

Evaluation of the mechanical behaviour of tufted preforms

Imen Gnaba*, Peng Wang, Xavier Legrand and Damien Soulat

University of Lille, ENSAIT, GEMTEX, F-59056, France

* imen.gnaba@ensait.fr

Abstract. 3-Dimensional fabrics have been developed in order to remedy the damage through-the-thickness of the laminate. An alternative to the multi-layered preforming is to use structures reinforced through-the-thickness in order to manufacture thicker and more complex pieces. Currently, the tufting technology is getting more interest due to its simplest and efficient process where it involves the insertion of binder threads via a single needle through the fabric. This technique of reinforcement through-the-thickness requires only one access to the preform which makes it suitable for three-dimensional shapes.

This study aims to improve the understanding of the mechanical behaviour of tufted preforms where an experimental investigation was performed in order to study the in-plane shear of tufted structures. The effect of the tufting process on the mechanical performance of dry fabrics is also highlighted in the present work.

Keywords: Reinforcement through-the-thickness, Tufting, In-plane shear behaviour.

1. Introduction

The large use of composite materials in several fields (aeronautics, space, defence...) is related not only to their excellent mechanical performance but also to their lightweight. The need for affordable composites that have significantly improved the through-the-thickness strength and resistance to delamination intensified the development of a wide variety of textile preforms [1].

The key of such growth consists on the overcome of the weak properties in the thickness of the laminate in terms of delamination and impact resistance [2-5]. The insertion of a binder through-the-thickness of the laminate provides connections between plies which improve the mechanical performance of the final structure [6-8].

The stitching technology is based on the sewing process which enquires a dual-threading system to link several fabric layers together by inserting stiff threads [9-12]. Although the tufting process represents the simplest one-sided stitching technique and it is specifically designed for the dry preform/liquid composite moulding process route. It involves the insertion of binder yarns, via a single needle, through-the-thickness of the laminate [13-15].

Tufted 3D-fibre composites and their mechanical properties have been deeply studied in literature [15-18]. Nevertheless, few studies [14, 19] focus on the impact of tufting on the mechanical behaviour of dry fabrics which is a key point for understanding the deformability of 3D fabrics during manufacturing [14].

This paper outlines the mechanical performance of dry tufted fabrics where an experimental investigation was performed in order to highlight the in-plane shear behaviour of tufted structures.



Therefore, a set of tufted and untufted specimens was conducted for the sake of studying the influence of the process parameters on the mechanical behaviour of dry preforms.

2. Materials and methods

2.1. Tufting process

Currently, tufting is becoming more widespread for through-the-thickness reinforcement. It is based on the sewing process which represents the simplest one-sided technique as illustrated in figure 1.

The insertion of tufts is carried out via a specific needle without generating any tension at the surface of the laminate which avoids thread crimping.

The tufting yarn remains in position due to the natural friction between the fabric and the thread. The threads can be fully inserted where the tufts exceed the depth of the laminate and the loops are formed on the underside of the structure or applied to a partial depth through the preform thickness.

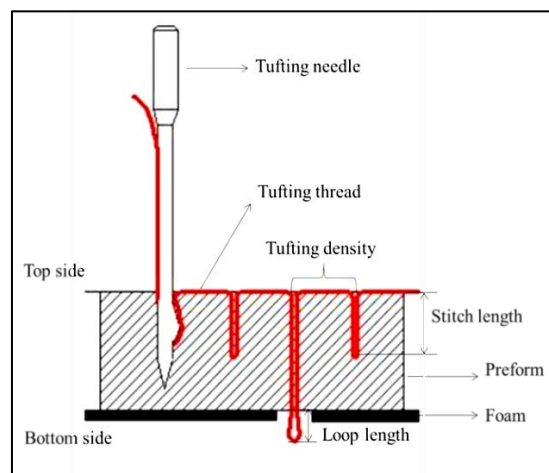


Figure 1. Illustration of the tufting technology.

Figure 2 presents the tufting machine developed in our laboratory in order to handle tufting structures. This bench is supplied by the following equipment:

- **Tufting device:** made with a tufting needle, with a diameter of 2 mm, which is connected to a pneumatic jack to control the tufting deepness.
- **Presser foot device:** controlled by another pneumatic jack allowing the application of a specific pressure during the tufting process.
- **Feeding device:** delivers the tufting thread during manufacturing.

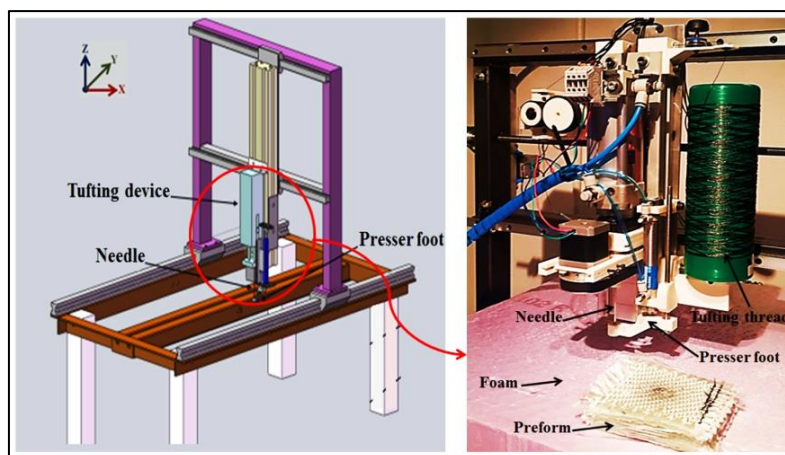


Figure 2. Tufting device (Gemtex-ENSAIT).

2.2. Preform manufacturing

The reinforcement fabric is an E-glass plain weave with an areal density 160 ± 2 g/m². The tested preforms were laminated with a single layer oriented at $\pm 45^\circ$.

The tufting technique was handled by inserting carbon thread possessing specific features: 2 * 1K 15 S 67 Tex.

The scheme of the tufting pattern is shown in figure 3 (a) where d_x and d_y are respectively the tufting spacing in the x and y axes and an example of dry tufted preform is mentioned in figure 3 (b).

Table 1 illustrates the main properties of tested preforms in the present work.

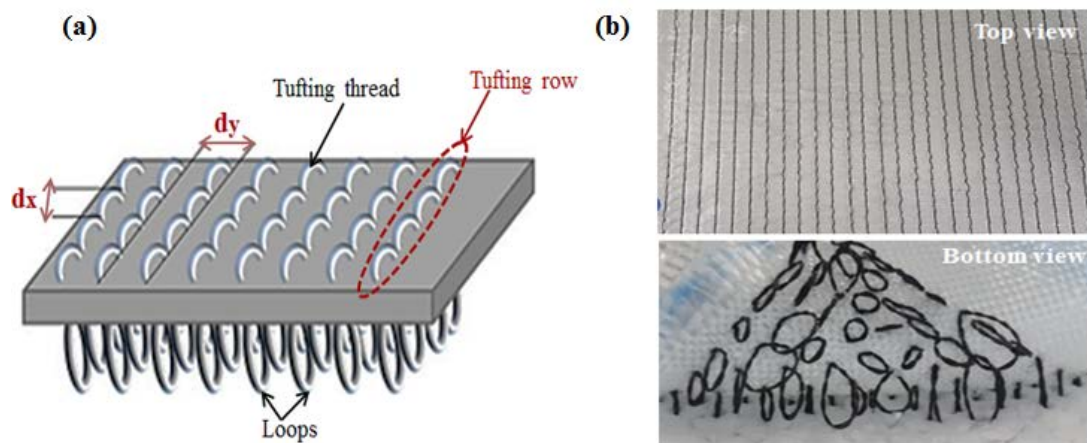


Figure 3. Illustrations of (a): Tufting pattern [20], (b): Top and bottom views of dry tufted preform.

Table 1. Main properties of tested preforms.

Characteristics	Untufted preform	Tufted preform
Areal density (g/m²)	622 ± 2	722 ± 2
Tufting spacing (mm)	-	$d_x = d_y = 10$

3. Mechanical characterisation

3.1. Experimental trials

An experimental investigation was performed in order to study the in-plane mechanical properties of tufted fabrics which are essential and complementary to understand the preforming behaviour.

In fact the tensile and bending characterisations of the same tufted fabrics were deeply described in [21, 22]. The results presented in [21, 22] show that the mechanical behaviours are highly influenced by the tufting process where the application of a specific tufting density improves the tensile properties as well as the bending characteristics which depends also on the areal density of the final structure.

The present study outlines particularly the in-plane shear behaviour of untufted and tufted fabrics. For this, a bias extension test was performed to characterise the shear behaviour of untufted and tufted preforms. Table 2 illustrates the main parameters of the bias extension test.

Table 2. The main parameters of the shear test.

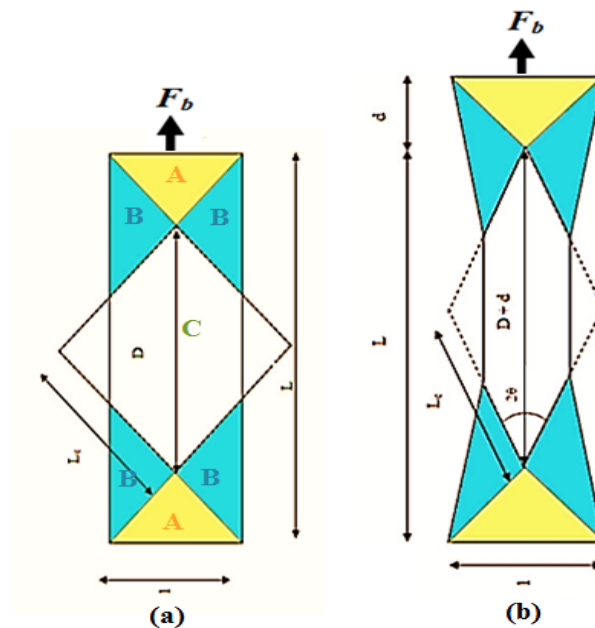
Parameters	Value
Test speed (mm/min)	30
Preform size (mm²)	210 x 70
Number of tested specimen	4

In this experiment, a tensile test is conducted on a rectangular sample where the fabric is orientated at $\pm 45^\circ$ relatively to the direction of the applied tensile load as mentioned in figure 4 (a). Great care should be taken to avoid any misalignment and fibre crimping.

During the bias extension test, three specific regions can be distinguished on the tested specimen as shown in figure 4 (b) [23-25]:

- **Zone A:** remains undeformed where the specimen has a clamped end avoiding yarn slippage.
- **Zone B:** one yarn direction is clamped at its end and the other direction is free.
- **Zone C:** the yarns in this region are free at their ends. The non-sliding and the stretching of the specimen lead to a pure shear deformation characterised by a shear angle “ γ ” related to the fabric size “ D ” and the displacement “ d ”. The theoretical shear angle can be calculated from equation (1), while the experimental shear angle is measured by optics measurements.

$$\gamma = \frac{\pi}{2} - 2 \times \cos^{-1}\left(\frac{D+d}{D \times \sqrt{2}}\right) \quad (1)$$

**Figure 4.** Bias extension test (a): Initial shape, (b): Deformed shape [23].

3.2. Results and discussions

From the bias extension test, it is possible to extract the main mechanical properties of the in-plane shear behaviour (load, displacement, shear angle...). Figure 5 (a) illustrates the typical load-displacement curves for the untufted and tufted preforms. It should be noted that each curve represents the average value of four tested specimens. The theoretical and measured in-plane shear angles are presented in figure 5 (b).

From the extracted data, it is obvious to mention that the evolution of the load is proportional to the variation of the strain where the rise of the displacement leads to an increase of the force as shown in figure 5 (a). This can be explained by the fact that the test direction is parallel to the direction of the tuft threads which creates tension deformation tufts and increases the shear force.

The experimental data show that the in-plane shear behaviour of untufted and tufted structures is quite similar where the maximum load and the stain at break are uniform for both tested preforms.

Hence, it is possible to say that the in-plane shear behaviour is not influenced by the addition of reinforcement through-the-thickness of the laminate.

Regarding the shear behaviour, it can be noted that the shear angle increases in accordance with the displacement. The shear angle-displacement curves reveal the same behaviour as the load-displacement curves where the curves are similarly coincident.

From a specific value of the shear angle, the measured angle is completely distinct to the theoretical angle (figure 5 (b)) which increases the shear rigidity. This high stiffness reflects the shear locking angle where there is no revolving movement within the fabric and the yarns are totally clamped. In this phase, the yarns are in lateral compression which allows reaching the shear load.

Thus, it is possible to conclude that tufting does not damage the in-plane mechanical performances of the final structure.

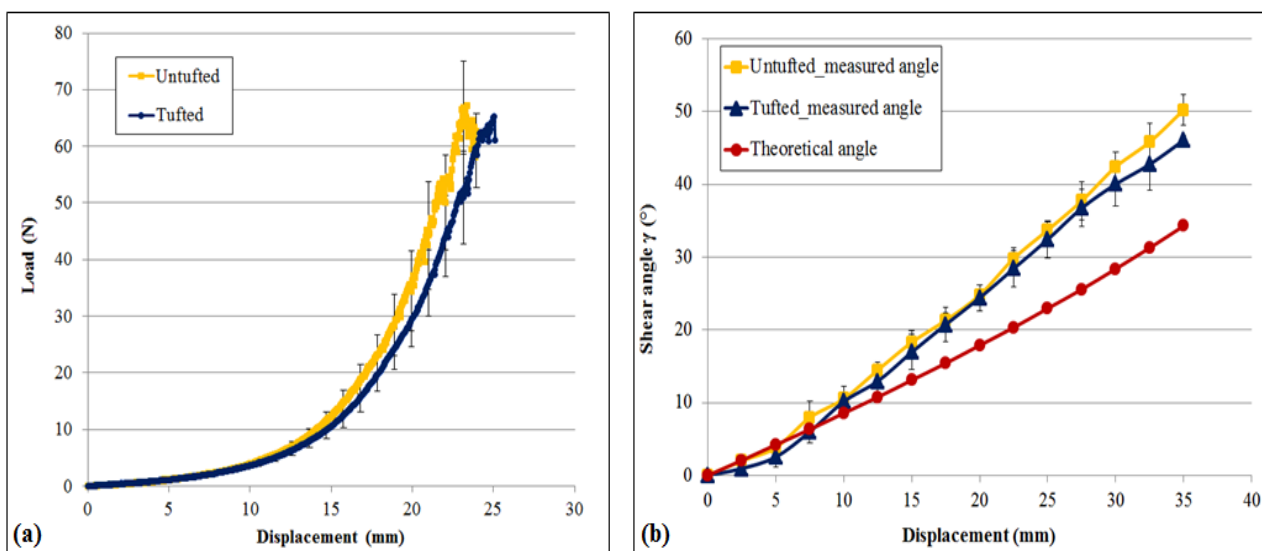


Figure 5. Illustrations of (a): In-plane shear load-displacement curves, (b): Theoretical and measured shear angles of tested preforms.

A macroscopic characterisation of the shape of the specimen, during the bias extension test, was conducted in order to understand the shear behaviour of untufted and tufted preforms. Figure 6 shows the shape deformation of tested samples during the shear trial where “d” represents the displacement.

The examination of the shape deformation reveals a significant deformation mechanism for both tufted and untufted specimens during the bias extension test. This deformation mechanism highlights the main shear properties where the different zones (A, B and C) are clearly identified with the occurrence of the wrinkling phenomenon at the end of the test

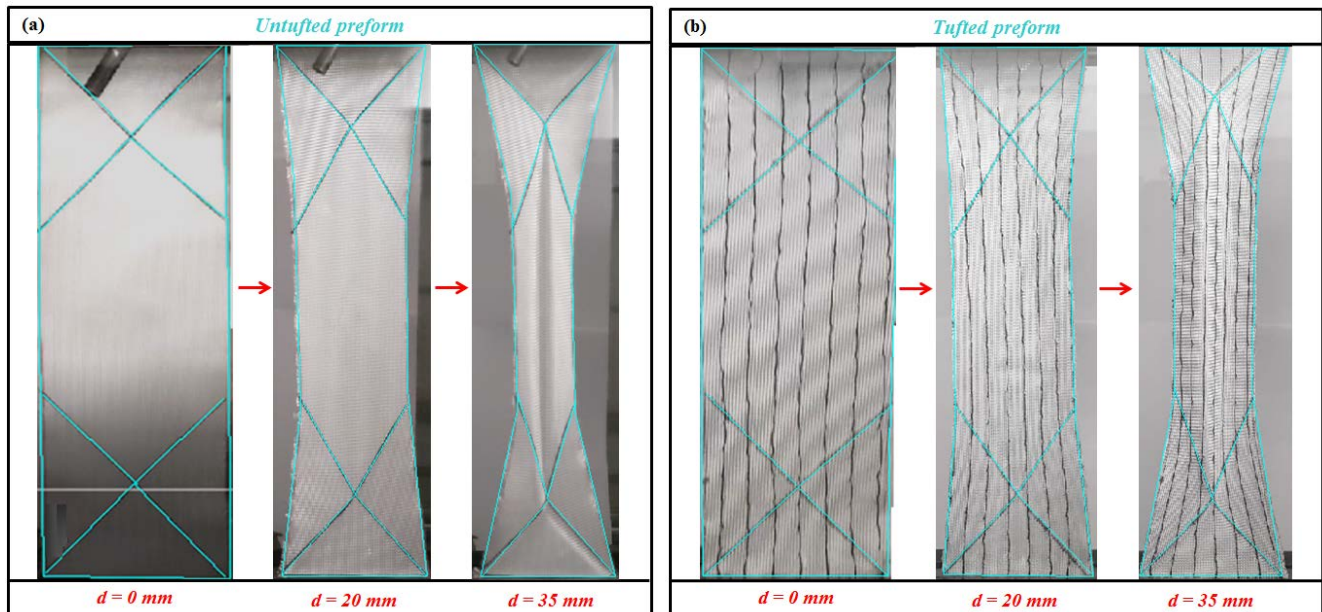


Figure 6. Shape deformation of (a): untufted preform, (b): Tufted preform.

4. Conclusion

The objective in this study was to better understand the impact of adding carbon tufts on the mechanical in-plane shear properties of glass weave reinforcement. Therefore, a bias extension test was performed for both untufted and tufted fabrics.

It was found that the increase of the displacement leads to an increase of the shear force which involves higher shear rigidity.

Regarding the shear angle which rises proportionally to the displacement up to a specific value where the angle becomes extremely large reflecting the shear locking angle.

From this research, it was proved that tufting does not necessarily weaken the in-plane properties of the final structure.

As future work, the studies about the in-plane shear using the picture frame is recommended in order to compare with results obtained by the bias extension test already carried out.

Subsequently, the preforming behaviour will be conducted by varying the shape of the punch (hemispherical, square box, tetrahedral...) to predict the feasible forming conditions.

Further efforts are ongoing in order to study the numerical in-plane shear behaviour of tufted structures.

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