Development of 3D warp interlock fabrics based on moroccan natural fibers

Z Samouh\textsuperscript{1,2,3,4}, O Cherkaoui\textsuperscript{2}, D Soulat\textsuperscript{4}, A R Labanieh\textsuperscript{3}, F Boussu\textsuperscript{3} and R El moznine\textsuperscript{1}

\textsuperscript{1}Laboratory LPMC, Faculty of Science El Jadida, Chouaib Doukkali University, EL Jadida, Morocco
\textsuperscript{2}Laboratory REMTEX, ESITH (Higher School of Textile and Clothing Industries), Casablanca, Morocco
\textsuperscript{3}Laboratory GEMTEX, ENSAIT, Univ. Lille North of France, F-59100 Roubaix, France
\textsuperscript{4}Author to whom any correspondence should be addressed

zineb.samouh@gmail.com

Abstract. The aim of this research is the valorization of Moroccan natural resources through the manufacturing of innovative 3D interlocks textiles. In order to investigate the potential of the sisal yarns used into 3D warp interlock fabrics, the 3D fabrics were studied at multi-scales (micro-scale, meso-scale and macro-scale). Before starting the manufacture of the 3D fabrics, different physical properties of the sisal fibers were analyzed according to standards. At the meso-scale, the mechanical and thermal properties of the sisal yarns constituting the 3D warp interlock fabric were studied according to standards. After these yarns and fibers characterizations, different types of architecture of the 3D warp interlock fabric have been designed and produced. Some difficulties have been revealed during the weaving process, which highlights the difficulty to handle the sisal yarns in order to obtain 3D fabrics to be used as a future fibrous reinforcement for composite material.

1. Introduction

Environmental issues, such as the greenhouse effect, the CO\textsubscript{2} emission and climate change have led researchers to develop alternative biomaterials to replace conventional ones. Scientists have found that natural fibers are one of the alternatives to synthetic fibers, offering several advantages including renewability, low density and biodegradability. Natural fibers, such as flax, bamboo, can be prepared into different forms (non-woven, unidirectional, bidirectional...etc.) for different applications mostly in composite materials [1, 2].

Among the fibrous structures applied in composite materials, 2D fabrics are characterized by their good mechanical properties in plane of the fabric. However, stacking of bidirectional woven structures without any through-the-thickness linking points provides low delamination resistant fibrous reinforcement for composite material. For this reason, the introduction of three-dimensional woven structures as reinforcement of composite materials seems to be interesting to improve the mechanical properties of the preforms applied to aerospace and automotive [3].

Several scientific works are carried out to develop and study the 3D warp interlock woven fabrics based on synthetic fibers used in the fields of aeronautics, space and/or defense as protective structures.
The complex behavior of 3D warp interlock woven structures is due to the multi-scale appearance of these textiles. In the literature, several stages of the elaboration of the fibrous elements are necessary to manufacture the 3D warp interlock textile. In other words, the elaboration of the 3D fabric is based on the development of the fibrous element (from the fiber to the yarn, then from the yarn to the elementary pattern and finally from the elementary pattern to the 3D fabric) [4, 5].

In general, fibers used for the manufacture of 3D woven structures are synthetic fibers such as glass fibers, carbon fibers...etc. [3]. However, the exploitation of the natural fibers to develop the 3D fabric is limited, e.g. flax [6]. The current work is a Franco-Moroccan bilateral cooperation program. This collaboration aims to broaden the field of application of Moroccan natural fibers and more precisely in the development of multi-layered fiber reinforcements.

Among the natural Moroccan fibers, pine cone fibers [7] and doum fibers [8] are the ones used to develop biocomposites. Sisal fiber, which we used, is originally from the northern regions of Morocco [9] and is currently applied mainly in traditional medicine [10]. Sisal plant is one of the most widely used natural fiber sources and is very easy to cultivate. In our study, it has been extracted from the leaves of one agave specie plant (*Agave sisalana*).

This work was carried out to develop the 3D warp interlock textiles based on Moroccan sisal fiber. The 3D fabrics were studied in multi-scale approach (micro-scale, meso-scale and macro-scale) to better understand their mechanical behaviors. Additionally, the study unveiled the difficulties to produce the 3D warp interlock fabrics at each step of the production.

2. **Materials and Method**

The preforms elaborated in this work are described under the micro-scopic, meso-scopic and macro-scopic scales in order to understand the behavior of these structures.

2.1 **Characterization of 3D warp interlock textiles at microscale**

The description of the 3D interlock structure in the microscopic scale corresponds to the smallest entity of the final preform, which is the fiber. In our work, the fiber used is a Moroccan sisal fiber. The tensile properties of the sisal fiber were analyzed according to ISO 507 standard, using universal load machine Zwick Z005.

2.2 **Characterization of 3D warp interlock fabrics at mesoscale**

At this scale, the properties of the yarn are identified. The yarn placement and their interlacement pattern inside the structure are studied. The sisal yarn used in this work were chosen from several types of twisted sisal yarns marketed by the Moroccan company *Sonajute*. The chosen type was 300/1. The properties of sisal yarns were analyzed according to the standard norms. The geometrical representation of the 3D fabric in the mesoscale is based on the definition of the 3D warp interlock fabric and the types of yarns constituting the preform. Boussu et al. [11], offers a general definition of the different components of the 3D warp interlock fabric (number of warp yarns, number of weft yarns, number of layers, woven pattern ...) to better describe the position of the different yarns located inside the woven structure. The studied 3D warp interlock fabrics of this work belong to the classification of 3D warp interlock fabrics. Based on the general definition given by Boussu et al. [11], the 3D interlock fabric is defined in Equation 1 [11]:

\[
3\text{D warp interlock } X_1^2 X_2 \{N\} Y_{1k}^2 Y_{2k}^2 \text{ Binding } W_{bk}^2 \{B_{ki}\} \text{ Surface } W_s^2 \{C_i\} \text{ Stuffer } S_i
\]  

(1)

Where:

- \(X_1\) represents the type of angle of binding warp yarn, O (orthogonal) or A (angle)
- \(X_2\) corresponds to the type of depth of the binding warp yarn, L (layer to layer) or T (through the thickness)
- \(\{N\}\) corresponds to the repetitive sequence of the different number of weft layers for each column of the 3D warp interlock fabric elementary pattern.
- \(Y_{1k}\) is equal to the path of the binding warp yarn of group \(k\)
- \(Y_{2k}\) is equal to the depth of the binding warp yarn of group \(k\)
• Binding term corresponds to binding warp yarns
• Wbk is related to the type of weave diagram on fabric surface of binding warp yarns of group k
• Bk i contains the numbering of binding warp yarns of group k with inter-ply i position
• Surface term corresponds to surface weave warp yarns and disappears if surface weave
  warp yarns are not included
• Ws is related to the type of weave diagram of surface weave warp yarns
• Ci contains the numbering of surface weave warp yarns with inter-ply i position
• Stuffer term corresponds to stuffer warp yarns and disappears if stuffer warp yarns are not included
• Si represents the numbering of stuffer warp yarns with inter-ply i position.

In order to describe the architecture and geometrical properties of the preform at the mesoscale the
definition of the 3D warp interlock fabric and the REV are introduced.

2.2.1 The Representative Elementary Element (REV) of 3D warp interlock fabrics. The Representative
Elementary Volume represents a unit cell of the preform. The unit cell is the elementary repeated unit of the structure. It describes the geometry of the structure, the interlacement pattern between the constituting yarns and number of layers. Four structures were designed and woven on the loom.

2.3 3D warp interlock textiles at macroscale
Based on the design of the 3D warp interlocks structures, textile structures were produced using the sisal yarn. The weaving process followed in this current study is illustrated in Figure 1.

![Weaving Process](image)

Figure 1. Weaving Process.

On the loom, the warp yarns are extended but the weaving of the 3D warp interlock fabrics is based on an area located between a set of warp yarns arranged parallel to one to another on a beam with a constant tension.

3. Results and Discussions
3.1 3D warp interlock fabrics at micro-scale
Characterization of the preform at the microscale involves the identification of the sisal fiber properties which is the smallest entity of the preform. The mechanical properties of the sisal fiber are summarized in Table 1. The average diameter of sisal fiber was 239.00 ± 80.2 μm. The average tensile strength of sisal fiber was 340.02 ± 70.4 Mpa. The average Young's modulus of sisal fiber was 12.5 ± 7.8 Gpa. The average elongation at break of sisal fiber is 3.2 ± 0.8%. The mechanical properties of sisal fiber in this current study are in agreement with the works studying sisal fiber in the literature [12,13].

| Mechanical Properties of Moroccan Sisal Fiber |
|-----------------------------------------------|
| Average diameter [μm]                         | 239.0 ± 80.18 |
| Elongation at break [%]                       | 3.2 ± 0.8    |
| Tensile strength interval [MPa]               | 186.9-7-409.4 |
3.2  3D warp interlock textiles at mesoscale

At this scale, the sisal yarns were characterized according to standard norms. The Representative Elementary Element (REV), which represents the repeated unit of the textile architecture characterizing the yarns interlacement pattern of the 3D fabric, was described.

3.2.1  Characterization of Moroccan Sisal Yarn. The linear density of the twisted sisal yarn was 3300 Tex. Table 2 illustrates the physical and mechanical properties of the sisal yarns. Thermogravimetric analysis of sisal yarns (Table 3) shows that the thermal degradation of sisal yarns is related to the degradation of the chemical components of sisal fiber (lignin, cellulose, etc.).

Table 2. Physical and Mechanical properties of Moroccan sisal yarns.

| Sisal Yarn | Diameter (mm) | Linear Density (Tex) | Tenacity (cN/Tex) | Twist level (tr/m) |
|-----------|---------------|----------------------|-------------------|-------------------|
|           | 1.75          | 3300                 | 13.1              | 80                |

Table 3. Thermal characterizing temperature of sisal yarns.

| Sisal Yarns | Thermal Decomposition Temperature of Hemicellulose of Sisal Yarns (°C) | Thermal Decomposition Temperature of Cellulose of Sisal Yarns (°C) | Thermal Decomposition Temperature of Lignin of Sisal Yarns (°C) |
|------------|--------------------------------------------------------------------------|------------------------------------------------------------------|------------------------------------------------------------------|
|            | 230                                                                      | 350                                                              | 385                                                              |

3.2.2  The Representative Elementary Volume (REV) of 3D warp interlock textiles. Four 3D fabric architectures with the same number of 4 layers have been designed to be produced on the same weaving loom. The definition of the four designed fabrics according to the Equation 1 [11] is as follows in Table 4:

Table 4. The designed unit cell of the four 3D warp interlock fabrics.
3.2.3 3D warp interlock preform at macroscale. After the production of the four fabrics, the main descriptive elements have been defined in the following table (Table 5) according to standard norms.

| Table 5. Characterization of 3D warp interlock textiles. |
|----------------------------------------------------------|
| 3D Warp Interlock Textiles manufactured                   |
| 3D Warp Interlock O-L 2-4-4 Binding {Twill 3 weft        |
| effect left shift } {1 5 9 - 2 6 10 - # - # - # - #}    |
| - Stuffer {# - 3 8 - 4 11 - 7 12 - #}                  |
| 3D Warp Interlock O-L 1-3-4 Binding {Twill 3 warp        |
| effect left shift } {1 5 9 - 2 6 10 - # - # - # - #}    |
| - Stuffer {# - 3 8 - 4 11 - 7 12 - #}                  |
| 3D Warp Interlock O-T 2-4-4 Binding {Basket 4-2}        |
| {1 2 5 6 9 10 - # - # - # - #} - Stuffer {# - 3 8 -   |
| 4 11 - 7 12 - #}                                        |
| 3D Warp Interlock A-L 5-3-4 Binding {Twill 6 weft effect |
| left shift} {1 3 5 7 9 11 - 2 4 6 8 10 12 - # - # - |
| # - # - # - # - #}                                      |
| Warp Yarn Count(yarn/cm) 3                               |
| Weft Yarn Count(yarn/cm) 3                               |
| Width (cm) 48                                             |
| Length(cm) 150                                           |
| Warp Yarn Count(yarn/cm) 3                               |
| Weft Yarn Count(yarn/cm) 2                               |
| Width (cm) 48                                             |
| Length(cm) 150                                           |
| Warp Yarn Count(yarn/cm) 2                               |
| Weft Yarn Count(yarn/cm) 3                               |
| Width (cm) 48                                             |
| Length(cm) 150                                           |
| Warp Yarn Count(yarn/cm) 3                               |
| Weft Yarn Count(yarn/cm) 3                               |
| Width (cm) 48                                             |
| Length(cm) 150                                           |

The warp yarns are subjected to stresses at the different phases of the weaving and its tension is regulated manually. The increase of the tension of the warp yarn will affect the embossing of the yarns. The linear density and the structure of the sisal yarn allow to have significant friction between the yarns at the time of opening the shed. After the insertion of weft yarn by shuttle, the packing of the weft yarn modifies the weft and warp reduction of the fabric. The structure of the sisal yarns makes the packing of the middle weft yarns supported. Thus, it is concluded that the process of weaving sisal yarns will influence the properties of the yarns and the properties of the fabrics.
4. Conclusion
This work aims to valorize the Moroccan natural resources for the development of 3D warp interlock fabrics. The Moroccan fiber exploited is the sisal fiber. The manufacturing of four architectures of the 3D interlock woven fabric is evaluated. The properties of the 3D woven preform are characterized at three scales: micro (fiber), meso (yarn) and macro (fabric). The sisal fiber shows interesting properties. However, weaving the used rigid yarn of this type of fiber represents a challenge and requires adjustment to the weaving loom and/or special treatment to the used yarn.

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