

Innovative monitoring of 3D warp interlock fabric during forming process

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Abstract. The final geometry of 3D warp interlock fabric needs to be checked during the 3D forming step to ensure the right locations of warp and weft yarns inside the final structure. Thus, a new monitoring approach has been proposed based on sensor yarns located in the fabric thickness. To ensure the accuracy of measurements, the observation of the surface deformation of the 3D warp interlock fabric has been joined to the sensor yarns measurements. At the end, it has been revealed a good correlation between strain measurement done globally by camera and locally performed by sensor yarns.

1. Introduction

3D shapes of composite material can be obtained by different options. One of them consists in using near-net-shape textile reinforcements which are mainly based on 3D structures with their adapted textile machinery [1] [2]. Another technic consists in using existing planar textile structures to be formed into the required 3D shape by a forming process. The latter approach needs to understand the forming behaviour of the textile reinforcement, especially for thick structure as 3D warp interlock fabric [3]. Indeed, depending on the initial woven pattern, the final 3D shape of the textile reinforcement can lead to different yarns' location which could affect the resulted mechanical properties [4].

Many studies have been focused on the analysis of the deformability of textile reinforcements during the forming stage [5] [6] [7], but they are generally restricted to the in-plane characteristic analysis of thin preforms. However, the forming behaviour of thick 3D fabric during the forming step seems not to be yet explored, and especially the kinematic of the fabric deformation. Thus, the present paper will investigate the deformability behaviour of the 3D warp interlock reinforcements made of commingled yarns during the forming step by measuring continuously the local and global deformation of yarns.

Automotive industry involved in the EU-research program FP7 MAPICC3D [8] has investigated the design and production of composite materials with fibrous reinforcement made with commingled E-glass/Polypropylene yarns inserted in 3D warp interlock fabric to cope with fast and low cost production requirements. To obtain 3D final shape of the composite part, the forming of the 3D warp interlock preforms constituted by commingled yarns [9] has been performed at room temperature on



dedicated mould. Then a thermo-compressing step has been applied to the 3D formed fabric in order to melt the polypropylene filaments all around the E-glass filaments to ensure a complete consolidation of the composite material.

2. Materials & Methods

To measure the deformations of the 3D woven structure, two different measurement methods have been done simultaneously:

- By measurements of the electrical resistance variation of piezo-resistive sensor yarns integrated in 3D warp interlock fabrics during the weaving process step.
- By measurements of the position of points by image correlation.

The elongation measurements made by image correlation allow to measure spatial position of points which are visible by the different cameras. Contrary from the previous method, elongation measurements made by resistance measurements of sensors can be made everywhere in the 3D warp interlock fabric by location of sensor yarns where data's of elongation are desired.

2.1 Description of the forming bench test

The bench test (Figure 1.a) has been developed at ENSAIT to better understand any type of textile behaviour during the stamping process at room temperature. The textile preform to be tested is initially integrated between two transparent blank holders in poly-methyl-methacrylate (Figure 1.b) and placed onto the bench test in order to respect the warp and weft directions alignment. The punch shape was a “gusset” for all stamping tests of this study (Figure 1.c).

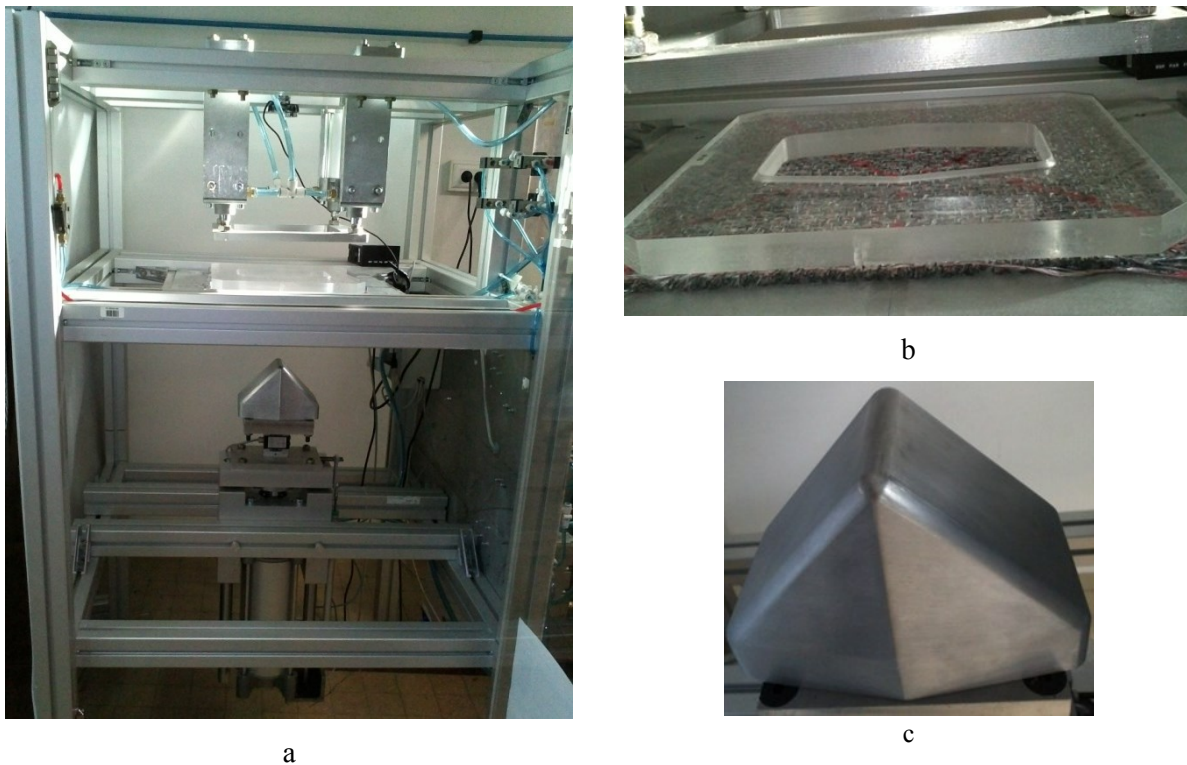


Figure 1 : a. Stamping bench test developed at ENSAIT, b. blank-holder and c. “gusset” punch

2.2 Sensor yarns production and calibration

In order to measure locally the forming behaviour of the 3D warp interlock fabric without any modification of the initial geometry, sensor yarns have been located in the two woven directions (warp and weft) as well as in the surface and in-situ of the textile structure. By the same, in order to keep the same mechanical characteristics of yarns used in the 3D warp interlock fabric, a specific conductive coating has been applied on the E-glass/Polypropylene commingled yarns [10] [11] [12]. In previous works, sensor yarns, made with different types of raw material as: E-glass [13] [14], para-aramid, polyethylene, carbon [15] [16], have proven their efficiency and accurate measurements during different mechanical characterizations [17] [16] [18] [19] [20].

The main interest of using the specific coating on the E-glass/polypropylene commingled yarn lies in the percolation threshold presented in Figure 2. Indeed, the sensitive measurement of the yarn strain during its elongation is directly linked to the important electrical resistance variation for the same elongation. Thus, using low concentrations of conductive particles (Figure 2 – Phase I), the resistivity comes to high value due to the long distance between conductive particles, which contributes to restrict the electrical current conduction. Using high concentrations of conductive particles (Figure 2 – Phase III), the resistivity of the coating reaches a low value due to a complete and well connected electrical network. Between these two configurations, the resistivity varies much more with the conductive particles concentrations because electrical paths are almost complete and a small increase of conductive particles concentration closes electrical paths; this can be qualified as the percolation threshold (Figure 2 – Phase II).

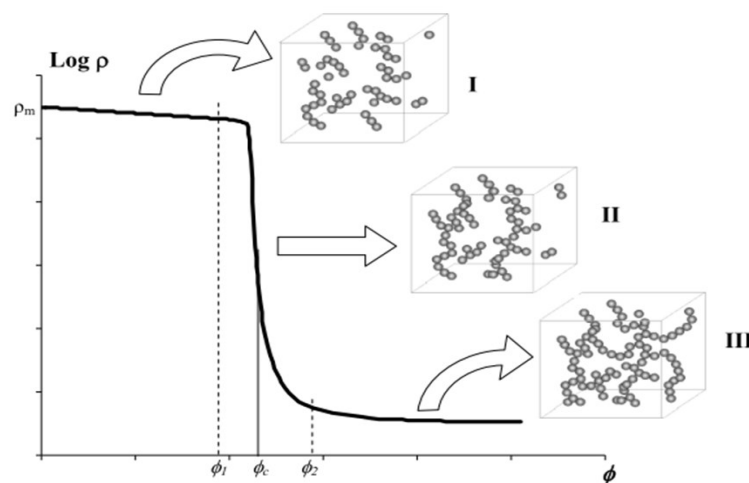


Figure 2 : Typical curve of percolation threshold (X axis: particles concentration – Y axis: Resistivity)

To apply the conductive layer on the yarn, a first coating is realised using the latex solution which helps to glue all the filaments located inside the yarn to ensure a more accurate mechanical load transfer. Based on this layer, the conductive layer is then applied onto the yarn surface with a precise thickness value following the experimental protocol. After this step, two connection wires are placed at each extremity of the sensor yarn and a drop of conductive coating is applied over the connection points. Then, a second layer of conductive coating is applied and, at the end, a last protective layer of latex solution is done all around the sensor yarn to prevent from abrasion and electrical interferences due to contact between sensors and metallic parts or between two sensors.

Before the insertion of these sensor yarns into the final fabric, a calibration step is necessary to check their capacity to detect the mechanical strain of the yarn. Then, the produced sensor yarns are clamped onto the tensile bench and a cyclic training period of strain elongation values located in the elastic zone of the yarn is applied to check their constant and reproducible electrical response as represented into Figure 3.

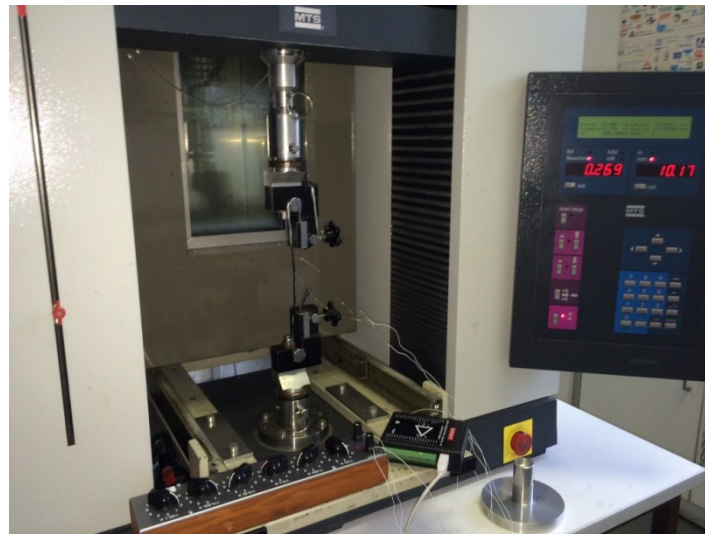


Figure 3 : Electromechanical tests performed for calibration of sensor yarn

As represented in Figure 4, a quite linear behaviour is deduced from the evolution of the elongation $\frac{L-L_0}{L_0}$ compared to the variation of resistance $\frac{R-R_0}{R_0}$ of the sensor yarn.

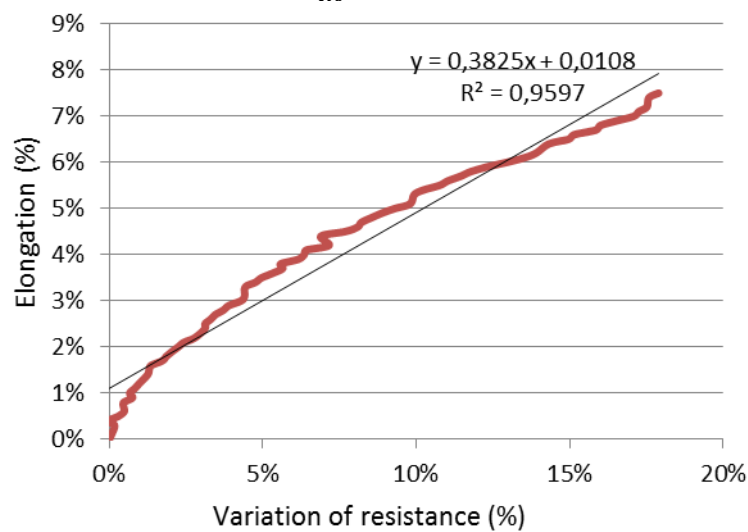


Figure 4 : Determination of linear behaviour between resistivity and elongation of the sensor yarn

The gauge factor (K) is then calculated using Equation 1 between two points P0 (time t0, electrical resistance R0, length L0) and P1 (t1, R1, L1).

$$K = \frac{(R-R_0)}{R_0} \times \frac{L_0}{L-L_0} \quad \text{Equation 1}$$

After this calibration step, sensor yarns are qualified to accurately measure the strain elongation with their own sensitivity given by the gauge factor.

2.3 Measurement of displacement by camera

In order to measure globally the forming behaviour of the initial and flat 3D warp interlock fabric, a set of three cameras has been used to measure the displacement of specific points painted on the fabric surface (see **Figure 5**).

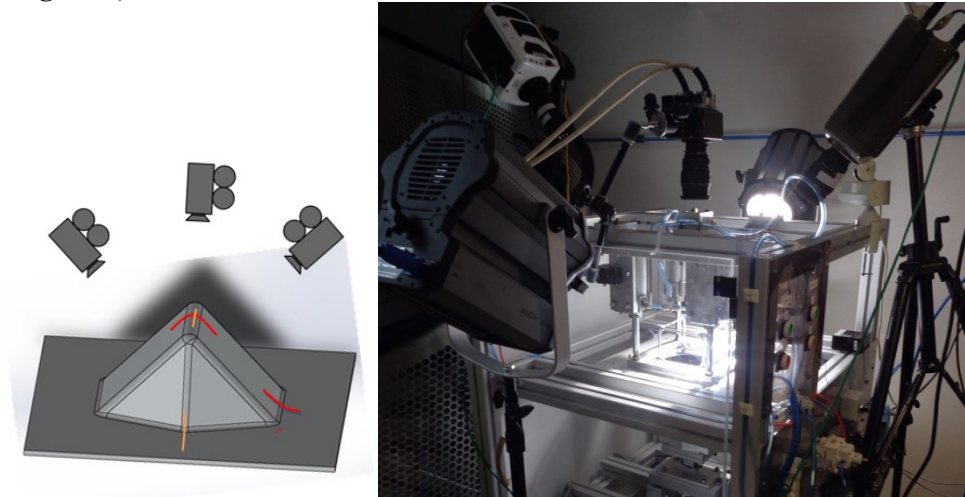


Figure 5 : Locations of the three cameras to observe the kinematic of the 3D fabric forming.

To measure the displacement of specific points, their spatial positions have been calculated by using the tracking software which helps to combine obtained images by the three cameras.

The initial position of points calculated by the tracking software is represented in Figure 6 left with the combination of pictures from camera 1 and camera 2 as shown in Figure 6 middle and right.

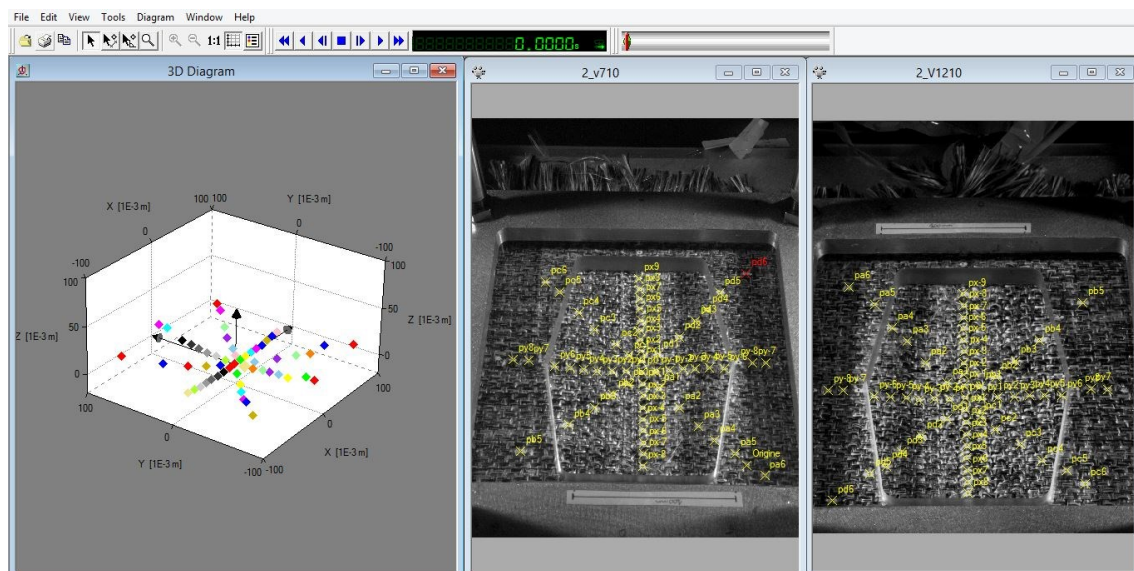


Figure 6 : Initial position of points calculated by the tracking software

2.4 3D warp interlock fabric production

A 3D warp interlock fabric made with E-glass and Polypropylene commingled yarns have been used corresponding to the following definition: 3D warp interlock A-L 6 2-2 Twill 2-2 [21]. This type of architecture has been previously selected based on several criterion of global forming behaviour for the production of 3D shape of thermoplastic composites investigated in the MAPICC project [8].

Different sensor yarns have been implemented inside the 3D warp interlock fabric, particularly at the centre and at the edges, both on the upper side and in the central layer, as represented in **Figure 7**.

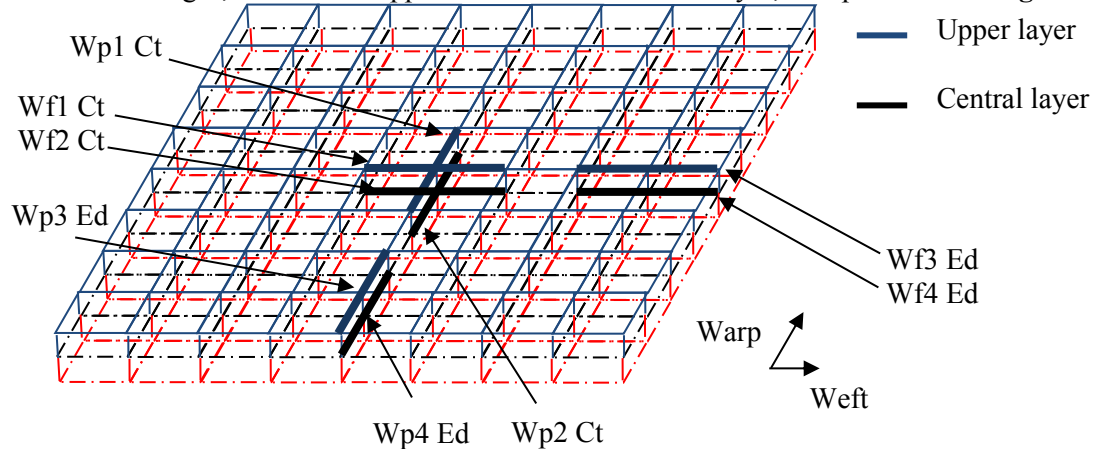


Figure 7 : Locations of the different sensor yarns in the warp and weft directions

Thanks to these 8 inserted sensor yarns, simultaneous measurements of their strain elongations provide in-situ and local understanding of the 3D forming behaviour of the 3D warp interlock fabric.

At the same time, elongation measurements of the 8 different sensor yarns are recorded, respectively:

- in the warp direction at the centre and upper layer for WP1 Ct, central layer for WP2 Ct,
- in the warp direction at the fabric edge and upper layer for WP3 Ed, central layer for WP4 Ed,
- in the weft direction at the centre and upper layer for Wf1 Ct, central layer for Wf2 Ct,
- in the weft direction at the edge and upper layer for Wf3 Ed, central layer for Wf4 Ed.

3. Experimental results

In the warp direction, the measurements of the sensor yarns (Wp1 Ct and Wp3 Ed) (locations described in **Figure 7**) are compared with the relative elongation in zones around the painted points at the upper surface of the fabric and recorded by the cameras.

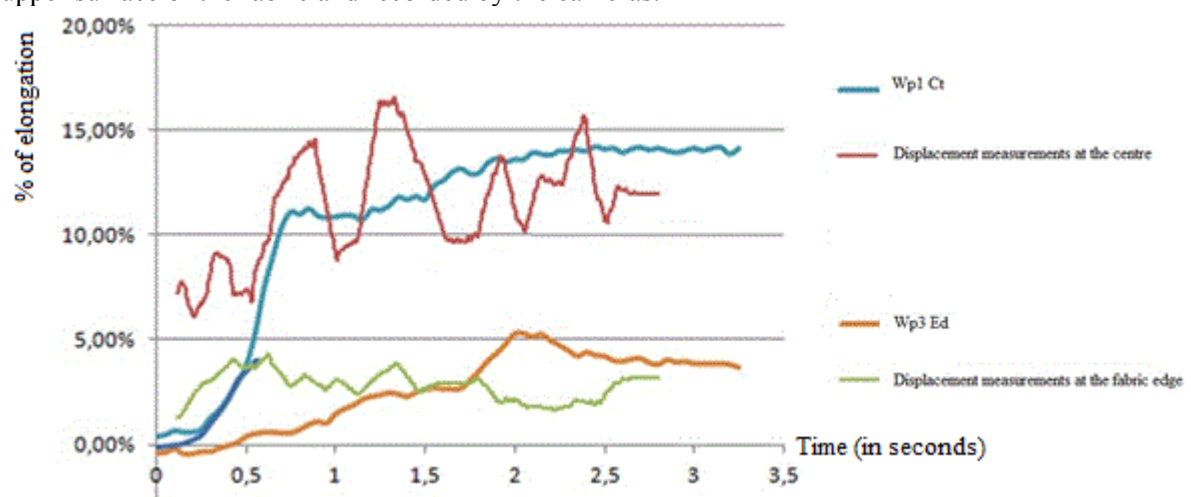


Figure 8. Measurements comparison between sensor yarns (Wp1 Ct and Wp3 Ed) and specific located points at the fabric surface in the warp direction.

In the weft direction, the measurements of the sensor yarns (Wf1 Ct and Wf3 Ed) (locations described in **Figure 7**) are compared with the relative elongation in zones around the painted points at the upper surface of the fabric and recorded by the cameras.

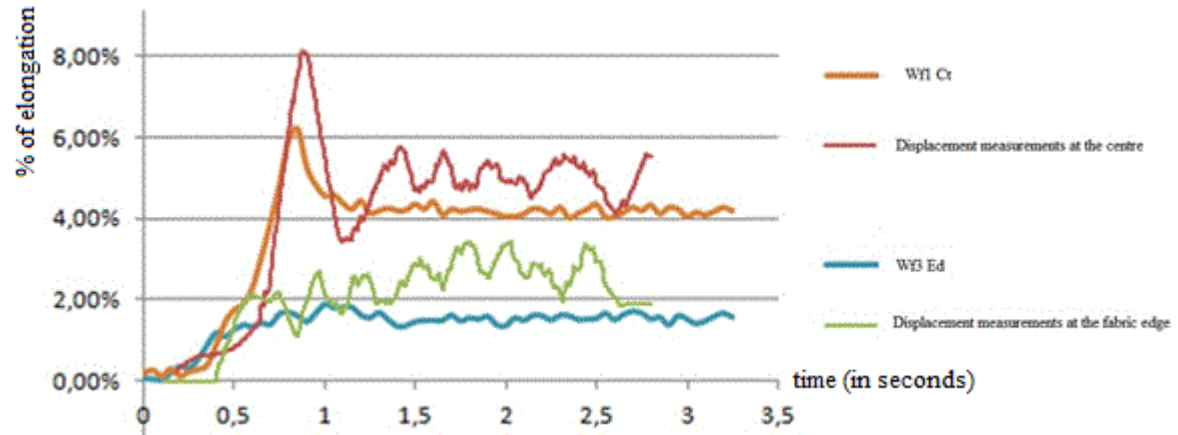


Figure 9. Measurements comparison between sensor yarns (Wf1 Ct and Wf3 Ed) and specific located points at the fabric surface in the weft direction

It has been observed that the measurements done by the sensor yarns are following the same trend as the measurements of painted points located at the fabric surface. Values of measurement are much higher in the warp direction than in the weft direction. Measurements done at the centre are also more important than those at the fabric edge. Elongation values of sensor yarns in the weft direction are lower than in warp direction due to their position in the 3D warp interlock fabric architecture.

4. Conclusion

In this study, we have investigated the forming capacity of thick 3D warp interlock fabric. Existing measurement of forming behaviour can be done by following painted points located at the top surface with specific equipment with cameras. Another possibility consists in using sensor yarns, inserted during the weaving process inside the 3D woven structure, to monitor during the forming process and measure their elongations corresponding to local deformation of the 3D warp interlock fabric. It has been observed a good correlation between strain measurement done globally by camera and locally performed by sensor yarns. The main advantage of this new monitoring of the 3D warp interlock fabric during the forming lies in the additional and accurate measurements of yarn strains located inside the thickness of the structure. Thus, an improved knowledge of 3D warp interlock fabric during forming process using gusset has been reached and helps us to define the suited architecture with respect to yarn's yield, end and pick densities, number of layers and weave diagram.

5. Acknowledgments

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