1. Introduction

Weight optimization of vehicles, from aircrafts to motor vehicles, is a priority for the development of structural products. Several initiatives, and specifically the “Green aircraft initiative”, aim to provide the industry with cost-effective structural materials. Hence, the development of one piece complex 3D fabrics offering high mechanical properties for structural applications presents a very promising future. However, many aspects must be improved in order to build optimised composite structures and improve, among others, delamination properties as well as positioning of fibres to accomplish net-shape fibre preforms.

For many years JB Martin worked to develop new technical textiles for the composites industry by proposing innovative products. In 2010, the research consortium of CTT Group (CTTG), JB Martin and CEGEP de Saint-Hyacinthe, obtained a NSERC-CCI, 5 year research and development grant, to build a research platform to develop thick 3D woven preforms. This provided the team with the ability to design and acquire the specialized equipment needed to create large scale 3D structural woven reinforcements. There are currently 2 patents pending as a result of the first phases of operation.

2. Traditional weaving process

Traditional weaving processes reach serious limitations when we try to fabricate complex 3D shapes. JB Martin's skills have pushed these limits to create complex thick fabrics. As an example, Non-crimp 3D orthogonal fabrics (NCS) for mass production were developed. Isotropic (yarn x-y-z) patterns were developed, optimising z direction links in order to improve the structural properties in all directions.

Tests and studies have been performed to characterize the fabrics and optimize performance, cost and production parameters.

3. 3D textiles dry preform

With the NRSERCCCI grant, a special weaving process was developed to help the aeronautics industry meet new levels for performance and cost, by producing dry textile 3D preforms. This process has the ability to produce complex structures for multilayer textiles and shaped preforms with optimised fibre distribution and orientation.
Prototypes of structural beams were made and will be presented. For this study, we will discuss complex 3D woven preforms with many types of interlocks and fiber placement. We will also present woven and stitched preforms.

This global project also includes a computer assisted design and manufacturing software, which allows the design of 3D textiles with a real-time 3D visualization engine. This software, in combination with the weaving process, is extremely powerful to create complex shapes, and allows the modeling and simulation of preforms with complex internal structure while at the same time being able to design and visualize the positioning of fibres inside the structure. These tools can also be used to create visual effects on the external surfaces of the parts.

4. Optimization of NCS fabric
The first NCS fabric was developed to have a quasi-isotropic pattern in the placement of x-y-z fibres. A NCS is a non-crimp structure made of straight warp and weft warps maintained by a binder.

We are currently exploring many configurations in order to optimize the mechanical properties of the fabrics by first, modeling an accurate configuration of binders and second, having a uniform density fabric after preforming it.

From the results obtained by our preliminary tests, we will work on the characterization of the NCS fabrics, and attempt to correlate physical properties to the performance of the fabric. We want to determine the parameters which have the largest impact on the structural performance, while remaining within the constraints of a particular type of preform. Some parameters could be helpful for an infusion and/or draping but could degrade the structures from a mechanical standpoint. Depending on the properties to optimize, a given parameter could be beneficial or detrimental to the final product.

Based on this, we make the following assumptions for NCS structures:

1. The binders allow the creation of a quasi-isotropic material by the use of a yarn in the "z" direction.
2. The binders allow the increase in inter-laminar strength and prevent delamination of the layers
3. The binders help the resin penetrate the fabric by capillarity of the fibres and through the open holes surrounding them.
4. It is possible to increase the mechanical properties of thick fabrics by modifying the binder angles to resemble interlocks (see Fig. 3; by adding ±45° angles inside the structure of the fabric.
5. It is possible to change the mechanical proprieties by changing the binding pattern.
6. NCS are more appropriate for plate or single curvature parts. NCS should not have good deformability properties due to the instability of the fibres when structures are bent.
7. It is possible to have a constant density after deformation by optimizing the binding structures and crimp of the fabric in some specific zones (Section 7).

Hence, we propose an approach to quantify and qualify each characteristic and find the relations between them.

For this purpose, we will design and produce several fabrics to validate the proposed assumptions. Furthermore, we will document the production process of each fabric to be able to reproduce the samples in a manufacturing environment.

5. Orthogonal binding

Orthogonal binder crimp is the most common way for weaving NCS. In this configuration, the binder thread moves from one surface to the other and crosses the fabric in a perpendicular pattern to create the "Z" reinforcement of the fabric, which produces a quasi-isotropic material.

Quasi-isotropic material means that we have the same proportion of fibres in X-Y-Z directions. It can be verified using measurements of the volume density of the final product. In order to compensate for small density anisotropies in the binding
direction, we can adjust the fibre size or the linear density of binging.

An example can be seen in Fig 2, where we have the same fibre size and density in all three directions. In this case we can assume that we have an isotropic material. In a standard weaving process, binders (Z) and warp (longitudinal or X) threads have a fixed linear density while the cross (Y) thread density can be adjusted by adjusting the spacing of the weft insertions.

**Fig. 2; Orthogonal isotropic NCS**

**5.1. Angle Interlock binding**

The angle interlock structure type allows for binding the non-crimp layers while providing a given orientation which results in ±45° reinforcement in the longitudinal direction (Fig. 3).

![Fig. 3; Angle Interlock configuration](image)

The major issue with this type of binding is that the thicker the fabric, the longer is the "float", i.e. the distance between two binders along the weft yarn (Fig 4). This makes the fabric difficult to handle without damaging the threads and affecting the orientation of the weft threads.

![Fig. 4; Float of weft yarn](image)

**5.2. Hybrid binding**

To optimize the binding, an attempt was made to change the weaving pattern of the binder thread as well as the weaving parameters. It was shown that, for the same proportions of fibres we can change the binding structure to change the properties of the final product. The binding pattern could be a mix of an orthogonal or interlock binding, for example to decrease the length of the float for the Interlock configuration. In the case of constant density, we can use both types of patterns, and also have some crimp between the layers, in order to have a constant density across the fabric.
5.2.1. Weaving pattern

The effects of the binding pattern on the mechanical properties, and on our weaving productivity, are also analyzed. The pattern is the type of structure (repetition and spacing) for the binding thread.

In our experiments we use three (3) types of well-known patterns; plain weave, warp rib weave and twill weave. (Fig. 5)

![Fig. 5; (a) Plain, (b) Warp rib, (c) Twill 2x2](image)

Depending on the binding pattern, the binder size and spacing are changed and we test the influence of these parameters. We also take into account the esthetical and productivity issues. Finally we focus on the drapability and density of the fabric, which are discussed in more detail below.

5.2.2. Weaving parameters

In this step, we measure the effect of the weft density on the fabric and also define the limitations of our test bed. This step is a key to determining the maximum fibre ratio that is possible on the weaving machine.

Fig 6 shows the differences in density according to the weaving parameters. In this case, all the fibres and structures are the same but the pick density of weft is higher in the left frame.

![Fig. 6; Same structure, different weaving parameters](image)

In our study, we also investigate the type of fibre for weft, warp and binder, to evaluate their influence on the mechanical and productivity properties.

6. Caracterisation tests

To validate our assumptions, an exhaustive test plan must be created. The tests will allow for the qualification of the required features and the quantification of the structural specifications. For test purposes it is sufficient to work with dry fibres, which are a close-enough representation of the final composite parts. This will allow us to develop our protocols and expertise on technical dry fibre testing.

Only a few parameters have to be tested to compare textile prototypes. We will focus on four (4) types of tests; characterisation, compaction, absorption and drapability.

6.1. Characterisation

The first step is to measure the basic properties of the material, namely thickness, surface density, relative fibre placement density, and porosity. The tests have to be performed for each prototype according to standard methods.
1. Thickness

**ASTM D1777-96(2011)e1**
Standard Test Method for Thickness of Textile Materials

2. Basis weight

**ASTM D3776/D3776M-09ae2**
Standard Test Method for Mass Per Unit Area (weight) of Fabric

3. Composition (% mass)

**ASTM D3775-12**
Standard Test Method for Warp(end) and Filling (Pick) Count of woven fabrics

4. Porosity

**ASTM D737-04(2012)**
Standard Test Method for Air Permeability of Textile Fabrics

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Table 1. Characterisation tests

The thickness (T) method will measure the thickness of the fabric. The thickness will be affected by the fibre density, weaving parameters and binding structure.

The basis weight (Bw) will provide a measure of the surface density of the fabric. Combined with the thickness we will be able to obtain a volume density.

Composition will show the proportion of each element of the fabric in mass, i.e. percentage of warp, weft and binder yarns.

By a combination of the test results we will calculate the fibre fraction (Ff) by volume, to estimate the volume fraction of the composite material.

The samples have to be standard for the basis weight and composition. In this case, we can assume that the fibre fraction can be calculated as:

\[ Ff = \frac{w}{axt(Ct \times Pc + Tt \times Pc + Bt \times Pb)} \]  

Where:

- \( a = \text{sample area} \)
- \( t = \text{sample thickness} \)
- \( W = \text{sample weight} \)
- \( Ct = \text{warp yarn density} \)
- \( Tt = \text{weft yarn density} \)
- \( Bt = \text{binder yarn density} \)
- \( Pc = \text{warp yarn proportion (by weight)} \)
- \( Pt = \text{weft yarn proportion (by weight)} \)
- \( Pb = \text{binder yarn proportion (by weight)} \)

The air permeability test will give us qualitative information on the volume density of the holes made by the binder going through the fabric. We should be able to measure the effects of the binder size on the porosity as well as the weaving specification for the pick density (pick/cm). This test could be limited by the fabric density.

6.2. Compression

The compression tests will allow us to understand the fibre behaviour of the textile when compressed in the moulding process.

This test will give us information about the behaviour of the fabric after multiple cycles of compression. This parameter is especially important for the RTM process, where the fabric is highly compressed in the mould.

We will measure material memory after 5 cycles, by measuring the thickness according to the pressure load on the sample. This test will show the limitations of compression of the material and its capacity to revert back to its original form. This property will be critical for the design of the preforms. This implies that according to the mould cavity and fibre fraction to reach, the material thickness will need to be designed to the final compaction requirements.

From these tests, we will be able to specify the limitations of compaction in percentage and have a handle on the need for pre-compaction of the preforms before draping in the moulds. In some cases, we expect that we will need to pre-compact the preforms to bring the structure to a stable density and thickness.

6.3. Resin flow

NCS will have interstices to help the resin flow through the fabric. This is due to binder openings. These holes will decrease the fibre fraction by creating resin rich regions, but should also help during the infusion process.
We also make the assumption that the binders themselves will help in the infusion process, regardless of the interstices, as these fibres, even if the structure is very compact, will allow infusion through the thickness of the fabric by capillarity of the yarn.

The air permeability tests should provide us with an indication of the porosity due to the interstices along the vertical yarns, but no information on the yarn capillarity behaviour. We will need to develop a new standard test to measure water permeability and absorption.

6.4. Drapability

Drapability tests will measure the capacity of the textile to take shape in a mould. These tests will measure the resistance of the fabric to draping around a specific shape.

Also, with these tests we will be able to have a handle on fibre misalignment behaviour through visual inspection. This characteristic will help the design of the fabric structure according to the preform geometry.

These tests are important in order to optimize the design of complex preforms with uniform density requirements.

7. Uniform density

One important issue with thick preforms is to optimize the distribution of fibers and voids when the reinforcement is bent on single or double curvature shapes.

Thick 3D woven structures produce fibre compression and separation when they are bent to form mechanically complex components. Because of the displacement of the fibres the volume density of fibres becomes non-uniform across its thickness. The reason for this effect is simple curvature radius adjustments, which change de surface density of the fabric depending on its thickness. This situation is not encountered, and rarely discussed in the literature, because most of the curved thick components produced to date were made from multiple thin layer overlaps, which are allowed to slip and to adjust to varying radius of curvature due to thickness.

CTT Group and CÉGEP-de-Saint-Hyacinthe developed a novel predictive mathematical model to project surface densities of 3D curved surfaces onto 2D planes. The effects of curvature on surface density of a thick preform have never been determined because most thick woven fabrics are made of multiple thin layers. Our model allows visualizing and optimizing the density of weaved structures which end up in a better 3D volume and surface density of fibers in the final shape.

8. The modeling

We created 3D structures using a commercially available engineering CAD tool. Any 3D shape can be designed and viewed in 3 dimensions. All dimensions are kept by the tool, and can be used for parameterisation of entire structures or sections of it.

The modeling begins with a least-squares fit of uniform 3D sub-surfaces, which are then decomposed in conical elements of various parameters. Since a single equation can be used to characterize all types of curved shapes,

\[ Ax^2 + Bxy + Cy^2 + Dx + Ey + F = 0 \]  

this equation is used to model sub-structural sections of 3D shapes and represent them either with a circle, ellipse, parabola or hyperbola. By least squares fitting of the sections with varying parameters of the conical equation we can extract a mathematically simple approximation for the curved section. The advantage of using conical equations is that all curvatures and shapes of 3D surfaces can be represented. The conical elements are then analyzed for their variable curvature using differentiation of angles and integration of projected surfaces of uniform density.

In order to accomplish this we start by defining the surface density of the material \((D_s)\), which depends
on the mass \((m)\) contained within the surface area \((S)\):

\[
D_s = \frac{m}{S} \quad (3)
\]

In the case of a spherical cap (Fig. 7 and 8) with a diameter \(A\) at the base and a height \(h\), included in a sphere of radius \(r\) centered at the origin \((0, 0)\), the defined 2D function represents a cross-section of the spherical cap. The revolution of this function around the \(y\)-axis will form the spherical cap in 3D because of its symmetry. The diameter at the base, \(a\) and the height, \(h\) are essentially the known variables and the radius \(r\) depends on the values of \(a\) and \(h\). An expression of the radius depending on \(a\) and \(h\) can thus be defined to be substituted in the equation of a circle, which will represent the cross-section of the entire sphere.

\[
r^2 = x^2 + y^2 \rightarrow \left(\frac{h^2 + a^2}{2h}\right)^2 = x^2 + y^2 \rightarrow y = \pm \sqrt{\left(\frac{h^2 + a^2}{2h}\right)^2 - x^2} \quad (5)
\]

The equation of a circle centered at the origin is then:

\[
r^2 = x^2 + y^2 \rightarrow \left(\frac{h^2 + a^2}{2h}\right)^2 = x^2 + y^2 \rightarrow y = \pm \sqrt{\left(\frac{h^2 + a^2}{2h}\right)^2 - x^2} \quad (5)
\]

The positive root is chosen for simplicity. This expression is then integrated between \(x = -a\), and \(x = +a\).

With this equation, we then apply a simple projection algorithm to determine the variability or gradient of surface density on the 3D perform (Fig.9).

First, the hypotenuses of each triangle formed by a constant predefined iteration of \(x\) and the dependent variable \(y\) are determined with the help of a Maple program.

\[
Hypotenuse = \sqrt{x[i]^2 + y[i]^2} \quad (6)
\]

The value of \(x[i]\) is constant, and the value of \(y[i]\) is not \(y\) evaluated at \(x = x[i]\), but the variation of \(y\); \(y[i] = y(x[i]) - y(x[i - 1])\).

Depending on the variation on \(y\) and \(x\), different curvature angles occur and this has a direct impact on the surface density in a given area of the spherical cap. The length of the arc superimposed on each of these hypotenuses is defined as:

\[
Arc = \int_{i=1}^{i} \left(1 + \frac{dy}{dx}\right)dx \quad (7)
\]
We compare the hypotenuses and circle of arcs because the hypotenuse resembles a flat projection. At curvature angles of 0 degrees and multiples of π, there is no notable variation of density. The maximal variation is at 45 degree angles. We need the minimum and maximum density variation (0 deg and 45deg) because the density variation depends on the curvature angle and the ratios between the length of the curved area and the length of the corresponding flat area (we consider that there is the same quantity of threads in both areas after the deformation).

Hence, the hypotenuses and arcs calculated are the measurement of a given area we need to define. Because of the spherical symmetry of the 3D shape (in this particular case), we can assume the density has circular symmetry all around the shape for a given height. In this way we can define areas in the shape of trapezes for which the height will correspond to either the arc or the hypotenuse, and the two bases will correspond to the two circumferences of the spherical cap at point x=x[i-1] and x=x[i], where the values of x at these points correspond to the radius of the circular base (when centered at the origin). The spherical cap can be considered as a piling up of truncated cones of different sizes, with a large base of B and a small base of b.

\[
\text{Trapeze area} = \frac{(B + b)h}{2} \\
b = 2\pi x[i] \\
B = 2\pi x[i-1] \\
\rightarrow \text{Trapeze area} = \frac{(2\pi x[i-1]+2\pi x[i])h}{\pi h(x[i-1] + x[i])} = \frac{2}{2}
\]

The value of h is either the hypotenuse or the length of the arc on the iteration. We can define a density factor with ratio of these two areas on the same iteration.

\[
\text{Factor} = \frac{(2\pi x[i-1]+2\pi x[i])}{2} \cdot \frac{\text{Arc of circle}}{\text{Hypotenuse}} = \frac{\text{Arc of circle}}{\text{Hypotenuse}} \equiv (9)
\]

This is simply the ratio of the lengths because we assumed that the threads do not move in or out of a certain area while we’re deforming the tissue, which is imprecise. Depending on the angles of deformation, the patterns of the threads are modified. We considered this negligible. The surface density, as defined in equation 2, depends on the quantity of threads. By projecting the displacement of the threads due to curvature we can redefine the surface density for each area and get the true density factor.

The algorithm we apply needs to be done for each layer of fabric since the deformation affects each one differently. The functions on which we apply the algorithm will differ because of the varying curvature radius depending on thickness. The functions can be considered similar (they have necessarily the same parameters), and the curvature angles are the same. We only need to apply the algorithm on the two layers at the upper and lower surfaces. In fact, the density factors on the lower surface are the inverse ratios of the density factors of the upper surface to maintain the symmetry and thus, the layers at the center have their density factors almost equivalent to the density factors when unbent. The density gradients between each layer need to be harmonized and progressively increased or decreased depending on the curvature. The convex surface is where the density is lowered because of the stretching. The shape will have its density augmented on the concave surface.

Although the dimensions of each trapeze are defined as an area with a certain density factor, the height of the trapezes (the hypotenuses and arcs of circle) are only used to delineate the zone of uniform density in the 2D surface.

Finally, the spherical cap can be considered as being a rounded cone, for which we must delineate the area which needs to be woven with the variable surface densities. The surface density factor is then derived for small elements of surface and is transformed into a percentage of increase or decrease applicable on the initial surface density. We modify the quantity of threads in specific areas according to these percentages so when the spherical
9. The weaving process

After determining the final density profile and density gradients needed in each area, we can then proceed to construct the 2D shape in our specially developed 3D weaving modeling tool (©EasyJC). Our special purpose modeling and weaving software allows us to define the 3D weaving patterns which are required by the pattern modeling presented in the previous section. Each weaving pattern is defined as a “zone”, which can be of variable size, but which represents an element sufficiently small compared to the final shape. For each zone element, the weaving pattern is carefully chosen to represent the calculated density gradient in an area of the final shape to be produced. Fig. 5 shows a typical 9 layer weaving pattern, where a progressive density (from top to bottom) weaving pattern is seen.

By defining the zone elements needed for each density factor, we can then “draw” the 3D projected shape in our software, as shown in Fig. 6. Each color represents a different density factor and weaving pattern. The calculated density factors reach approximately 17% above and below the uncurved density in this case.

Fig. 6: Uniform density 2D projected spherical cap

The final 2D thick model of the shape is then complete, and can be exported as JC5 binary data, which is then loaded directly onto our weaving machine to produce the final shape.

10. Conclusions

Traditional weaving is limited in its ability to produce complex 3D preforms. A special weaving process was developed to produce dry textile 3D preforms. This process has the ability to produce complex structures for multilayer textiles and shaped preforms with optimised fibre distribution and orientation. Our team is in the process of testing various parameters of thick weaving using NCS and Interlocks, to create structurally optimized 3D woven shapes with uniform density.

Using mathematical modeling of the projected surface densities of 3D curved thick preforms we are able to create 3D shapes of uniform surface density weaved in 2D on a standard weaving machine. The final 3D shapes offer optimal fiber placement for uniform surface density. Our next step is to optimize our patterns and test them for different usage and different load patterns. We then expect to push the limits for lighter and stronger parts that will be easier to manufacture and more consistent. Our technology will also allow us to insert reinforcement
in weak points in a perfectly optimized orientation for even stronger parts. The next goal will then be to create more and more shapes for the different needs of the composite industry.

References


[8] ASTM D3776 /D3776M -09ae2; Standard Test Method for Mass Per Unit Area (weight) of Fabric

[9] ASTM D3775-12 ; Standard Test Method for Warp(end) and Filling (Pick) Count of woven fabrics