INFLUENCE OF ONE SIDE STITCHING ON THE PERMEABILITY OF COMPOSITE REINFORCED BY TRANSVERSE SEWING

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Abstract
The strengthening of the conventional 2D laminates by transverse seams has been developed to compensate the inherent weakness of these materials, such as the delaminating and impact behavior. Moreover, these seams play an important role in draining and improving the impregnation ability of the reinforcements. In this context, our study will focus on the influence of the pattern seam, called One Side Stitching (OSS) on the permeability of conventional 2D fabric reinforced by transverse seams. The in-plane permeability tensor (K_1, K_2 andβ) for both stitched and unstitched fabrics with similar fiber volume fractions is obtained through a permeability measuring device based on the unidirectional flow method. The results show that the presence of these seams generates an important impact on the local permeability gradients. These gradients are located around the seams.

1. Introduction

In recent decades, two large families of 3D reinforcements have been developed for overcoming the inherent weaknesses of conventional 2D laminates, such as preventing delamination and impact behavior. One of these technologies is called the 3D weaving, including interlocks or orthogonal 3D. The other, mainly aims to strengthen conventional 2D fabrics in the third (thickness) direction. It is well recognized that the technology of through the thickness sewing is a good alternative in the strengthening of composite structures preforms [1-2]. Beyond the mechanical strengthening in the third direction, this technology also finds applications in the assembly of dry performs. This approach aims the reduction of the cycles and the production costs of molding processes such as the RTM. This goal is reached by a significant reduction of the time of handling and positioning the preforms in the mold. However, the presence of the sewings within the reinforcement is not neutral. Studies showed that the sewings disrupted the fibrous reinforcement permeability. In certain cases, these sewings can lead a draining effect which improves the impregnation process [3-4].

Thus, the study of the permeability of sewn preforms becomes as important as that dedicated to the mechanical performances of sewn composite structures. From the measurements of the permeability of non-crimp stitched fabrics, Lundström [5] founds that the stitching leads to some variations of the fabric geometry which change the permeability. Chiu and Cheng [6] stated that the stitching has not any influence in the fluid direction, but it is as an obstacle for the fluid in the perpendicular direction which reduces the permeability. For performs with

±45° stitching pattern, Talvensaari [7] found an opposite tendency of the permeability which is increasing with a higher stitching density. This result is explained by the fact that the needle threads tension of the stitching machine was higher than other experiments [8]. Rieber [8] applied lower needle threads tension with the same stitching pattern as Talvensaari [7]. This study revealed that the permeability K_1 of preform with stitching in the fluid direction was lower than that without stitching. The permeability K_2 of the fabric with stitching still stays constant. This phenomenon follows the same tendency as the results of Chiu and Cheng [6].
This article is principally dedicated to evaluate the permeability of dry stitched preforms and analyze the phenomena induced by the presence of these seams. The in-plane permeability of the stitched reinforcement will be compared with unstitched textile.

2. Stitching process

As we known, stitching is one of the most common techniques used to ameliorate out of plane mechanical properties of composite structures. In this field, two new technologies used to achieve the automated stitching are widely concerned: one is Tufting; the other is called One-Side Stitching (OSS). Actually, tufting is the most accessible and most practiced technology for composite applications. The seams obtained by this technology are called "open seams", because they are stitched without internal nodes. The thread loop is sewn with a very low tension which can protrude over the backside or stay inside the perform (Figure 1a). It is possible to vary the angle of inserting the thread in the Z direction. Open seams cannot bring an optimal improvement of the mechanical properties. According to this disadvantage, the other technology (OSS), developed in recent years, forms closed seams by two needles and only one thread. One needle enters perform under an angle of 45° formed a loop underneath, and then a catcher needle synchronizes with this needle, bought the thread back through the preform to the top side (Figure 1b).

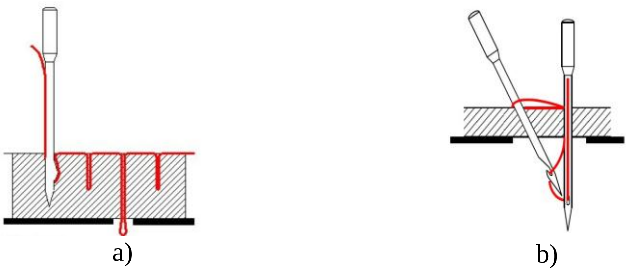
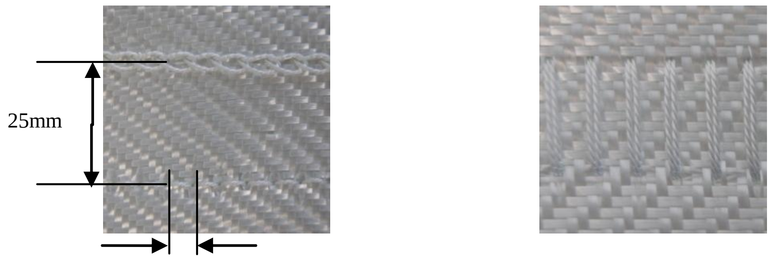


Figure 1. Automated stitching process: a) Tufting; b) OSS.

This study will focus on One Side Stitching (OSS). It should be noted that, both the sides of preform show different arrangements. The particular arrangement of the stitching is shown by Figure 2. This figure also shows the stitching parameters used in our study. Obviously, the thread in the top side is along the warp direction. On the back side, it's perpendicular to the warp direction.
All the tests were carried out in our laboratory by using a KUKA robot equipped with two interchangeable stitching heads (Tufting and OSS). The needles' diameter is 2 mm. The stitching yarn is made of three fiber glass strands of 179 Tex, twisted together in 136 turns / meter, supplied by Tissafil Company (France). The strands' composition is: 62% of fiber glass and 38% of Polyester.



a) Face b) Back

Figure 2. Overview of a stitched preform in OSS a) Face; b) Back.

3. Theoretical consideration

3.1. Permeability measurement in unidirectional flow

The permeability describes the ability of the fluid passing through the porous medium by using the Newtonian fluid model, called Darcy's law. Darcy's law is frequently expressed by the Equation (1).

$$V = -\frac{K}{\mu}\nabla P \tag{1}$$

Where V is the flow velocity (m.s^{-1}); ∇P represents the pressure gradient; K is the permeability of the textile (m^2); μ is the fluid viscosity (Pa·s). The flow front position is determined during the experiment. The data were recorded by counting fixed intervals by using the methodology developed by the Polytechnic School of Montreal [9]. This procedure is used to estimate the permeability values, which is combined with the Darcy's law in a constant pressure gradient. For the unidirectional flow, the pressure gradient is usually expressed by:

$$\frac{dP}{dx} = -\ \frac{P_0(t)}{x_f} \tag{2}$$

During the experiment, the inlet pressure has a slight change at the beginning of the injection, which should be obtained by the function of time. And the velocity of the flow front can be measured by the flow front position x_f. So by combining with the Darcy's law, it can be obtained Equation (3):

$$\frac{dx_f}{dt} = -\frac{KP_0(t)}{\mu\emptyset x_f} \tag{3}$$

Note that $\emptyset$ is the porosity of perform. P_0 represents the inlet pressure (Pa); x_f is the coordinate of the advanced front flow.
After integrating and rearranging Equation (3), the following expression of the flow front position comes as Equation (4):

$$x_f^2 = \frac{2K}{\mu\emptyset}\int_0^t P_0(t)dt \tag{4}$$

It is easy to get the permeability along the flow direction:

$$K = \frac{x_f^2 \mu \emptyset}{2\int_0^t \boldsymbol{P_0(t)dt}} \quad (5)$$

During the experiment, the flow front position x_f and the time t were recorded at each 20mm, which has a parabolic relation between these two values. For each recorded values, it is easy to obtain the transient permeability by using the Equation (5). And the unsaturated permeability which is focused corresponds to the stable value of the transient permeability.

3.2. In-plan tensor permeability

The in-plan permeability of orthotropic (anisotropic) reinforcements consists of two principal permeability values, $\boldsymbol{K_1}$ and $\boldsymbol{K_2}$. For such reinforcements, an elliptic flow front can be observed in a radial flow. Thus, in order to have a complete characterization of the in-plan tensor permeability, it is necessary to determine the orientation (angle $\boldsymbol{\beta}$) of this tensor, which can get the principal directions of the principal axes [10]. The measurement data obtained from this bench by using the unidirectional flow method requires three measurements: the warp direction ($\boldsymbol{K^{0°}}$), the weft direction ($\boldsymbol{K^{90°}}$) and another between these two directions, in our case, the direction 45 ° ($\boldsymbol{K^{45°}}$) Figure 3.

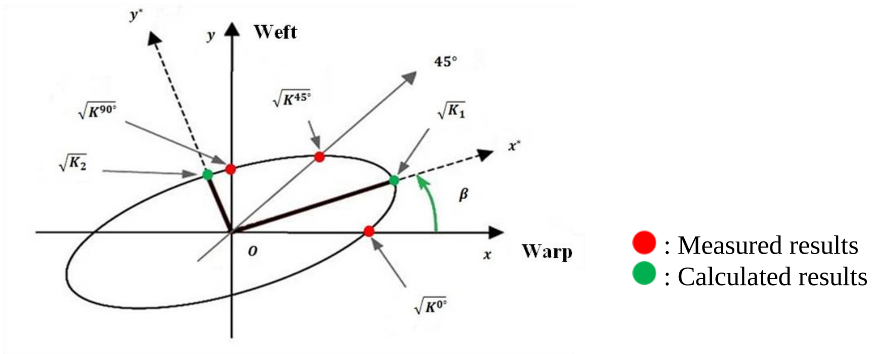


Figure 3: Tensor of the plan permeability obtained by the unidirectional flow method.

From three unidirectional measurements, an equation which represents the relation of the figure 3 can be obtained, Equation (4) [10]:

$$\begin{bmatrix} K^{0°}cos^2\beta & K^{0°}sin^2\beta & 0 \\ \frac{K^{45°}}{2} & \frac{K^{45°}}{2} & \frac{K^{45°}}{2}sin^2\beta \\ K^{90°}sin^2\beta & K^{90°}cos^2\beta & 0 \end{bmatrix} \begin{bmatrix} \frac{1}{K_1} \\ \frac{1}{K_2} \\ \frac{1}{K_1} - \frac{1}{K_2} \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \quad (4)$$

4. Experimental

4.1. Materials and sample preparation

Both for the stitched and unstitched performs, the measurements have been conducted with 20 layers of glass fiber twill 2-2 with a surface weight of 270 g / m². The unstitched preforms were obtained by stacking the layers on top of each other all in the same direction. And the stitched preforms were contained by using One Side Stitching (OSS). The test samples were sewn by arranging the rows of stitching parallel to the warp direction of the basic fabrics. The stitching length between two rows is 25mm. Each sample is cut out to a dimension of 100 × 400 mm^2 (cutting by Cutter after tightening and fixing preforms). It is important to note that the presence of the seams disrupts the orthotropic structure of the basic material. In accordance with the conventions used in composite materials, it is necessary to redefine the orthotropic axes. Then, the direction 0° is the warp direction, which is also the direction of the seams. The direction 90° is the weft direction, which is perpendicular to the rows of the seams. For this experiment, the samples were cut out along the directions: 0°, 90° and 45°. Figure 4 provides an overview of these samples.

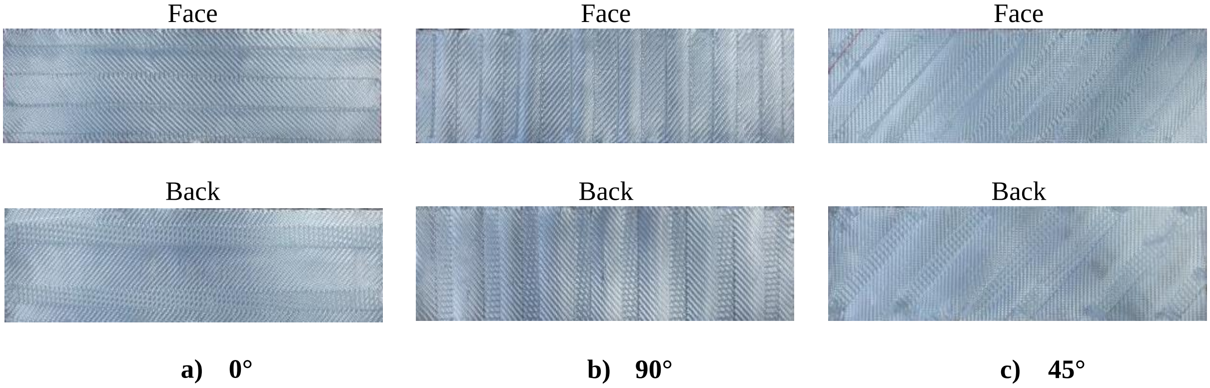


Figure 4. Stitched samples, a) 0°, b) 90°, c) 45°.

4.2. Permeability measurement Apparatus

The permeability measurements were conducted in an unsaturated regime by using the small scale bench test (Figure 5). The special feature of this device is that the lower part of the mold is movable for measuring the different cavity heights corresponding to different fiber volume fractions. The upper part is made of thick glass with a measuring grid plate for monitoring the advancing flow front. A camera was disposed above the mold, which is used to record the advanced front fluid during the fluid flow through the mold and has a function to make correction of the results during the analysis.
The device provides a pressure sensor, which is fixed near the injection position.

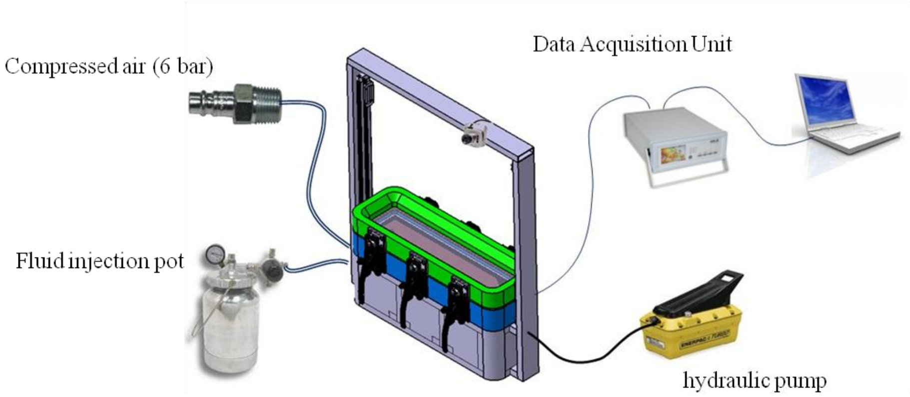


Figure 5. Diagram of the experimental device for permeability measurement

5. Experimental conditions

Stitched and unstitched performs were tested with a cavity height of 5.22mm. The fiber volume fractions obtained are respectively: 42.2% for unstitched twill and 45.2% for stitched twill. That is to say, the stitching seams bring about 7% volume fractions. These volume fractions were obtained by weighing small samples of 10×10 cm^2 by a microbalance. The impregnation fluid is a rapeseed oil bought from the market, having a viscosity of 66 mPa·s under the temperature about 21℃. This was measured by an Anton Paar MCR 502 rheometer.

The fluid is injected through the compression pot with a pressure of 2 bars in the rectangular mold. It is important to take some special precautions in order to avoid the edge effects on the path of the fluid. For this purpose, the silicone gel is interposed between the preforms edges and the mold wall. To take account of the fluctuations of the injection pressure, this one is recorded in the function of the time, during the experiment. We also record the advanced front fluid by a manual pointer held.

6. Results

Three directions 0°, 90° and 45° of samples were tested for five times to get an average result. For the stitched preforms in the direction of 0°, the flow at the beginning of experimentation is strongly disrupted by the presence of seams. But this tendency seems to stabilize towards the end of the process, Figure 6. Among the seams, it is visible that the advanced fluid profile is different at the three moments.

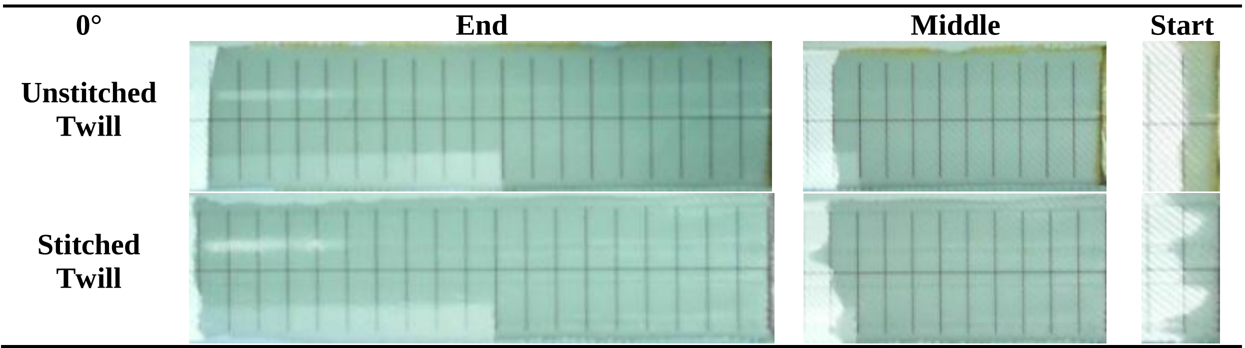


Figure 6. Flow fronts position of the samples in the 0°direction.

In the direction of 90 °, this phenomenon does not exist. The flow is uniform for both stitched and unstitched preforms, Figure 7.

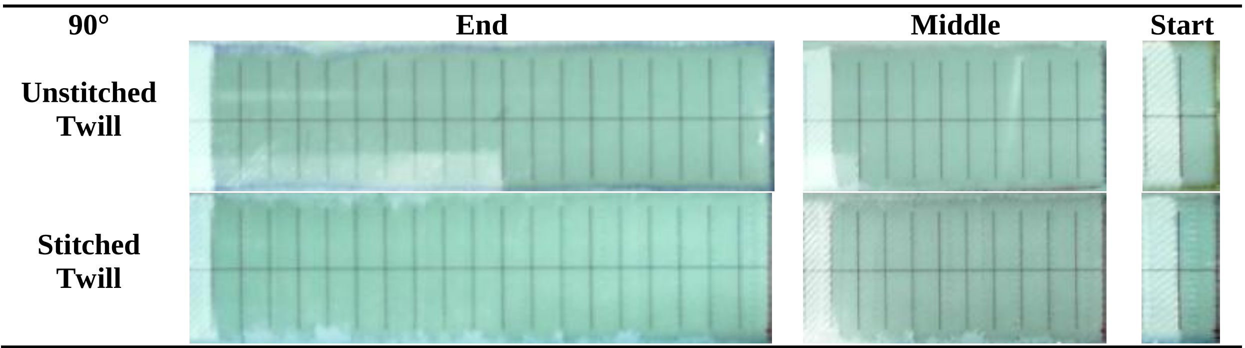


Figure 7. Flow fronts position of the samples in the 90° direction.

In the 45 ° direction, there exists a slightly disturbed flow with an inclination close to 45 ° for the unstitched preforms, as well as for the stitched preforms, Figure 8. However, for the stitched preforms, previous studies [11] have not revealed this phenomenon. Other experiments will be conducted to confirm whether the phenomenon is due to the effects of undetected edges or the structure of the reinforcement.

45° **End** **Middle** **Start**

Unstitched Twill

Stitched Twill

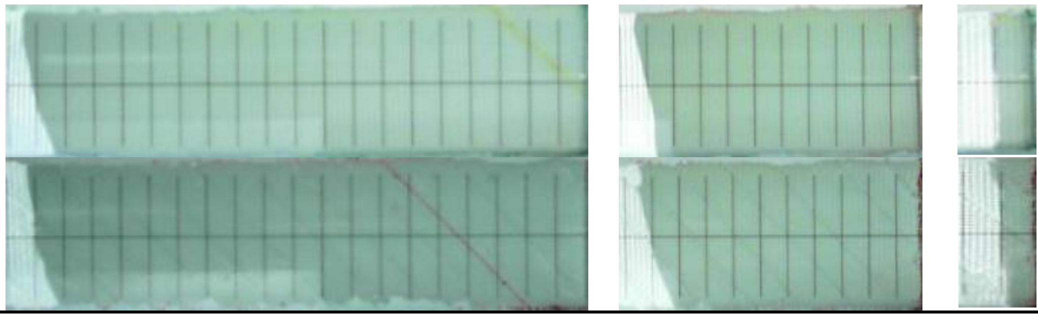


Figure 8. Flow fronts position of the samples in the 45°direction.

The permeability measurement values in the 0°, 45° and 90° directions are summarized in Table 1. The permeability in the 45°direction is identical for both reinforcements (stitched and unstitched), while it is found slight differences in the other two directions. Therefore, more significant differences for the principal permeability $\boldsymbol{K_1}$ and $\boldsymbol{K_2}$**,** corresponding to the shape of the ellipse of the radial flow (anisotropy ratio $\boldsymbol{K_1/K_2}$ and the ellipse orientation angle β relative to the *x* axis), these values are summarized in Table 1:

		K measurement [E-11 m^2]			K principal [E-11 m^2]			
	$\boldsymbol{V_f}$ (%)	$\boldsymbol{K^{0°}}$	$\boldsymbol{K^{45°}}$	$\boldsymbol{K^{90°}}$	$\boldsymbol{K_1}$	$\boldsymbol{K_2}$	$\boldsymbol{K_1/K_2}$	$\boldsymbol{\beta}$ (°)
Unstitched	42.2	2.7 ± 14%	2.1 ± 13.6 %	1.6 ± 13 %	2.7	1.6	1.7	5.5
Stitched	45.2	2.85 ± 17 %	2.1 ± 6.7 %	1.3 ± 6.7 %	3.0	1.3	2.3	11.3

Table 1. Summary of measurement and calculated permeability values for both reinforcements.

7. Discussion and conclusion

Overall, the results presented in Table 1 show very slight differences between the stitched and unstitched Twill 2-2. However, it should be noted that these two preforms have been tested for two close but not strictly identical volume fractions. As well known, the permeability of a given reinforcement is directly influenced by the fiber volume fraction. In order to well appreciate the influence of stitching on the permeability of any textile, it should have been more rigorous to design and test stitched reinforcements with the same fiber volume fraction ($\boldsymbol{V_f}$), including the seams. However, our choice is deliberate, since our goal is to compare the macroscopic permeability of two identical stacks between the unstitched and stitched twill.

The OSS stitching is quite special, in the fact that it generates an especial flow path of the stitching thread. In the case of samples in the 0 °direction, on the upper face, the stitching thread forms loops aligned in the flow direction. On the bottom and the thickness of the preform, these threads are disposed perpendicularly to the flow direction and then become a hindrance to the fluid flow.

This particular arrangement directly influences the progress of the fluid and generates local meso-scopic permeability in the preform. Thus, as shown in Figure 9, the fluid passes through the loops much easier on the surface. So it is clear that the flow moves faster at the loop-stitched. The flow is delayed in the area where the stitch is perpendicular to the flow direction. And the intermediate flow corresponds to the area without stitching (the space between two rows of stitching).

(a)

(b)

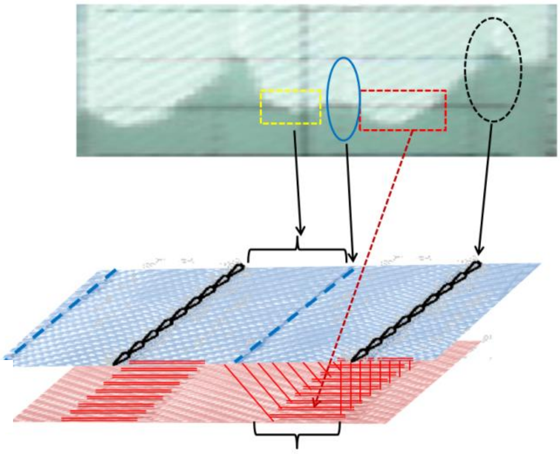


Figure 9. (a) Flow fronts position; (b) the stitching process.

In conclusion, under the conditions of our experiments, the macroscopic permeability of the reinforcement has not been significantly affected, despite the presence, in the mesoscale, of permeability gradients on the surfaces and the thickness of the preform. This result is explained by the particular arrangement of the stitching thread obtained by the OSS technology.

However, to complete the study, it would be interesting to vary certain parameters such as the stitching length, for a better understanding of the influence of this type of stitching on the permeability of reinforcements.

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