Manufacture and characterization of 3D warp interlock fabric made of flax roving

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Abstract. The present study carries on the characterization of dry reinforcement structure for composite material. Yarn properties were analyzed to select the optimal level of twist. The influence of 3D-warp interlock structure’s bending type was also investigated. Structures, made with 1000Tex flax roving, were woven on a dobby loom. Physical characterization and mechanical testing (tensile test) were conducted on the four different binding structures (AL, AT, OL and OT) to provide relevant data and identify the influence of the binding warp yarns’ path inside 3D warp interlock structure.

1. Introduction

The number of publications about composites materials reinforced by natural fibre keeps increasing. Flax fibre is the strongest natural fibre, with a Young's modulus nearby 100 GPa [1]. Flax is a cellulosic fibre. Extracting the fibre from the plant is a long and specific process. The use of flax fibre as reinforcement structure became common in automotive and sport sectors [2] by the end of the 70's. Fibre architecture and fibre ratio have a preponderant role on the composite material's mechanical properties and failure mode [3, 4].

The main role of fabric inside a composite material is to resist to mechanical stress. Nowadays, most of the composites are made of multi-layers 2D woven fabrics. A 3D-warp interlock fabric is a multi-layer fabric in which layers are linked together by binding warp yarns [4]. This structure allows linking yarns on the z-direction, unlike 2D woven fabrics. Consequently, composite based on 3D-warp interlock structure shows higher through the thickness strength, delamination resistance and interesting improvement in impact damage tolerance [5]. 3D warp interlock fabrics are studied under many other aspect as characterization [6-11], or 3D modelling [8, 10-13].

Characterization of the roving can help us to optimise the process of weaving. Influence of twist value, for a given value of linear density of the roving, on tensile parameter was analysed. The most suitable value of twist was selected to proceed to the weaving. The aim of this study is to investigate the influence of 3D warp interlock structure's bending type, on dry preform. Structures, made with 1000Tex flax roving, were woven on a Dornier HTVS 4/S dobby loom machine. The weaving of 3D warp interlock structure requires weaving machine's adaptation [14-16]. For example, inserting weft yarn system must be adapted to thick fabric. The speed of weaving is significantly lower. This kind of fabric is also more subject to abrasion than traditional 2D fabric.

Physical characterization and mechanical testing have been conducted on four structures with different binding types to identify their influence on 3D warp interlock structure behaviour.
2. Materials and methods
Roving characterization has been realized first, and then 3D warp interlock fabric characterization.

2.1. Roving scale
Rovings used in this study were provided by Depestele Group, France. Two different linear densities have been compared. Roving is not twisted, only a cohesion agent maintains the filaments inside the yarn and contributes to 10% of the weight of the roving.

At this scale, the linear density, the twist level, and the tensile behaviour have been studied. Twist has been measured according to the ISO 2061 standard. Tensile test has been realized according to NF EN 2062 standard. The tensile machine is equipped of a 10kN cell. The length of the sample is 200mm. A preloading of 2N is applied before starting the test. The displacement rate during the test is 100mm/min. The tenacity, which allows comparing different linear density, is determined by

\[
\text{Tenacity} = \frac{\text{Load}}{\text{Linear density}}
\]  

2.2. 3D warp interlock scale

2.2.1. Definition
3D warp interlock fabric links the different layers of the weft yarns through-the-thickness thanks to binding warp yarns. Binding warp yarns, of this fabric, can be characterized by their path in the structure [4].

![Figure 1: Scheme of 3D warp interlock fabric with the constitutive yarn](image)

Surface weaver warp yarns (Figure 1, 1) give a specific surface aspect. Stuffer warp yarns (3) define longitudinal properties of the fabric. Binding warp yarns (4) define through the thickness properties of the fabric and ensure cohesion. Weft yarns (2) guarantee transverse properties of the fabric and define the number of layer of the fabric. Boussu et al. [3] sorted this fabric depending on the path of the binding warp yarn in the fabric. Binding warp yarn can be inserted diagonally (A, angle) or perpendicularly (O, orthogonal) to the surface of the fabric. The binding warp yarn can link a part of (L, layer to layer) or the whole (T, through the thickness) layer of the fabric. Figure 2 and 3 illustrate the four different types of woven diagrams. The placement of the binding warp yarns depends on the selected weave diagram.
2.2.2. Parameters of production
A dobby loom (Figure 4) has been used to produce 3D warp interlock fabrics. Warp and weft yarns are 1000Tex flax roving. Four structures, corresponding to the four binding types, have been woven. The selected weave diagram is Twill 6, weft effect. The warp and weft densities are respectively 5 and 13 yarns/cm.

![Figure 4: Production on dobby weaving loom](image)

2.2.3. Characterization
The thickness of the manufacturing fabrics is determined according to the NF ISO 4603 standard. More than 30 samples have been done. Average values of mechanical test with standard deviation have been calculated. The areal density is determined according to the NF EN 12127 standard. Warp and weft
densities are checked according to the NF ISO 4602. Warp crimp is determined according to the ISO 7211-3 standard. Binding and stuffer warp yarns crimp are determined separately and for each layer of the fabric.

Tensile tests have been realized according to the ISO 13934 standard. The size of the sample is wider than the one stated in the standard, in order to keep at least two complete woven patterns. A preloading of 10N is applied before starting the test. Then the displacement rate of the test is 100mm/min. Five samples are tested in warp and weft directions.

3. Result and discussion

3.1. Result of the roving characterization

3.1.1. Linear density

Figure 5 shows linear density of two different rovings (Tex 500 and Tex 1000) as a function of the twist. During twisting the linear density increases. Fibres lose their alignment, and twist counterbalance the gain of weight.

![Figure 5: Linear density versus twist](image)

3.1.2. Tensile test results

For the two linear densities, the tenacity and strain at break seem to have a similar evolution (Figure 6 and 7). The tenacity first increases until a maximum, and then decreases. First, the twist gives to the roving a higher mechanical performance by increasing the cohesion. After a specific number of twists, the loss of alignment of fibres in the roving is the cause of the decrease of properties. This specific number of twist is close to 75 rounds/m.

The strain at break increases as a function of the twist value. The number of fibres in the cross-section increases and the roving becomes stiffer.
Figure 6: Tenacity of the two linear densities versus twist

Figure 7: Deformation of the two linear densities versus twist
3.2. Results of the characterization of 3D warp interlock fabrics
A twist of 30 rd/m was selected to realize the woven structure. As the permeability decreases as twist level increases, this twist value was chosen to have equilibrium in properties.

3.2.1. War and weft densities
The warp density is determined during the warping step. The weft density is defined during the weaving. Results in Figure 8 can also be expressed by column by centimetre. Warp densities are slightly higher than the instruction and weft densities are slightly lower than the instruction. These differences are caused by the crimp of fabric after the weaving.

![Figure 8: Warp and weft densities of the four manufactured 3D warp interlock fabrics](image)

3.2.2. Warp crimp
The digit following term “Weaver” or “Stuffer” in Figure 9, is the minimum depth of the yarn in the 3D warp interlock structure. According to this definition, T structures which only have a binding yarn's path, don't show results in other depth. These structures present a higher binding warp crimp than L structures. The length of roving used to weave this type of structure depends on the geometry (cf. Figure 2). For similar reasons, O structures present a higher binding warp crimp than A structures.

The weft crimp was also studied. The stuffer warp crimp and the weft crimp evolve in order to stabilize the fabric after the weaving.
3.2.3. **Thickness and areal density**

Figure 10 presents results of the thickness determination for the four fabrics. L structures present a higher thickness than T structures. The binding warp yarn, through the thickness of L structures, creates over-thickness.

Figure 11 presents results of thickness measurements. According to these density values, the theoretical areal density must be 1.8kg/m². Experimental values are close to this theoretical value. The difference between these values is caused by the crimps of the fabric after weaving.
**Figure 10:** Thickness of the four manufactured 3D warp interlock fabrics

**Figure 11:** Areal density of the four manufactured 3D warp interlock fabrics
3.2.4. *Tensile tests*

Figure 12 displays a typical load-strain curve obtained during a tensile test, in the warp direction, of the structure A-T. The first peak is caused by the stuffer warp yarns' failure. The second peak is caused by the binding warp yarns' failure. This phenomena displays only on T structures. The distance between the peaks depends on the difference of length between stuffer warp yarn and binding warp yarn.

Figures 13 and 14 display averaged results of the tensile tests. Divided by the number of yarns in the tested section, the failure load is in the same order of magnitude for all tested fabrics. The stress at the first peak in warp direction and the deformation at break in weft direction are also in the same order of magnitude. In both case, stuffer warp yarn and weft yarn present the same failure load and deformation. The deformation failure of binding warp yarns depends on the crimp of the binding warps and the deformation failure of the stuffer warp yarns.

![Load-strain curve for A-T structure in warp direction obtained on the tensile test machine](image)

**Figure 12:** Load-strain curve for A-T structure in warp direction obtained on the tensile test machine
Figure 13: Failure load of the four manufactured 3D warp interlock fabrics (warp & weft directions)

Figure 14: Deformation failure of the four manufactured 3D warp interlock fabrics
4. Conclusion

The optimized twist value in order to increase the mechanical performance of the 3D warp interlock fabric has been identified. Linear densities and deformation at failure are increasing function of the twist. Tenacities are also depending on the twist until a maximum value, after which the performance decreases.

The binding warp yarn's path of 3D warp interlock fabric affects different properties as the thickness, the density, the crimp or the tensile behaviour. The most remarkable phenomena is provided by T path structures with the appearance of a second peak during the tensile test. Bias and preforming tests will be realized to complete the study.

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