Influent product and process parameters on the mechanical behaviour of 3D warp interlock fabrics made with E-glass yarns

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Abstract. 3D weaving process has been more and more used as reinforcement for composite materials. However, 3D weaving applications are recent and the mechanical properties of the 3D warp interlock fabrics are not well known. Tensile tests have been performed both in the warp and weft directions of the fabrics, indeed they lead to different behaviour regarding the architecture. Results from experiments have been statistically analysed using PLS regression. This study led to correlations between fabrics parameters and mechanical behaviour. Moreover, it revealed that fabrics parameters such as the binding type, the yarns crimp and the picks density have influence on the quasi-static mechanical behaviour.

Keywords: 3-D reinforcement; Mechanical properties; Weaving; E-glass fibres; Para-aramid fibres.

1. Introduction
Textile architectures used as fibrous reinforcement for composite material can be declined into various structures depending on their initial process. Planar or tubular parts can be easily obtained from large scale production processes as flat weaving and knitting, braiding and tubular knitting, non-woven and non-crimp fabrics [1,2]. However, the choice of the suited textile architecture, according to the several process and product parameters as well as the manufacturing costs and quality, seems to be quite a challenge [3,4]. To solve this issue, a better knowledge of the textile material may help to find the suited architecture for the dedicated final application [5,6]. Among all these textile materials, 3D fabrics and, especially the 3D warp interlock fabrics, have been largely described as a promising solution for many applications due to their specific consolidation mode into the thickness [7]. Due to the presence of the linking warp yarns inside the thickness of the 3D warp interlock fabric architecture [8], they tend to increase the quasi-static intra-ply delamination resistance [9-13] and high speed impact resistance [14-19].

Despite all of these existing research results, the optimized combination of product and process parameters of a 3D warp interlock fabric, responding to given specifications of the final composite material solution, still remains a challenge. One of the reasons that could explain this difficulty may lie in the lack of experimental and modelling knowledge of this specific 3D textile reinforcement. Moreover, clear understanding of the influence of product and process parameters, considered alone or combined together, has not yet been revealed.

Thus, the objective of this paper is to provide additional knowledge on mechanical behaviour of different 3D warp interlock fabric architectures made with different types of yarn’s raw material,
especially E-glass and para-aramid yarns. An experimental characterization of these different 3D woven architectures has been achieved to measure the influence of product parameters on their mechanical behaviour in tensile and bending. Then, a statistical analysis will help us to highlight the influent product and process parameters according to their different mechanical behaviours.

2. Material and Methods
Several woven architectures have been considered to measure their influence on the mechanical behaviour of 3D warp interlock fabrics.

2.1. Types of raw materials
It has been decided to use the E-glass EC9 900 Tex (see Table 1).

| Type of yarn | Provider (Country) | Nominal linear density (Tex) | Maximal breaking force (N) | Elongation at maximal breaking force (%) | Tenacity (N/Tex) | Tenacity (MPa) |
|--------------|-------------------|-----------------------------|---------------------------|-----------------------------------------|-----------------|---------------|
| E-glass      | PPG (US)          | 900                         | 308.0 ± 48.1              | 2.7 ± 0.4                                | 0.96            | 2526          |

2.2. List of architectures
All these architectures have been produced on the same dobby loom in order to keep constant the process parameters; as the end density to 10 warp yarns/cm. The chosen architectures aim at reflecting the existing classification of 3D warp interlock fabrics [11] with Angle (A) or Orthogonal (O) binding warp yarns types and Layer-to-layer (L) or Through-the-thickness (T) linking warp yarns paths. A total of 3 layers of weft yarns for the 3D warp interlock fabrics without stuffer warp yarns and 4 layers of weft yarns for the 3D warp interlock fabrics with stuffer warp yarns have been chosen. Different well-known weave diagrams as Twill, Satin and Basket have been selected to measure their influence on their mechanical behaviour.

3. Results and discussion
According to the obtained results based on different physical and mechanical characteristics of the 3D warp interlock fabrics, explanations of material behaviour could be linked to the different product parameters. Assuming that the number of tests done is sufficient, the use of a statistic tool could help us to more deeply detect these product parameters influences on the material behaviour of the different 3D warp interlock fabrics.

3.1. Introduction to PLS Regression
The PLS Regression [20][21] has been used in this study in order to find potential links between fabric properties and tensile behaviour that have not necessarily been revealed in the previous analysis. Moreover, the low number of samples can lead to high standard deviation, so these results have to be compared with global analysis. For each architecture, the explanatory variables that are assumed independent are: the binding step, the binding depth, the picks density, the binding warp yarns average crimp, the stuffer warp yarns average crimp, the weft yarns average crimp, the binding angle A, the binding angle O, the binding path L, the binding path T.

3.2. Results with PLS Regression
Figure 1 shows results for E-Glass fabrics. Maximal load and strain at maximal load have been analysed with PLS Regression. These graphs show the fabrics characteristics that are the most influent on a mechanical parameter. It can increase or decrease the value of this parameter. For instance, regarding maximal load in the weft direction, picks density has the highest influence on
maximal load increase, whereas O binding angle has the highest influence on maximal load decrease.

Figure 1. Influent parameters on tensile behaviour for E-glass fabrics.

Considering the obtained results, the main influent parameters as the pick density in the weft direction and stuffer warp yarns crimp in the warp direction are highlighted regarding their link to the mechanical behaviour of 3D warp interlock fabrics made with E-glass yarns. However, second order influent parameters as: the binding depth, O and A binding type, binding warp crimp, L and T binding path may explain the difference of mechanical performance of 3D warp interlock fabrics made with E-glass yarns. For instance, for the strain at maximum load in the warp direction (for the first peak), more the binding depth value is, higher the strain value will be. This binding depth reflects the capacity of the binding warp yarn to be “stored” in the thickness of the 3D woven architecture which could help the material to more elongate during tensile test and increase the global strain value. On the contrary, more the binding depth value is high, less the maximum load, the strain at maximum load will be in the weft direction. This reflects a resulted inverse behaviour in the warp and weft directions of the 3D warp interlock fabrics.

By the same, more the binding path of 3D warp interlock fabric is close to L binding, less the strain value at maximal load value will be. This L binding path reflects also the capacity of the yarn to be layer to layer linked in the thickness of the 3D warp interlock fabrics and then tend to be more “straight” compared to T binding (through-the-thickness) which consume more length of binding yarn inside the 3D woven structure.

4. Conclusion

The main objective of this study aims at providing more knowledge on 3D woven structures used as fibrous reinforcement for composite material, especially here the 3D warp interlock fabrics. Several architectures, based on the existing classification into four main clusters as O-L, O-T, A-L and A-T woven structures, have been designed and produced with the same E-glass yarns. Several physical and mechanical parameters have been chosen to characterize these 3D warp interlock fabrics both in the warp and weft directions as: the bending rigidity, the warp and weft yarn crimp, the strain at maximum load and the maximum load values. A deeper analysis, done with PLS regression statistical tool, have revealed second order increasing and decreasing influent parameters, whom mechanical behaviour of 3D warp interlock fabric depends on.
Future works will be engaged to test the same types of 3D warp interlock fabrics with other raw materials types. Additionally, bias tests and forming tests will be also studied to check the material behaviours of 3D warp interlock fabrics to provide complementary knowledge on their moulding capacity for complex 3D shape of composite materials.

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