e-mail: peng.wang@ensait.fr

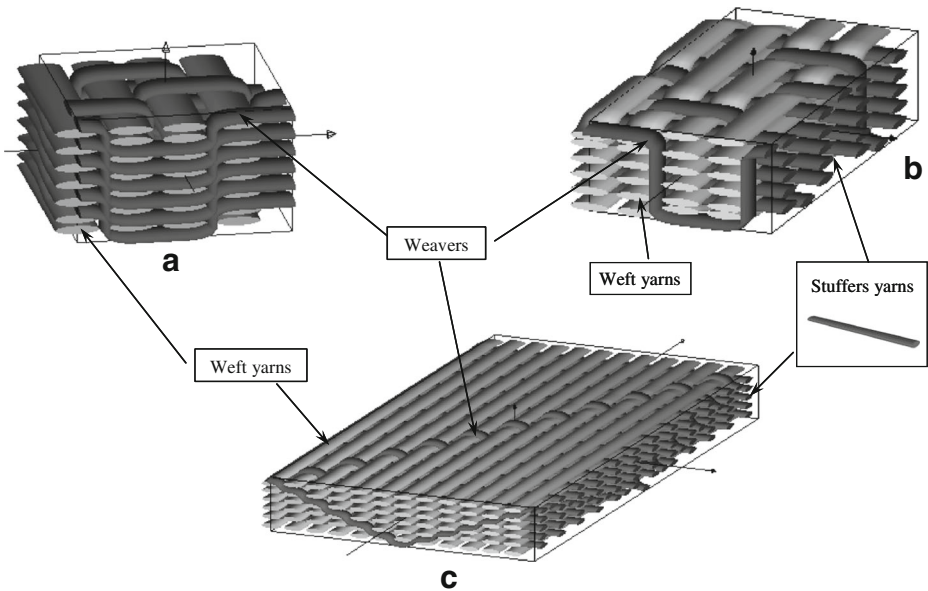
intimately at the filament level [3, 9]. The main advantage of commingled yarns is that the thermoplastic resin is uniformly distributed in the reinforcement to reduce the flow length of the thermoplastic after melting [9, 10]. For this property and also the feasibility for a low-cost and quick production, glass fibres and polypropylene (GF/PP) commingled yarns have been employed in various components for automotive applications (bumpers, front, back and side protections, spoilers) [11]. Associated to semi-structural pieces, significant progress in the manufacturing process, and in the understanding of the mechanical behaviour [12], lead to realize structural applications such as vehicle front end and crash structures [13]. However, industrial demands in transport industry increasingly require first the use of preforms constituted from commingled yarns and second the feasibility to obtain from these preforms some complex shape with high curvatures and large deformations. For the first level if some works focuses on the weaving [14, 15] or on the knitting [7] technology of Glass/PP commingled yarns, few research concerns the feasibility to produce 3D-preforms from these yarns. The 3D textile preforms can be produced according to several technologies, but due to advancements made in 3D weaving process, 3D woven composites have evolved as an attractive structural material for multi-directional load bearing and impact applications, due to their unique transverse properties such as stiffness, strength, fracture toughness and damage resistance [16]. Consequently in our case, we have been focused on the realization of 3D woven warp interlock composite made with commingled Glass/PP yarns.

Forming the 3D warp interlock preforms constituted by commingled yarns [1, 17] can be performed at room temperature and followed the resin consolidation stage due to their similar textile structure. The “cool” forming is better controlled and seems to be more economical. The increase of temperature and the resin consolidation phases after the preforming can be carried out under the isothermal condition thanks to a closed mould. In this case, it could easily avoid the defects experienced during the non-isothermal thermoforming, especially for the thick preform (e.g. the multilayered and 3D warp interlock fabrics).

Many studies focused on the analysis of the deformability of textile reinforcements during the forming stage [18–25], but they are generally restricted to the in-plane characteristic analysis of thin preforms. The present paper will investigate the deformability behaviour of the three-dimensional (3D) warp interlock reinforcements made of commingled yarns during the forming step to optimize the architecture of warp interlock composites. Glass/Polypropylene (PP) commingled yarns will be woven with different architectures. Then, the resulted Glass/PP commingled thermoplastic fabrics will be formed by the stamping process with a hemispherical punch. The characterisations of deformability behaviour are performed on the plane and cross the thickness of the warp interlock preforms. The experimental data allow analysing systematically the forming behaviour influenced by the warp interlock architecture: layer to layer, orthogonal and angle interlock. It can be finally point out that the layer to layer interlock preform has a better stamping behaviour with the homogeneous thickness and weaker interlayer sliding. In addition, no defects presents in the forming with layer to layer interlock fabric nevertheless the defects depend on the manufacturing parameters such as tool loads, blank holder pressure ....

## 2 3D Warp Interlock Preforms

3D warp interlock architectures can be woven on both dobby or Jacquard looms equipped with special devices for the warp tension of yarns and good shed opening [26]. Three main types of 3D warp interlock architectures are presented in Fig. 1: layer to layer, orthogonal and angle



**Fig. 1** 3D warp interlock structures **a** layer to layer, **b** orthogonal and **c** angle

warp interlock architectures, which have been woven as flat panels with a given thickness [27–33].

The principal difference between the three main 3D warp interlock architectures is the evolution of warp yarns (weavers and stuffers yarns) in the structure [34]. As for the layer to layer architecture family, all warp yarns link two layers of weft yarns or more, but not all the layers, unlike to the orthogonal warp interlock family where some warp yarns link all layers of weft yarns from a weft layer to an another.

The manufacturing process needs to be adapted for each architecture, taking into account different characteristics like increased differences in warp yarn consumption during the weaving of the warp interlock fabrics. With different way of linking, each family of architecture has different properties [35, 36]. For example, higher through-thickness elastic and strength properties can be achieved by using 3D orthogonal interlock woven composites [37, 38]. Angle-interlock structure has relatively straight weavers yarns inclined at an angle to the warp direction [31], it permits more elongation in the warp direction than in the weft. The increase in the number of layers in angle-interlock structures makes the structures more difficult to bend. However, the increase in the number of layers showed little influence on the shear rigidity [39, 40]. The layer to layer warp interlock structure tends to be more rigid in compression and has good formability [33].

The three different warp interlock preforms with six layers described in Fig. 1 have been woven using commingled thermoplastic yarns. These three-dimensional weavings have been performed by an automated dobby loom developed by GEMTEX laboratory (Fig. 2). In order to analyse and directly compare the stamping behaviour of each warp interlock structure, the specimens have been woven with identical commingled yarns (E-glass/polypropylene hybrid yarns) and with the same warp and weft densities (18 yarns/cm). The tensile tests have been performed to avoid the risk of the yarn breaks during the weaving of warp interlock fabric. The main properties of the commingled yarns and the warp interlock preforms used in this study



**Fig. 2** Weaving machine and 3D warp interlock preform with E-glass/PP commingled yarns

are shown in Table 1. It can be noted a thicker layer to layer warp interlock preform, a thinner orthogonal warp interlock preform and a moderate angle warp interlock preform even if their warp and weft densities are equal.

The surface dimensions of the samples used in the following experimental analyses are  $300 \times 300 \text{ mm}^2$ . The fine coloured yarns, called “tracers”, have been woven on the preform surfaces to form a grid to conduct a set of measurements (see Fig. 3). It allows monitoring the intra-ply deformation of the fabric during the forming process. The upper and bottom yarns are symmetrical to the mean plane of the interlock preform. On another hand, the measurements have been done with the help of the “tracers” yarns motion shown in Fig. 3 (the monitoring points on the upper and bottom layers). These monitoring points can complete the measurement data not only in-plane but also through-the-thickness of the preform. Figure 4 presents a layer to layer warp interlock specimen, the red “tracers” yarns and the 25 markers drawn on the bottom layer can be observed.

### 3 Analysis of Preforming Behaviour

#### 3.1 Hemispherical Preforming Experiment

The forming with a hemispherical punch is performed on a specific preforming device shown in Fig. 5 [41, 42]. This device permits to analyze the possibilities of the double-curved shape manufacturing with a given textile reinforcement in different forming conditions (shape and thread of punch, position and pressure of blank-holder...). The given 3D warp interlock fabric is placed between the blank-holder. Then, four pneumatic jacks, connecting to the blank-holder, apply an adjustable pressure on the fabric. In order to monitor the important forming parameters by optical measurement such as the material draw-in, the in-plane shear and the inter-layer sliding..., the “open-die” forming system is used. Another electric jack linked to the

**Table 1** The main properties of yarns and the 3D warp interlock preforms

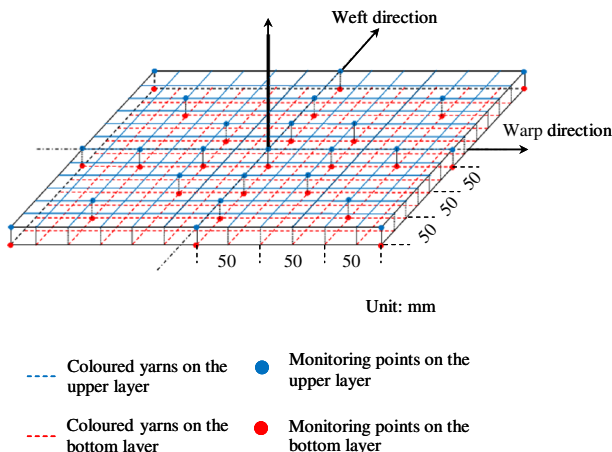
Fibres	Diameter ( $\mu\text{m}$ )		Mass fraction (%)
Polypropylene	47		28.4
E-Glass	17		71.6
Commingled yarn	Properties		Value
	Linear density (tex)		636
	Strain at break (%)		4.25
	Tenacity (cN/tex)		20.8
3D warp interlock preform	Density (yarns/cm)		Thickness (mm)
	Ends	Picks	
	Layer to layer		
Orthogonal	18	18	3.7
Angle	18	18	3.1
	18	18	3.5

punch imposes a movement (punch displacement) and a load sensor acquires the punch force during the forming step.

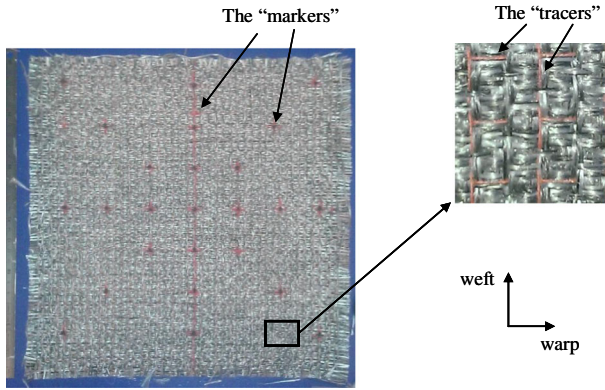
The stamping of three different architectures of the warp interlock fabric corresponding to a 75 mm punch displacement and a 0.2 MPa blank-holder pressure is carried out in Fig. 6. The deformed  $0^\circ/90^\circ$  plies after the forming process are figured out. Different results corresponding to the influence of warp interlock architecture can be observed. In order to improve the understanding of warp interlock reinforcement structures and predict the suitable architecture for double-curved shape forming, the investigation of stamping behaviour of each warp interlock structure will be performed by analyzing the characterizations of in-plane, out-of-plane and through-the-thickness of the preform.

### 3.2 Forming Defects Observation

The manufacturing defects, such as misalignment, slippage of yarns network, wrinkling and buckles, can be developed in the useful zone of the deformed fabric after forming [43–45]. It is possible to modify the defects by optimisation of the forming parameters, but forming defects



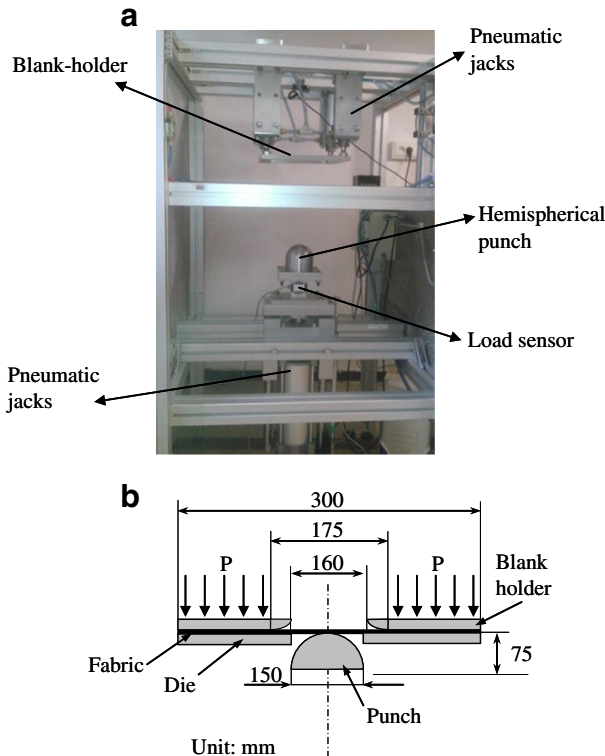
**Fig. 3** Locations of the monitoring points and coloured yarns



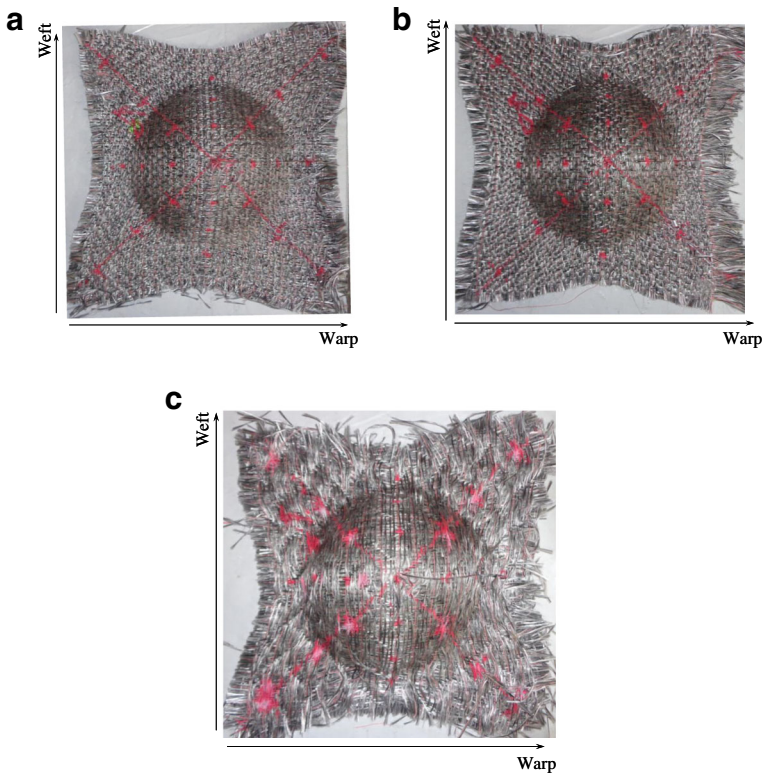
**Fig. 4** The 3D warp interlock specimen prepared for experimental preforming

depend strongly on the characteristics of textile fabric. The common defects mentioned above have a negative influence on the performance of the final composite part. Consequently, the minimization of the forming defects is significantly important in the double-curved shape forming.

The zoom of the useful zone of the deformed plies are presented in Fig. 7. The hemispherical 3D ply without any flaws can be obtained for layer to layer and orthogonal warp interlock



**Fig. 5** The experimental preforming device



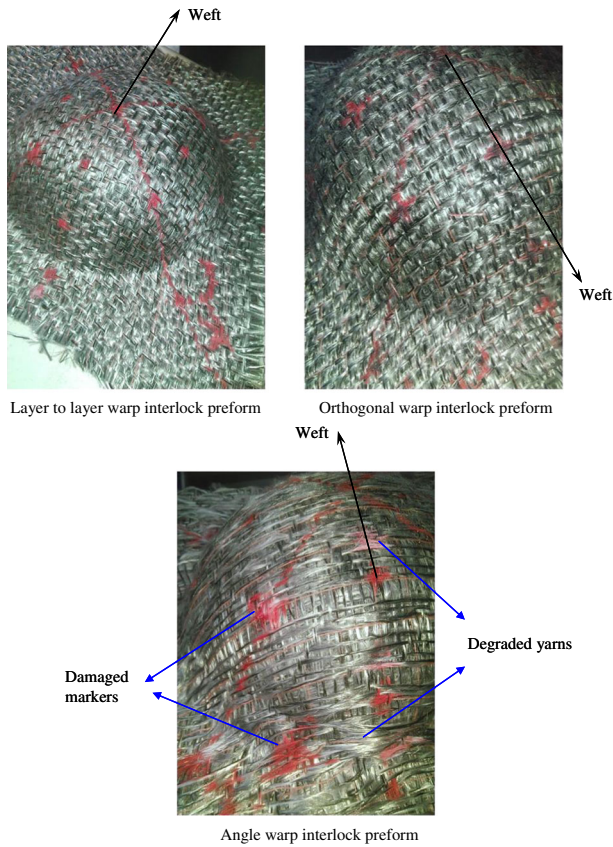
**Fig. 6** The deformed fabrics after forming, **a** for layer to layer warp interlock preform, **b** for orthogonal warp interlock preform, **c** for angle warp interlock preform

fabrics. On the contrary, in the forming of angle warp interlock fabric, the heavy slippage of yarns network can be observed in both warp and weft directions (Fig. 7a) as the angle warp interlock preform has a relaxed architecture compared to other warp interlock structures. More sliding appears in warp direction than in weft direction due to the presence of the more binding points in weft yarns. In addition, the misaligned yarns and the buckles can be noted on the deformed angle warp interlock preform because of the poor in plane compression behaviour (see Fig. 7a). Due to the slippage of yarns network, some yarns, located between the inter-laminar planes, are degraded by friction. Markers corresponding to the monitoring points are damaged by forming defects, the measurements such as in-plane shear and inter-ply sliding cannot be achieved for the angle warp interlock preform.

### 3.3 In-Plane Characterizations

#### 3.3.1 Material draw-in

Material draw-in in the warp and weft directions for three warp interlock fabrics are shown in Fig. 8, which is measured via pictures taken from a central point of view and perpendicular to the surface of the preform, sufficiently distant from it in order to reduce errors due to the shooting. The material draw-in is quasi symmetrical in the warp and weft directions. The maximum value is slightly higher in the weft direction for the layer to layer and orthogonal



**Fig. 7** Observation in the useful zone

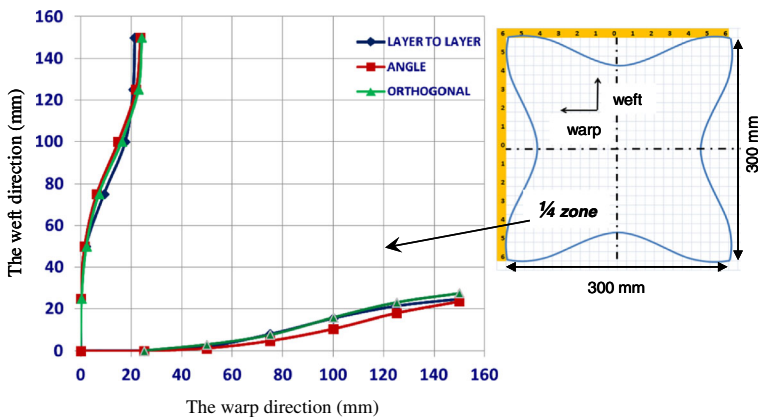
warp interlock architectures (6 % higher in the weft direction than in the warp direction). It can be explained by the evolution of warp yarns in such structures: some warp yarns of orthogonal warp interlock architecture are deeply bended from one surface to the other, thus preventing slippage of the yarns in the structure while weft yarns follow a smoother evolution. In the layer to layer architecture, the difference is explained by the fact that all the bending warp yarns only link two successive layers.

The presented stamping test for each warp interlock structure was repeated three times. A good reproducibility was obtained. Each curve in Fig. 8 shows the mean value of the corresponding measurement data.

### 3.3.2 In-Plane Shear

As the most important deformation mode of textile composite, the intra-ply shearing effects corresponding to the in-plane shear angle are measured. Figure 9 presents the mean in-plane shear angle of the upper and bottom layers of the deformed preforms (the measurement precision is  $\pm 0.5^\circ$ ). These measurements cannot be achieved for the angle warp interlock preform due to the slippage of yarns network. The experimental data presents the quasi symmetrical results to the point 0 (at the top of the hemisphere). The maximum shear zone





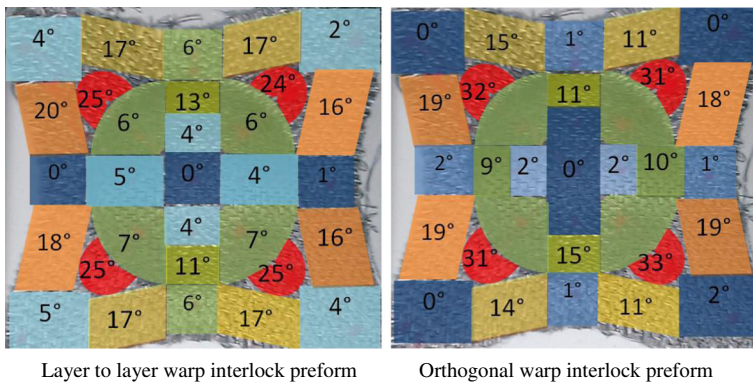
**Fig. 8** Material draw-in in warp and weft directions (distribution in 1/4 zone of the deformed ply)

can be observed in the diagonal direction on the edge of the useful region (the red region in Fig. 9). The maximum in-plane shear angles 25° and 33° are noted for layer to layer and orthogonal warp interlock preforms. Comparing the in-plane shear in the useful zone, the layer to layer warp interlock fabric seems more rigid than the orthogonal warp interlock fabric as the layers are lined one by one (see Fig. 1a and b).

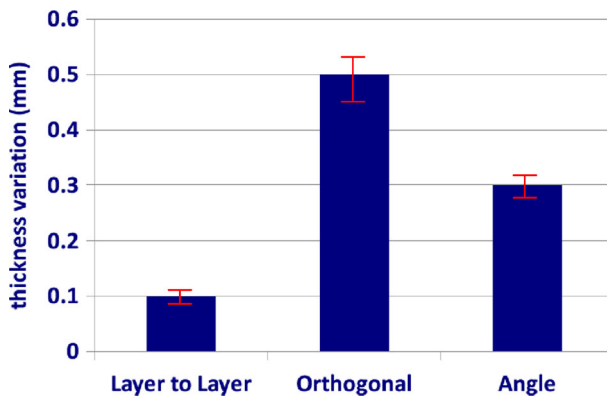
### 3.4 Measurements Through-the-Thickness

#### 3.4.1 Thickness variation

In order to analyse the compressibility of the warp interlock structures during manufacturing, the thickness of the deformed ply after the forming are measured with a contact method over the surface with the help of nine precise locations (these locations before the forming are shown in Fig. 3). Compare to the initial thickness of the preform, the mean value of the thickness decrease for three warp interlock fabrics is shown in Fig. 10. This through-the-thickness variation is identical in warp and weft directions. The mean diminution of layer to layer, orthogonal and angle warp interlock fabrics is respectively 0.1, 0.5 and 0.3 mm with a standard deviation of 4.9 %, 18.5 % and 10.6 %. The measurement data presents a strong



**Fig. 9** In-plane shear measurements



**Fig. 10** The thickness variation after the forming for three different warp interlock fabrics

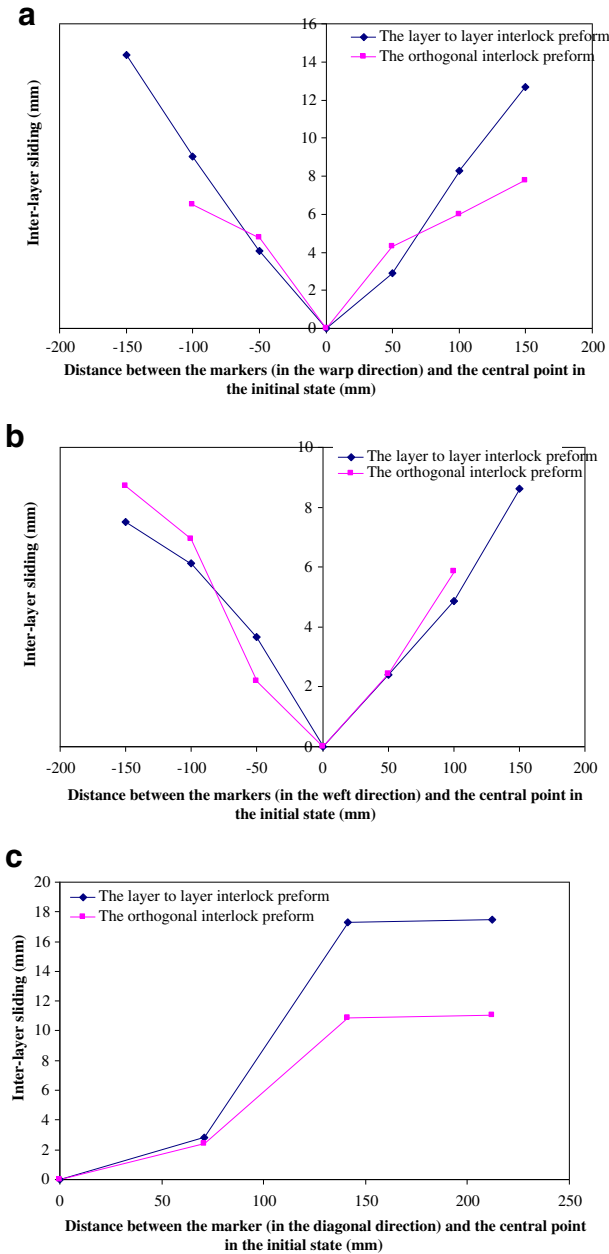
thickness decrease with a poor homogeneity for orthogonal warp interlock preform, as each binding warp yarns link six layers of weft yarns (Fig. 1) and consequently weft yarns can move onto the interface and insert into each other during the compression effects. The binding location is not constant, which leads to an irregularity of the thickness. On the contrary, 2.7 % diminution of the thickness can be neglected in the stamping of layer to layer warp interlock preform. More binding warp yarns are present in the thickness of the preform and each layer is linked, which better preserves the whole architecture during the yarns motions and deformation (4.9 % standard deviation).

### 3.4.2 Inter-layer sliding

The relative slippage between the two outer layers (the maximum inter-layer sliding) is monitored by the motion of the upper and bottom surfaces of the preform. The 50 locations are chosen and marked vis-à-vis on upper and bottom surfaces (Fig. 3). The movement of these markers will be tracked by an optical method [42]. Then the inter-layer sliding is determined as the distance between the projection on the mid-surface of two measurement points on the opposite surfaces [46].

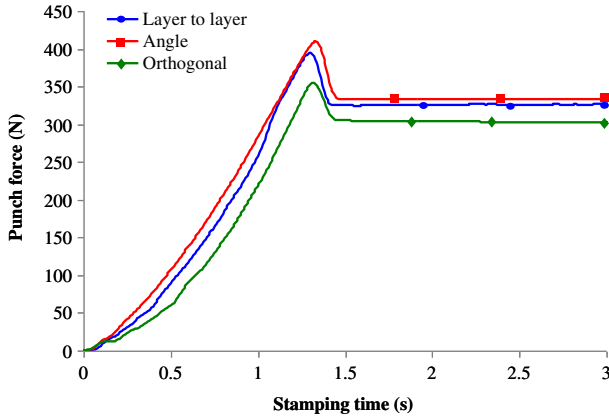
Figure 11 presents the slippage of inter-laminar with respect to the distance between the markers and the zero point (located at the top of the hemisphere) in the warp, weft and diagonal directions of layer to layer and orthogonal warp interlock preforms. At the zero point, the sliding can be neglected and then this inter-sliding augments flowing the increasing of the distance to the top of the hemisphere. Some markers are damaged due to the edge effects. In the warp direction, the sliding is more important for layer to layer warp interlock preform (maximum sliding value about 14.4 mm) than for orthogonal warp interlock preform (maximum sliding value about 7.8 mm). On the other hand, in the weft direction it can be noted that the maximum sliding is about 8.7 mm for two warp interlock preforms and the sliding is slight greater at the same location for orthogonal warp interlock preform.

The experimental data shows that the sliding is greater in the warp direction than in the weft direction for layer to layer and orthogonal warp interlock architectures. It can be indicated that the solicitation of warp yarns during the stamping process with a symmetry structural punch (hemispherical punch) leads to a larger structure deformation when weft yarns are solicited in the same time. For the orthogonal warp interlock structure, a slight difference of slippage in the warp and weft directions can be observed due to the thin structure which increases the inter-



**Fig. 11** Inter-layer sliding of the different warp interlock preforms after the forming

layers friction. Regarding the layer to layer warp interlock preform, a greater sliding can be observed in the warp direction than in the weft direction. In layer to layer warp interlock structure, all warp yarns link at least two weft layers. It reduces the motions freedom of the warp yarns and consequently generates the sliding of inter-laminar when the deformation of upper and bottom layers is different.



**Fig. 12** Punch force evolution during the stamping stage for three different warp interlock preforms

The inter-sliding in the diagonal direction is important as it follows the maximum in-plane shear in this direction. Figure 11c presents the mean sliding in the diagonal direction. The maximum value is reached on the edge of the useful zone of the hemisphere (17 mm for layer to layer warp interlock preform and 11 mm for orthogonal warp interlock preform). The inter-sliding remains quasi constant in the rest of the region where the preform is in contact with the black-holder due to the high applied pressure (0.2 MPa).

### 3.5 Monitoring of the punch force

The punch force during the stamping is measured by a 500 N ( $\pm 0.3\%$ ) load sensor. Figure 12 reveals the evolution of the effort versus forming time for three different warp interlock preforms. The three curves have similar evolution. The effort of punch increases rapidly during the deformability of the preform. After the relaxing of efforts, due to the inertia effects after the maximum punch displacement has been reached, a constant effort of punch to maintain the final shape of the deformed preform can be noted on the force-time curves.

It can be observed that the punch force is quasi equal for layer to layer and angle warp interlock preforms. As the less binding points in the orthogonal warp interlock architecture (the thinnest structure of our study), the preform is less rigid and consequently the stamping effort is smaller (35 N) than the other warp interlock structures (layer to layer and angle warp interlock structures).

## 4 Conclusions

Due to the fact that the material draw-in occurs more significantly in the weft direction than in the warp direction, and due to a higher inter-sliding effect between the two external layers in the warp direction than in the weft direction, stamping tests with a hemispherical punch indicate that weft yarns keep more motion's freedom in the structure than warp yarns. Indeed, the greater draw-in in the weft direction reveals that the weft yarns can more easily move in the structure without affecting the displacement of the entire woven structure.

The angle warp interlock structure highlights the poor stamping behaviour due to the significant defects. The through-the-thickness measurements done on the deformed preforms indicate a non-homogeneity in thickness of the orthogonal warp interlock structure. The layer

to layer warp interlock structure presents the best deformability during the forming process, by a compromise between, fabrication flaws, thickness variation and structural integrity.

As the double-curved shape forming depends not only on the preform structure but also on the forming parameters (tool loads, blank holder pressure, temperature...). Therefore it is important to predict the feasibility of forming process through the numerical simulations. The aspect of numerical analyses of 3D warp interlock thermoplastic composite forming process need to be developed in our future works.

**Acknowledgments** This study has received the support from the European Commission through the large-scale integrating collaborative project MAPPIC 3D - number 263159-1 - and entitled: One-shot Manufacturing on large scale of 3D up graded panels and stiffeners for lightweight thermoplastic textile composite structures

## References

1. Wang, P., Hamila, N., Boisse, P.: Thermoforming simulation of multilayer composites with continuous fibres and thermoplastic matrix. *Compos. Part B* **52**, 127–136 (2013)
2. Lebrun, G., Bureau, M.N., Denault, J.: Evaluation of bias-extension and picture-frame test methods for the measurement of intraply shear properties of PP/glass commingled fabrics. *Compos. Struct.* **61**, 341–352 (2003)
3. Svensson, N., Shishoo, R., Gilchrist, M.: Manufacturing of thermoplastic composites from commingled yarns—a review. *J. Thermoplast. Compos. Mater.* **11**, 22–56 (1998)
4. Hou, M., Ye, L., Mai, Y.M.: Review—advances in processing of continuous fibre reinforced composites with thermoplastic matrix. *Plast. Rubber Compos. Process. Appl.* **23**(5), 279–293 (1995)
5. Miller, A.H., Dodds, N., Hale, J.M.: High speed pultrusion of thermoplastic matrix composites. *Compos. Part A* **29**(7), 773–782 (1998)
6. Nowacki, J., Neitzel, M.: Thermoforming of reinforced thermoplastic stiffened structure. *Polym. Compos.* **21**(4), 531–538 (2000)
7. Zaixia, F., Zhang, Y., Yanmo, C., Hairu, L.: Investigation on the tensile properties of knitted fabric reinforced composites made from GF–PP commingled yarn preforms with different loop densities. *J. Thermoplast. Compos. Mater.* **19**, 113–126 (2006)
8. Shekar, R.I., Kotresh, T.M., Prasad, A.S.K., Rao, P.M.D., Ananthkrishnan, T., Kumar, M.N.S.: Hybrid fabrics for structural composites. *J. Ind. Text.* **41**, 70–103 (2011)
9. Hufenbach, W., Böhm, R., Thieme, M., Winkler, A., Mäder, E., Rausch, J., Schade, M.: Polypropylene/glass fibre 3D-textile reinforced composites for automotive applications. *Mater. Des.* **32**, 1468–1476 (2011)
10. Mäder, E., Rausch, J., Schmidt, N.: Commingled yarns—processing aspects and tailored surfaces of polypropylene/glass composites. *Compos. Part A* **39**, 612–623 (2008)
11. Fitoussi, J., Bocquet, M., Meraghni, F.: Effect of the matrix behavior on the damage of ethylene–propylene glass fiber reinforced composite subjected to high strain rate tension. *Compos. Part B* **45**, 1181–1191 (2013)
12. Hufenbach, W., Langkamp, A., Hornig, A., Zschoyge, M., Bochynek, R.: Analysing and modelling the 3D shear damage behaviour of hybrid yarn textile-reinforced thermoplastic composites. *Compos. Struct.* **94**, 121–131 (2011)
13. Griffiths, B.: Glass-reinforced thermoplastic succeeds in car crash structure. *Compos. Technol.* 52–54 (2006)
14. Mountasir, A., Hoffmann, G., Cherif, C.: Development of weaving technology for manufacturing three-dimensional spacer fabrics with high-performance yarns for thermoplastic composite applications: an analysis of two-dimensional mechanical properties. *Text. Res. J.* **81**(13), 1354–1366 (2011)
15. Mountasir, A., Hoffmann, G., Cherif, C., Loser, M., Muhl, A., Grossmann, K.: Development of non-crimp multi-layered 3D spacer fabric structures using hybrid yarns for thermoplastic composites. *Procedia Mater. Sci.* **2**, 10–17 (2013)
16. Ansar, M., Xinwei, W., Chouwei, Z.: Modeling strategies of 3D woven composites: a review. *Compos. Struct.* **93**(8), 1947–1963 (2011)
17. Wang, P., Hamila, N., Pineau, P., Boisse, P.: Thermo-mechanical analysis of thermoplastic composite prepregs using bias-extension test. *J. Thermo Compos Mater.* (2012). doi:10.1177/0892705712454289

18. Vanclooster, K., Lomov, S.V., Verpoest, I.: On the formability of multi-layered fabric composites. 17th International Conference on Composite Materials (ICCM17), Edinburgh, UK (2009)
19. Prodromou, A.G., Chen, J.: On the relationship between shear angle and wrinkling of textile composite performs. *Compos. Part A* **28A**, 491–503 (1997)
20. Zhu, B., Yu, T.X., Zhang, H., Tao, X.M.: Experimental investigation of formability of commingled woven composite preform in stamping operation. *Compos. Part B* **42**, 289–295 (2011)
21. Allaoui, S., Boisse, P., Chatel, S., Hamila, N., Hivet, G., Soulat, D., Vidal-Salle, E.: Experimental and numerical analyses of textile reinforcement forming of a tetrahedral shape. *Compos. Part A* **42**, 612–622 (2011)
22. Allaoui, S., Hivet, G., Soulat, D., Wendling, A., Ouagne, P., Chatel, S.: Experimental preforming of highly double curved shapes with a case corner using an interlock reinforcement. *Int. J. Mater. Form.* (2012). doi: [10.1007/s12289-012-1116-5](https://doi.org/10.1007/s12289-012-1116-5)
23. Khan, M.A., Mabrouki, T., Vidal-Sallé, E., Boisse, P.: Numerical and experimental analyses of woven composite reinforcement forming using a hypoelastic behaviour. Application to the double dome benchmark. *J. Mater. Process. Technol.* **210**, 378–388 (2010)
24. Padaki, N.V., Alagirusamy, R., Deopura, B.L., Fanqueiro, R.: Studies on preform properties of multilayer interlocked woven structures using fabric geometrical factors. *J. Ind. Text.* **39**(4), 327–346 (2010)
25. Thomanny, U.L., Ermanni, P.: The influence of yarn structure and processing conditions on the laminate quality of stampformed carbon and thermoplastic polymer fiber commingled yarns. *J. Thermo Compos Mater* **17**(3), 259–283 (2004)
26. Parnas, R.S.: *Liquid Composite Molding*. Hanser Garner Publications (2000)
27. Ha-Minh, C., Boussu, F., Kanit, T., Crépin, D., Imad, A.: Effect of frictions on the ballistic performance of 3D Warp interlock fabric : numerical analysis. *Appl. Compos. Mater.* **19**, 333–347 (2012)
28. De Luycker, E., Morestin, F., Boisse, P., Marsal, D.: Simulation of 3D interlock composite preforming. *Compos. Struct.* **88**(4), 615–623 (2009)
29. Bilisik, K.: Multiaxis three-dimensional weaving for composites: a review. *Text. Res. J.* **82**(7), 725–743 (2012)
30. Chen, X., Waterlon, L., Tsai, L.J., Potiyaraj, P.: An overview on fabrication of three-dimensional woven textile preforms for composites. *Text. Res. J.* **9**(81), 9–32 (2011)
31. Potluri, P., Hogg, P., Arshad, M., Jetavat, D., Jamshidi, P.: Influence of fibre architecture on impact damage tolerance in 3D woven composites. *Appl. Compos. Mater.* **19**, 799–812 (2012)
32. Padaki, N.V., Alagirusamy, R., Deopura, B.L., Fanqueiro, R.: Studies on preform properties of multilayer interlocked woven structures using fabric geometrical factors. *J. Ind. Text.* **39**(4), 327–346 (2010)
33. Zhang, Y.F., Sun, F., Wang, Y.J., Chen, L., Pan, N.: Study on intra/inter-ply shear deformation of three dimensional woven performs for composite materials. *Mater. Des.* **49**, 151–159 (2013)
34. Nauman, S.: Geometrical modeling and characterization of 3D warp interlock composites and their on-line structural health monitoring using flexible textile sensors. Ph.D thesis, University of Lille 1 (2011)
35. El Hage, C., Aboura, Z., Younès, R., Benzeggagh, M.L., Zoater, M.: Analytical and numerical modeling of mechanical properties of orthogonal 3D CFRP. *Compos. Sci. Tech.* **69**, 111–116 (2009)
36. EL Hage, C., Aboura, Z., Younès, R., Benzeggagh, M.L., Zoater, M.: Analytical approach and experimental studies of 3D behavior textile composite with carbon reinforcement of the interlock 2.5D type. 1th International Francophone Congress of Advanced Mechanics. IFCAM01, Aleppo-Syria (2006)
37. Naik, N.K., Azad, S.N.M., Durga Prasad, P., Thuruthimattam, B.J.: Stress and failure analysis of 3D orthogonal interlock woven composites. *J. Reinf. Plast. Compos.* **20**(17), 1485–1523 (2001)
38. Unal P.G.: 3D-Woven fabrics. In: Jeon, H.-Y. (ed.) *Woven Fabrics*. ISBN 978-953-51-0607-4. (May 2012). Publisher InTech
39. Chen, X., Taylor, L.W., Tsai, L.J.: An overview on fabrication of three-dimensional woven textile preforms for composites. *Text. Res. J.* **81**(9), 932–944 (2011)
40. Chen, X., Spola, M., Paya, J.G., Sellabona, P.M.: Experimental studies on the structure and mechanical properties of multi-layer and angle-interlock woven structures. *J. Text. Inst.* **90**(1), 91–99 (1999)
41. Najjar, W., Legrand, X., Pupin, C., Dal Santo, P., Boude, S.: A simple discrete method for the simulation of the preforming of woven fabric reinforcement. *Key Eng. Mater.* **504–506**, 213–218 (2012)
42. Najjar, W., Legrand, X., Dal Santo, P., Soulat, D., Boude, S.: Analysis of the blank holder force effect on the preforming process using a simple discrete approach. *Key Eng. Mater.* **554–557**, 441–446 (2013)
43. Potter, K., Khan, B., Wisnom, M., Bell, T., Stevens, J.: Variability, fibre waviness and misalignment in the determination of the properties of composite materials and structures. *Compos. Part A* **39**, 1343–1354 (2008)
44. Boisse, P., Hamila, N., Vidal-Sallé, E., Dumont, F.: Simulation of wrinkling during textile composite reinforcement forming. Influence of tensile, in-plane shear and bending stiffnesses. *Compos. Sci. Tech.* **71**(5), 683–692 (2011)
45. Ouagne, P., Soulat, D., Moothoo, J., Capelle, E., Gueret, S.: Complex shape forming of a flax woven fabric; analysis of the tow buckling and misalignment defect. *Compos. Part A* **51**, 1–10 (2013)
46. Bel, S., Boisse, P., Dumont, F.: Analyses of the deformation mechanisms of non-crimp fabric composite reinforcements during preforming. *Appl. Compos. Mater.* **19**, 513–528 (2012)