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3D warp interlocks p-aramid fabrics for composite reinforcement and ballistic vest applications: Effect of yarn density on its formability characteristics

M A Abtew [1,2,3,4,*], C Loghin[1], I Cristian[1], F Boussu[2,3], P Bruniaux[2,3], Y Chen[4] and L Wang[4]
1 Faculty of Textiles, Leather and Industrial Management, Gheorghe Asachi Technical University of Iasi, Iasi, Romania
2 University of Lille 1 Nord de France, Lille, France
[3] Ecole Nationale Supérieure des Arts et Industries Textiles, GEMTEX, Roubaix, France
[4] Soochow University, College of Textile and Clothing Engineering, Suzhou, China

E-mail: abtew.mulat@tuiasi.ro

Abstract. The material forming capability becomes one of the most important characteristic of textile performance in the manufacturing of three-dimensional (3D) components to fit a 3D surface in various technical applications. In this study, different forming characteristics of 3D warp interlock fabrics in dry fabric condition were investigated. 3D warp interlock architecture with different areal density from same para-aramid yarn with a linear density of 168dtex were systematically designed and produced on automatic dobby loom with standard atmospheric conditions. The approach utilizes a low speed forming process with a predefined hemispherical shape of punch for the analysis of different forming behaviour of the fabrics specimen. The same blank-holder pressure was chosen for all the samples for better comparisons. Among several forming properties, some important characteristics have been observed, measured and analysed for a better understanding of the material forming behaviour of the different samples specimen. The research results with independent warp and weft yarn densities show a significant impact on the forming behaviours 3D warp interlock fabric. Moreover, the result of the investigation also will give a better understanding on different forming behaviours of 3D warp interlock fabric with various densities while applying in different textile application including women soft body armour.

1. Introduction

Nowadays developing different textile materials for many technical applications involve low cost manufacturing techniques along with its better specific performances. Due to these reasons, 2D textile fabrics are extensively substituted by the 3D woven fabrics which are developed through advanced textile weaving techniques due to their better performance. For example, according to different researches, 3D woven fabrics show better ballistic and impact resistance with better moulding ability than 2D woven fabrics due to their through-thickness binder fibres in the fabric construction [1-3]. This is mainly due to the integrated fibres into the 3D fabric structure which can increase the resistance both in warp and weft directions [4]. Generally, formability of fabric is largely affected by the freedom of relative movement of yarns within the fabric under small shearing force. Various researchers have been carried out various experimental and theoretical studies to investigate the mouldability behaviour of different textile material and their factors during and after deformation [5-12]. In some composite applications, the material should also possess good mouldability properties in order to develop the three-dimensional shape without further processing. Apart from composite application, in the design and developments of women soft body armour components, good mouldability behaviour of the material with better structural integrity is very important. However, there are different internal and external factors which affect the mouldability properties of 3D warp interlock fabric weave diagrams. The effect of 3D warp interlock woven architectures on moulding behaviour of non-impregnated structure has been investigated using complex shape of punch with edges and corners during low speed forming process. Layer to layer 3D warp interlock fabric architecture with long floats of yarns shows better moulding behaviour [13]. Another study also tried to investigate the mouldability of angle-interlock woven fabrics with different structural parameters using shear test and mouldability tester. Fabric density and number of weft layers show great effects on mouldability of angle interlock fabrics [5].

The purpose of this study is to investigate the formability properties of 3D warp interlock fabrics manufactured with different yarn density. The forming behaviours of preforms were tested using pneumatic formability testing machine using predefined hemispherical punch mounted on a hydraulic press with a low-speed stamping process. The outcome of this study will further helps to incorporate the mention parameter in the forming process while applying the 3D warp interlock fabric as composite reinforcement and in different technical applications including women female soft body armour panel.

2. Materials and experimental methods

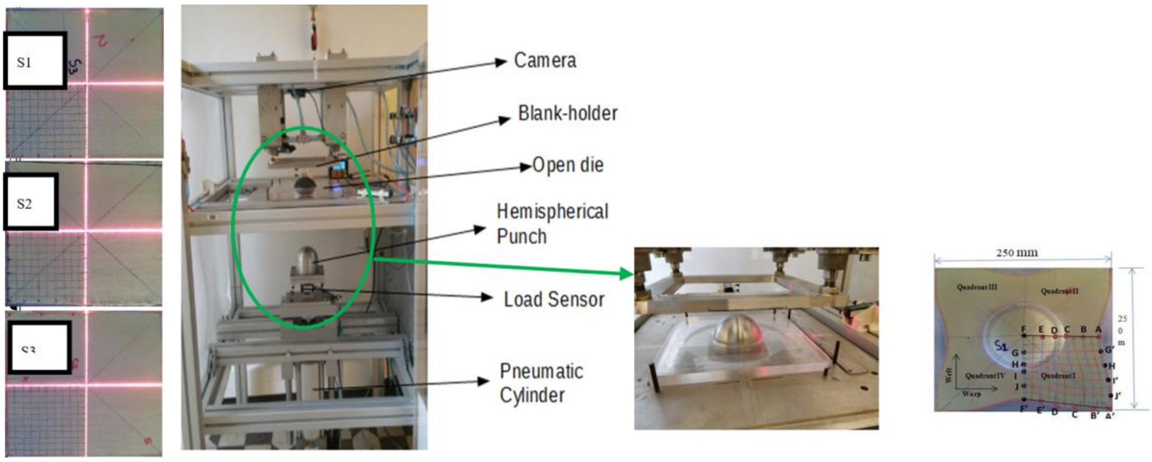
2.1 Materials and sample preparations

Seven layer 3D orthogonal layer-to-layer interlock fabric preforms having different yarn densities were produced using an automatic dobby loom for the test. First, appropriate peg plans for the intended designed fabrics were planned using DB weave software and then transferred to the machine for production. The three different 3D warp interlock fabrics were produced with similar warp and weft para-aramid 168Tex yarns. The three fabrics (S_1, S_2 and S_3) were manufactured with 49, 38 and 64 weft yarns/cm and 32, 42 and 35 warp yarns/cm respectively. From each fabric, five replicas of squared 250 mm X 250 mm dimensions were prepared and tracking lines were drawn on the quarter surface of preform for better forming property analysis as illustrated in Figure 1 (a). Before and after forming test, the samples were "conditioned" under standard conditions of relative humidity and temperature in order to avoid the effect of moisture content and regain during and after formability testing for further analysis.

2.2 *Mouldability property test*

A specific and modified pneumatic based formability testing machine which is adapted to a fast, safe and ambient temperature stamping process has been used. Moreover, a predefined hemispherical punch mounted in a hydraulic press with low stamping process were used to form the different 3D warp interlock and 2D fabric sample preforms with similar parameters. Different important parameters including the blank holder pressure and velocity of the punch have to be properly considered and settled throughout the forming process for better deformability results. The test was carried out using constant stamping velocity of 45 mm/s, 2 bars (0.2MPa) blank-holder pressure and deformed using a 150mm diameter hemispherical punch at the preforms centre to a depth of 65mm. Figure 1 shows the Pneumatic based mouldability testing machine set up and the moulding process. The bench consists of static blank holder, an open die and pressure actuators for applying pressure at the four edges of the preform at the top of the bench.

The required shape of different 3D warp interlock fabric sample (S_1, S_2 and S_3 as indicated in Figure 1(a) was given by the hemispherical non-heating punch through controlled vertical motion governed by four pneumatic jacks at the bottom of the machine as shown in Figure 1 (b). The local and global information of the test were captured using digital camera located on the top of the forming bench while forming process as shown in Figure 1 (c).



a) b) c)

Figure 1. Pneumatic based mouldability testing machine set up and the moulding process (a) The prepared sample preforms, (b) Forming machine set-up and (c) Deformed samples.

3. Results and discussion

The forming behaviour of 3D warp interlock fabrics produced with different yarn densities of p-aramid fibre has been analysed and discussed in this sections.

3.1 Evolution of punching force with time while forming process

During the forming process, the punching load values and its corresponding average punching time of different 3D warp interlock preforms were automatically recorded. While testing, we have tried to keep constant both the external and internal parameters during forming of the different preforms for better result and comparisons. The preforms show (Figure 2) similar force vs. time curve trends with different categorised parts.

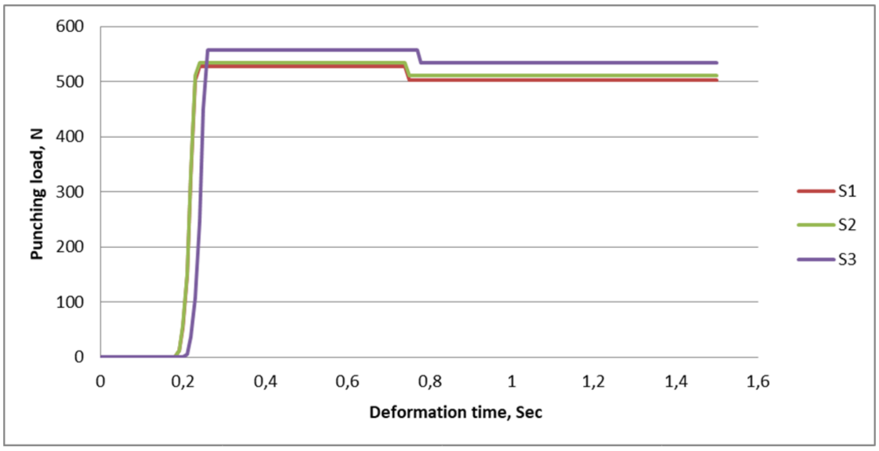


Figure 2. Stamping force vs. moulding time relationship while deformation of different preforms.

First, the force has a very small value and then rapidly increased through time until maximum deformational height has been reached. Then, the force becomes constant when the maximum deformational height of the preform reached to keep the final deformed shapes for all preforms. Based on Figure 2, the result clearly shows that sample S_3 with higher fabric density possesses higher punching load with time to attain the maximum deformational shape than the other preforms. Moreover, as it is observed, both sample S_1 and S_2 show similar curve trend and quasi equal punching load amount throughout the curve due to their very close fabric density. Similarly, since the deformation is directly related to the load, sample S_3 shows maximum load and maximum displacement, whereas sample S_2 shows minimum load and displacement. This indicates that fabric density has also a positive influence, and directly proportional to the load vs. moulding displacement. This shows the punching force needed for forming the different preforms to achieve the predefined maximum deformation is influenced by fabric density of the preforms.

3.2 Material drawing-in value while forming
In the material forming process, in general the dimensions of the sample preforms in every direction will be deformed. Such deformations of material will bring the consumptions of some of the preforms dimension toward the centre of deformation. This consumption of materials' dimensions is called drawing-in values. However, such material consumption during forming will have different values for the different material. This is due to the fact that, consumed material draw-in values will be affected by based on internal and external factors including material characteristics. Among the different material characteristic, fabric density.is considered one of the main factor which could affect the forming behaviours of the textile materials. In our investigations, the values of the material draw-in values were observed during forming process. Precise photographic pictures for the formed preforms were taken at the centre top surface at reasonable distant for analysing the different forming behaviours including drawing-in values as shown in Figure 1(c).

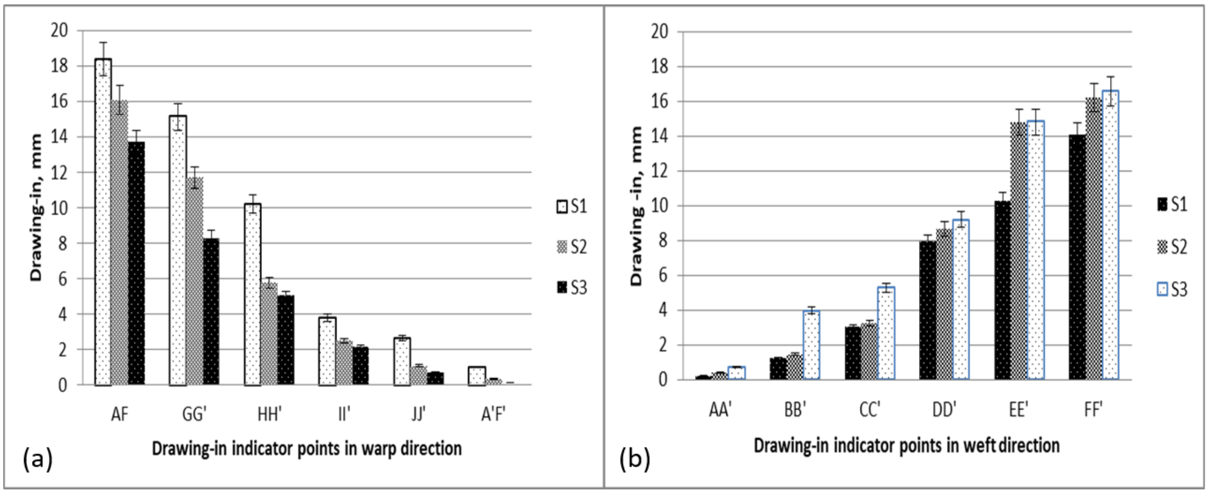


Figure 3. Drawing-in values of preforms at different selected points in (a) warp, and (b) weft directions.

Its values for the different preforms were analysed using a quarter of the deformed materials since its values is expected similar to the other four quadrant sides. The effects of fabric density while developing 3D warp interlock fabrics on the drawing-in values of preforms both in the warp and weft directions during forming are presented in Figure 3(a) and (b).

Based on the observation, even though the overall fabric density has an effect, weft and warp yarn density also independently shows an effect on material drawing-in values in its respective yarn directions. For example, S_3 has very less drawing-in values while deformation as compared to the

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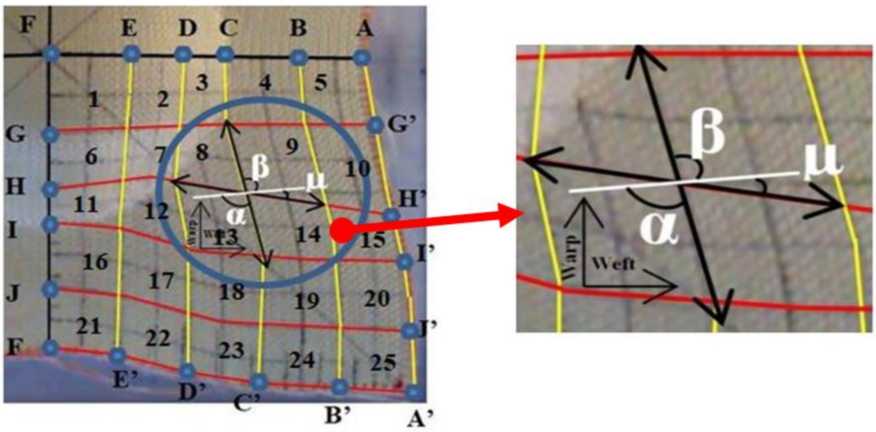
other 3D warp interlock samples, namely S_1 and S_2 in all indicated regions of warp direction. However, S_3 shows better drawing-in value in the weft direction relative to the other 3D warp interlock fabric samples. This shows that even though S_3 has higher overall fabrics density than all the samples, its drawing-in values were affected by the corresponding yarn density both in weft and warp direction compared to the other preforms. This is also supported by the other sample; sample $S_{1,}$ which shows a better drawing-in values as compared to sample S_2 and S_3 in warp direction than in weft direction. Besides, the maximum and minimum drawing values were achieved at the central and edge points of the preform while forming. The drawing-values are inversely proportional to the yarn density in their respective directions. Samples S_1 and S_3 show the maximum and minimum drawing-in values at central points of warp direction (Point AF) and maximum central point's drawing-in values in weft direction (point FF'). This is due to the fact that, sample S_3 has high warp density and less weft yarn density as compared to the other 3D warp interlock fabrics.

3.3 In-plane surface shear angle of different fabrics while deformation

Intra-ply shear is one of the most important properties which determine how a fabric will behave when subjected to a wide variety of complex deformations and considered as the primary deformation mechanism during forming of o 3D shapes. It is also characterized by a change of fibres orientation, due to rotation of the yarns at their crossovers. The amount of in-plane shear is indicated by a shear angle μ, which is defined as the complement of the enclosed angle, (α and β), between the warp and the weft yarns as indicated in Figure 4 (b). Shear angle (μ) is the difference between the extended angles measured while deformation to the angle of initial position.

After capturing the deformed preform efficiently, the in-plane shear angles were measured using ImageJ software with an accuracy of ±0.1°. The average in-plane shear angle values of one quadrant were used to represent the other surface due to its quasi-symmetric moulding by hemispherical punching as shown in Figure 4 (a).



a) b)

Figure 4. (a) Quadrant (1/4th) sectionss of preformed sample (b) In-plane shear angle measurement, and (c) In-plane shear angles measurement at different sub-regions of the quadrant sections.

As discussed earlier, for each sub-region the two opposite angles designated as: α and β, show the angle values between warp and weft yarns at initial position before deformations. After forming process, the in-plane shear angle measurement of the different preform for each category were measured based on Figure 4 (b).

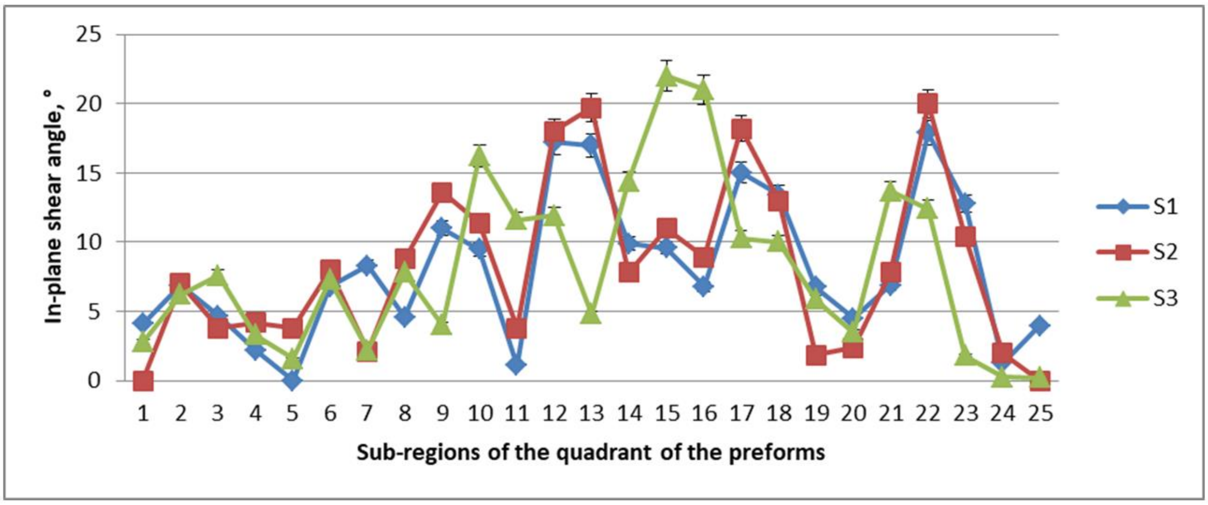


Figure 5. In-plane shear angles measurement of the different preform at catagorized sub-regions of the quadrant sections.

As shown in the Figure 5, even though there is no very clear relation between the obtained results, sample S_2 shows higher in-plane shear angle values as compared to the other preform in majority sub-regions. On the contrary, S_3 shows the lower in-plane shear values as compared to other 3D warp interlock sample preforms. This shows that the fabric density has an impact in shear angle and as it is increased, the in-plane shear angle values of the sub-region have been decreased. This might be due to the fact that as the yarn density increases, they are coming closer and compresses in the sub-region. Consequently, the compressed yarns can increased the shear angle value which later has a probability of reaching the shear locking point. However, due to complexity for better understanding, the quadrant sections were further segregated to different sub-regions.

Table 1. In-plane shear angle segregation in sub-regions.

No.	Range of shear angle	Designated colour for region
1.	0 – 3.99	White
2.	4 – 6.99	Green
3.	7 – 9.99	Blue
4.	10 – 13.99	Yellow
5.	≥ 13	Red

The designation and categorizations of the different sub-region in two smaller groups were classified using with different colour as shown in Table 1.

4. Conclusions

This particular study investigated the effect of density on the formability behaviours of 3D warp interlock fabrics for the applications of composite and light weight ballistic vests. Based on the investigations result, maximum punching load vs. time to get highest deformation was observed in 3D warp interlock sample with higher fabric density. This clearly showed that fabric density has an impact and directly proportional to the punching force which is needed for forming the different preforms to achieve the predefined maximum deformation at specified time. This is due to the fact that, preform with high fabric density is more rigid and consequently needs high punching loads than the smaller fabric density preform. Further analysis of the investigation also shows that even though the overall fabric density showed an effect on the deformability, drawing-in values in specific direction were mainly influenced by the respective yarn densities. Moreover, as it is also observed, even if there are no clear inter-relations between in-plane shear angle with preform fabric density, S_3 and S_1 show higher and lower shear angle as compared to the other preform in majority sub-regions. As the fabric density increases, the in-plane shear angle of the sub-region has been reduced. This might be due to the fact that as the yarn density increases, they becomes closer and compresses in the sub-region which also creates more rigid fabric with high frictional resistance between the yarns to resist the shear angle formation and its recover from the deformed positions.

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