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Manufacturing and characterization of tufted preform with complex shape

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Abstract. An alternative to the multilayered preforming is to use structures reinforced through-the-thickness in order to manufacture thicker and more complex pieces. Stitching technology is developed to bind dry reinforcements together or to strengthen composites in thickness performance by inserting structural yarns. Tufting process represents the simplest one-sided sewing technology and it is specifically designed for dry preform/liquid composite molding process route. Currently, the tufting technology is getting more and 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 structures and complex shaped textile composites. This paper aims to improve the understanding of the mechanical performance of tufted structures. An experimental study was developed, which included tensile and bending behaviours of tufted and un-tufted preforms, in order to evaluate the effect of tufting on the mechanical performance of dry preforms. The influence of the process parameters (tufting density, loop length, tufting yarns…) on the mechanical performance of the final structure is also highlighted.

Keywords: reinforcement through-the-thickness; tufting process; mechanical behaviour; dry scale; manufacturing

1. Introduction

Composite materials are widely used in various industrial sectors such as transportation, aerospace and energy mainly thanks to their lighter weight with a higher mechanical performance. However, the weak properties in the thickness of laminates, in terms of stiffness, fatigue resistance, imply in the framework of thick pieces sensitivity to delamination. This problem has led to the large use of three-dimensional preforms with reinforcement through-the-thickness.

Through-the-thickness reinforcements provide mechanical connections between ply which improve the mechanical properties of the laminates as mentioned by Mouritz *et al.* (2010, 2000, and 1999) and Chen *et al.* (2011).

Stitching technology has been developed to bind several fabrics plies together by inserting stiff yarns as detailed by Henao *et al*. (2010), Sickinder *et al*. (2001) and Pèrés *et al*. (2007).

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Nevertheless, the tufting process is much simpler than the sewing technique which represents the one-sided stitching technology. The tufting process involves the insertion of additional threads, via a single needle, through the fabric layers.

In literature, the mechanical performances of tufted-reinforced composites have been one of the main subjects and deeply examined in several researches (Henao *et al.* 2010, Liu *et al.* 2017, Dell'Anno *et al.* 2007, De verdiere *et al.* 2009 and Treiber 2011).

The mechanical behaviour of composite pieces is extremely related to the draping stage of dry reinforcement. The formability defects of the preform such as fiber breakage and misalignment as shown in numerous studies (Hamila *et al.* 2008, Boisse *et al.* 2010, Zhu *et al.* 2011, Boisse *et al.* 2011, Peng *et al.* 2013, Allaoui *et al.* 2014 and Haanappel *et al.* 2014) present an area of weakness in the final composite structure.

However, few studies (Liu *et al.* 2015 and Saboktakin 2013) outline the impact of tufting on the mechanical properties of dry tufted fabrics which is a key point for understanding the preforming behaviour. Dry stage is an essential step to predict the influence of through-the-thickness reinforcement and the formability of multilayer preforms.

The work shown in Liu *et al.* 2015 highlights the mechanical behaviour of tufted reinforcement during the preforming process where the tufting technique affects significantly the forming properties where the orientations of tuft threads influence the material draw-in, the inter-ply sliding and the wrinkling phenomenon during forming. Fig. 1 outlines the wrinkling aspects in tufted and un-tufted preforms where the increase of the tufting density leads to a reduction of the inter-layer sliding during the preforming test.

Nevertheless, the preforming behaviour of the reinforcement is strongly dependent on the tensile properties (Boisse *et al.* 2001 and Hivet *et al.* 2013), the bending stiffness (De Bilbao *et al.* 2010, Syerko *et al.* 2012 and Liang *et al.* 2014) and the in-plane shear behaviour (Cao *et al.* 2008, Launay *et al.* 2008, Colman *et al.* 2014 and Norsat-Nezami *et al.* 2014) of the dry preform.

Therefore, this paper aims to improve the understanding of the mechanical behaviour of dry through-the-thickness tufted preforms. Therefore, an experimental investigation was performed in order to highlight the tensile and flexural behaviours of tufted and un-tufted fabrics.

The effect of the manufacturing parameters, such as the tufting density and the orientation of tuft threads, is deeply described in the present work.

2. Materials and methods

2.1 Tufting technology

Previously, the tufting technology was used only for carpet and warm garment manufacturing. Now, it has become one of the most efficient technologies for through-the-thickness reinforcement. It is based on the stitching process as shown in Fig. 2, however, this one requires only one-sided access to the preform, as shown in Fig. 2, which makes it suitable for complex and three-dimensional shapes. Gnaba *et al.* (2018) have deeply detailed the tufting technology and its influence on the mechanical performance of the final structure.

The insertion of tufts is carried out locally via a hollow needle without generating any tension at the surface of the laminate which avoids the shearing and crimping aspects.

The tufting technology is more efficient and simpler than the stitching process, where the loops are not interlocked and the tufting threads remain in their position owing to the natural friction between the fabric and the binder yarns.

(a) Un-tufted preform (b) Tufted 10mm (c) Tufted 5mm

Fig. 1 Wrinkling phenomenon in various preforms

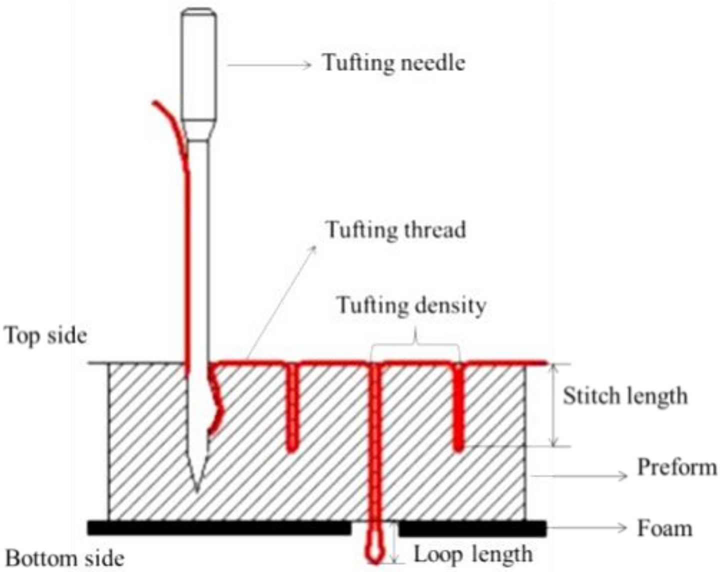


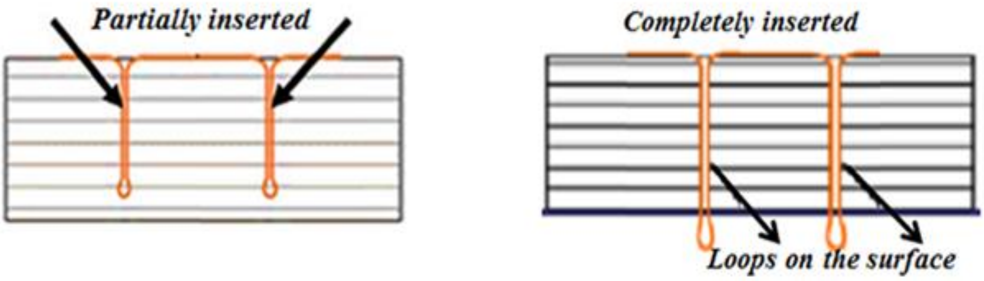
Fig. 2 Illustration of the tufting process

The threads can be fully or partially inserted through the preform thickness. In one hand, a loop of yarn is formed on the underside of the structure when the needle penetrates the whole preform thickness (Fig. 3(b)). In the other hand, the loops are fully retained within the laminate for a partial tufting (Fig. 3(a)).

The tufting technology shows more opportunities to develop through-the-thickness materials, especially with the advances in devices from manual to fully automatic where numerous studies conducted by Heano *et al.* (2010), Dell'Anno *et al.* (2007), Chehura *et al.* (2014) and Liu et *al.* (2015) have been carried out to automate the tufting apparatus. Fig. 4 presents the automatic equipment developed in our laboratory in order to handle the tufting structures.

The present device is equipped with the following elements where full details of the tufting machine are presented in the publication of Liu *et al.* (2015):

- ***Tufting device*** can move along the x and y axes. It is made with a tufting needle which is



(a) Partially inserted loops (b) Completely inserted loops

Fig. 3 Schema of thread arrangement in tufted preform

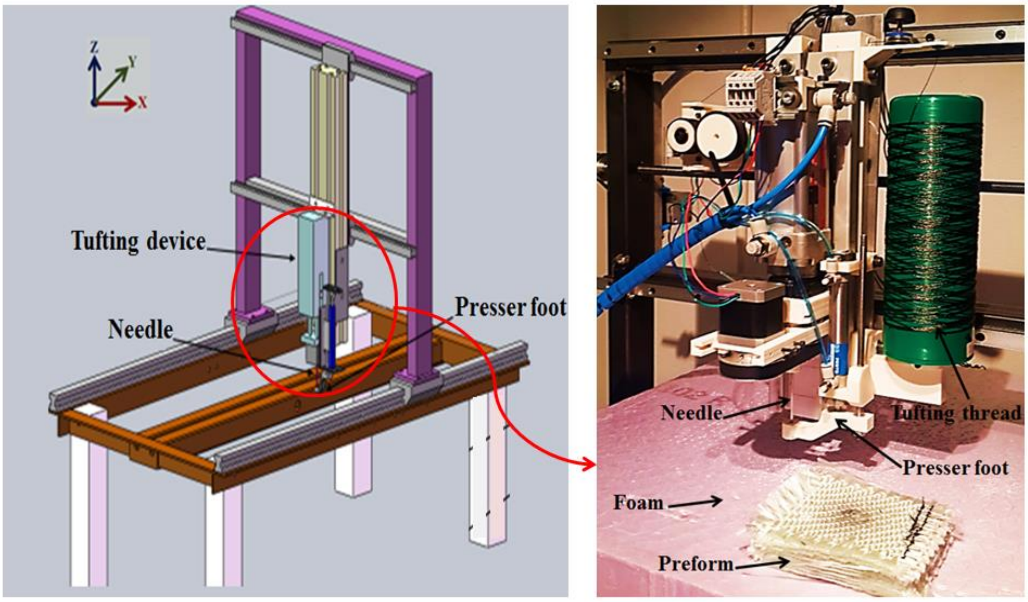


Fig. 4 Tufting device (*ENSAIT-Gemtex*)

connected to a pneumatic jack, which makes it possible to control the tufting deepness. The choice of the needle depends on the type of the preform as well as the properties of the tufting thread.

- ***Presser foot device*** is controlled by another pneumatic jack allowing both the attachment of the preform and the application of a pressure during the tufting process.
- ***Feeding device*** which delivers the tufting yarn.
- ***A mobile framework*** which allows the movement of the various equipment.

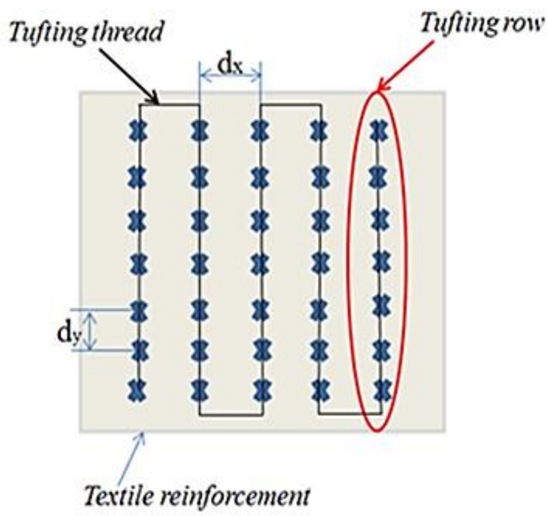
2.2 Preform manufacturing

The reinforcement fabric is a balanced E-glass plain weave with an areal density 160 ± 2 g/m². The dry lay-up of the preforms was laminated with four plies oriented at $[0/90°]_4$.

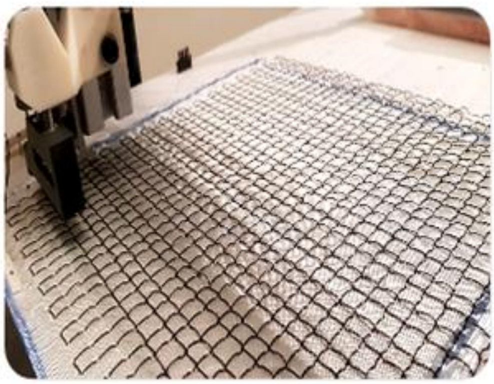
Tufting requires the insertion of high performance yarns through the laminate thickness in order to improve interlaminar properties. In the selection of yarn material, a compromise should be established between the suitability for the manufacturing process and the mechanical performance of the final structure. Also, the diameter of the tufting thread should be appropriate to the needle size.

In the present work, the tufting process was followed by inserting carbon yarn, having the following features 2* 1K 15S 67 Tex and supplied by Schappe Technique FR, into the several plies of the glass fabric. It should be noted that a needle of 2mm diameter was used in order to tuft the fabrics.

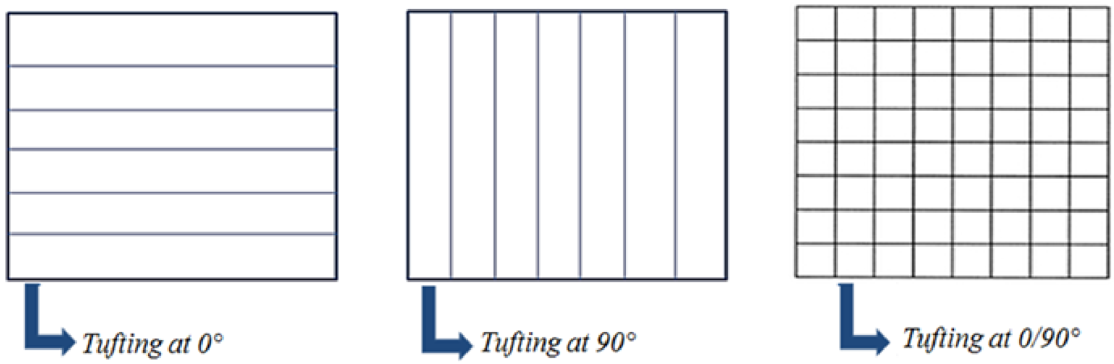
Various types of tufted specimens with different tufting densities and tuft threads orientations were performed. The tufting spacing is shown in Fig. 5 (a) where d_x and d_y are respectively the tufting distance in the x and y directions. Fig. 5 (b) shows an example of dry preform tufted at 0/90° and the orientation of tuft threads is illustrated in Fig. 5 (c). The main properties of these samples are listed in table 1.



(a) Schema of tufting pattern



(b) Example of dry preform tufted at 0/90°

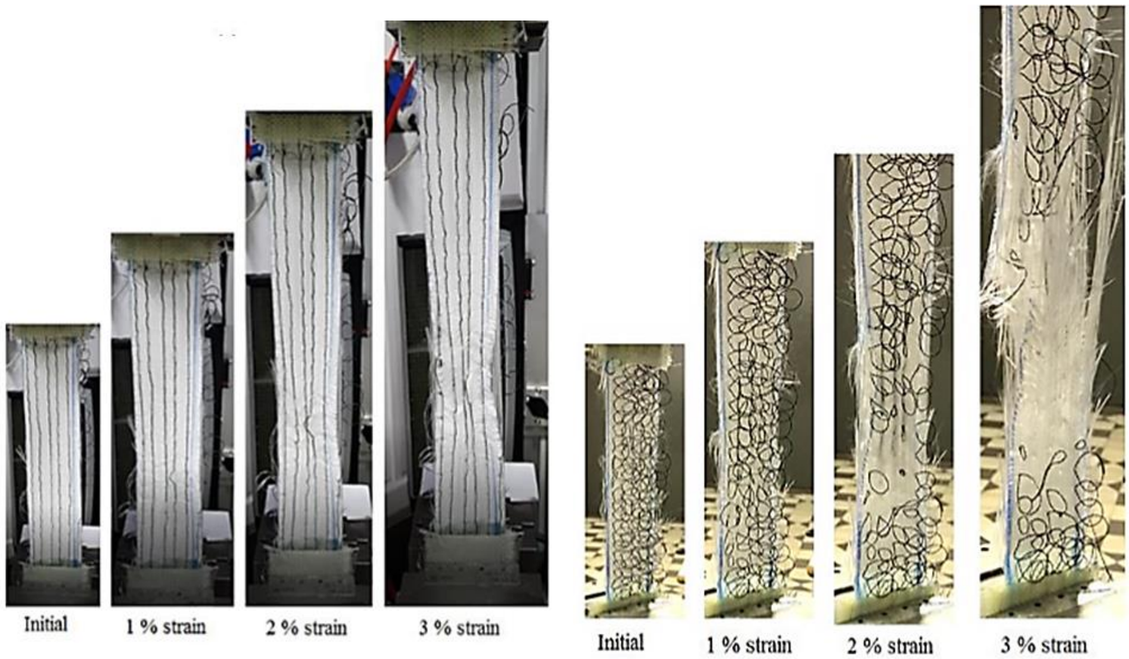


(c) Tuft thread orientations

Fig. 5 Main properties of tufting process

Table 1 Main properties of tested preforms

References	Areal density (g/m²)	Tufting spacing (mm)	Tufting orientation (°)
Un-tufted	622 (±20)	-	-
Tufted 0°	722 (±20)	10	0
Tufted 90°	722 (±20)	10	90
Tufted 0/90°	778 (±40)	10	0/90



(a) Front view (b) Back view

Fig. 6 Example of tufted preform at 90° during the tensile test

3. Mechanical characterization

The mechanical behaviour of tufted fabrics was performed in the present work. The tensile characterizations were studied using the tensile bench (INSTRON) with a loading speed of 100 mm/min and the dimensions of the sample are 300 x 50 mm² where 200 mm is the distance between the two jaws. It should be noted that the test is carried out in the transverse direction (90°).

The test was repeated five times for each tufted specimen. An example of a tensile test of tufted fabric at 90° is shown in Fig. 6.

Regarding the flexural behaviour, the bending stiffness were studied using the KES or cantilever tests as mentioned in Fig. 7. The specimen dimensions are 80 x 10 mm² and the test were performed five times for each structure.

The publications (De Bilbao *et al.* 2010 and Bilisik 2011) studied deeply the bending behaviour of through-the-thickness reinforced fabrics.

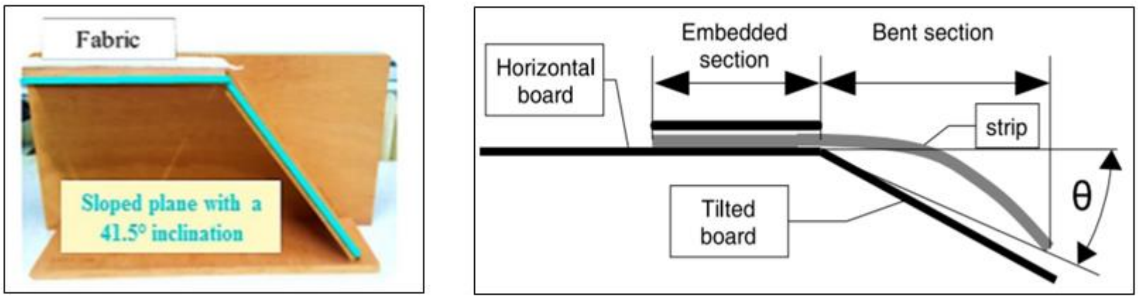


Fig. 7 The cantilever test for fabric (De Bilbao *et al*. 2010)

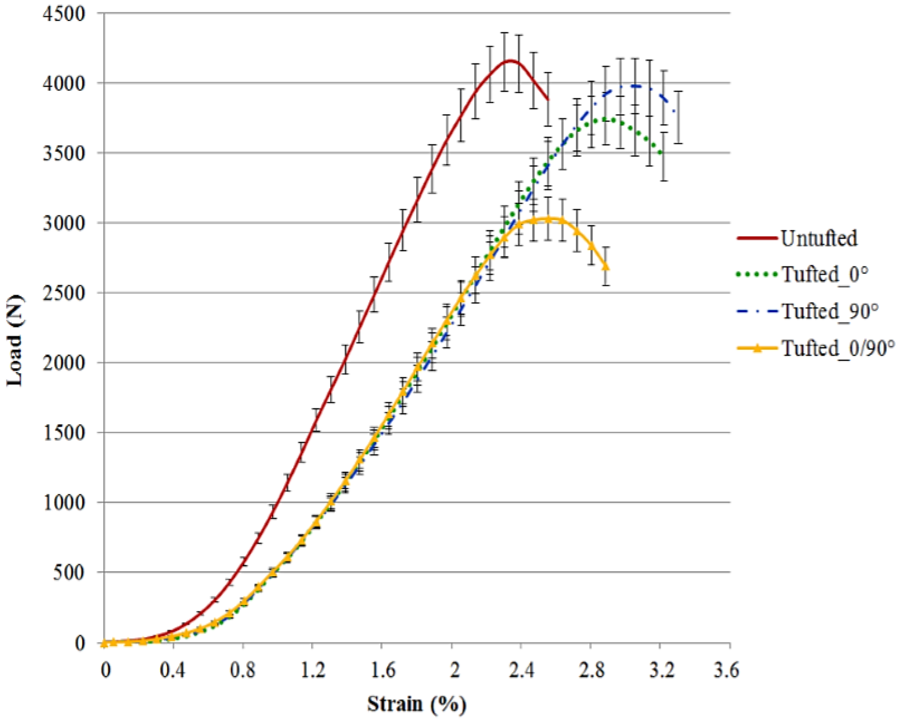


Fig. 8 Typical tensile load/strain curves of tufted and un-tufted structures

The flexural stiffness are calculated using a specific formula (Ep.1) where M matches with the areal density of the material and C is the experimental flexural length.

$$G\ [N.m] = M\ [g/m^2] * C^3\ [m^3] \quad (1)$$

4. Results and discussions

The typical load-strain curves for each preforms are illustrated in Fig. 8. It should be noted that each curve represents the average value of five tensile tests. Table 2 details the tensile properties obtained from the tensile test.

Table 2 Tensile properties of tested preforms

References	Maximum load (N)	Failure strain (%)
Un-tufted	4149	2.3
Tufted 0°	3743	2.9
Tufted 90°	3977	3.0
Tufted 0/90°	3030	2.6

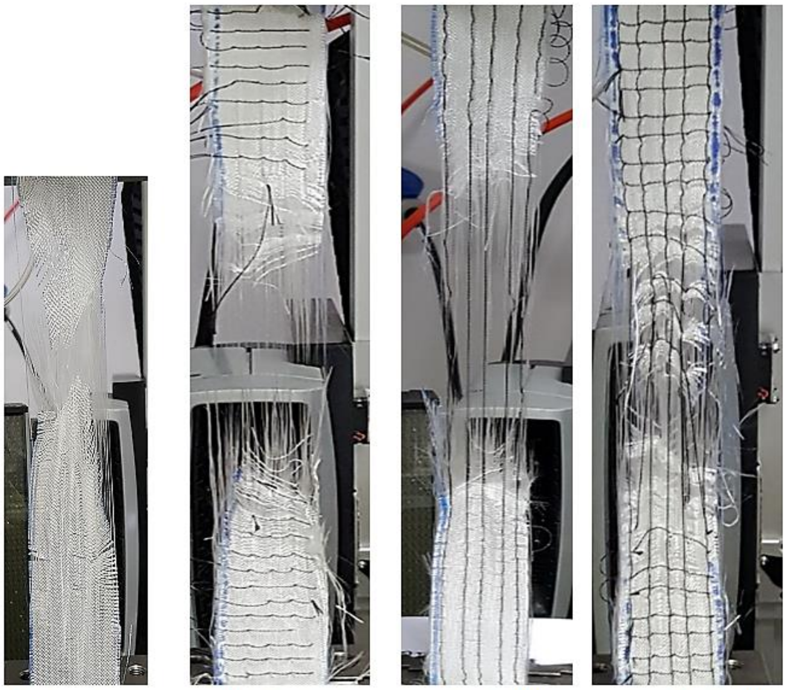


Fig. 9 Failure sections of tested preforms during the tensile test

In general, all load-strain curves exhibit a non-linear trend at large strain. The tensile load increases in function of the strain. For all tufted specimens, the through-the-thickness threads, especially the tufted thread orientations, influence significantly the tensile behaviour. Of the extracted results, the specimen tufted in the same direction as the tensile test (tufted 90°) exhibited a greater strength than those tufted in the other directions (tufted 0°, tufted 0/90°). The maximum load of the specimen tufted at 90° is higher than the maximum force of tufted 0° and tufted 0/90°. However, the un-tufted specimen has the greatest tensile strength where the maximum load is around 4149 N. All tufted preforms exhibited a larger failure strain than the un-tufted structure independently of the tufting orientation as mention in Fig. 9.

Results indicate that tufted preforms present similar slopes where the tensile curves display an increase in strain as the load increases. In this region, the load straightens the fiber bundles by removing fiber crimp and fiber misalignment. A linear response in the tensile behaviour of

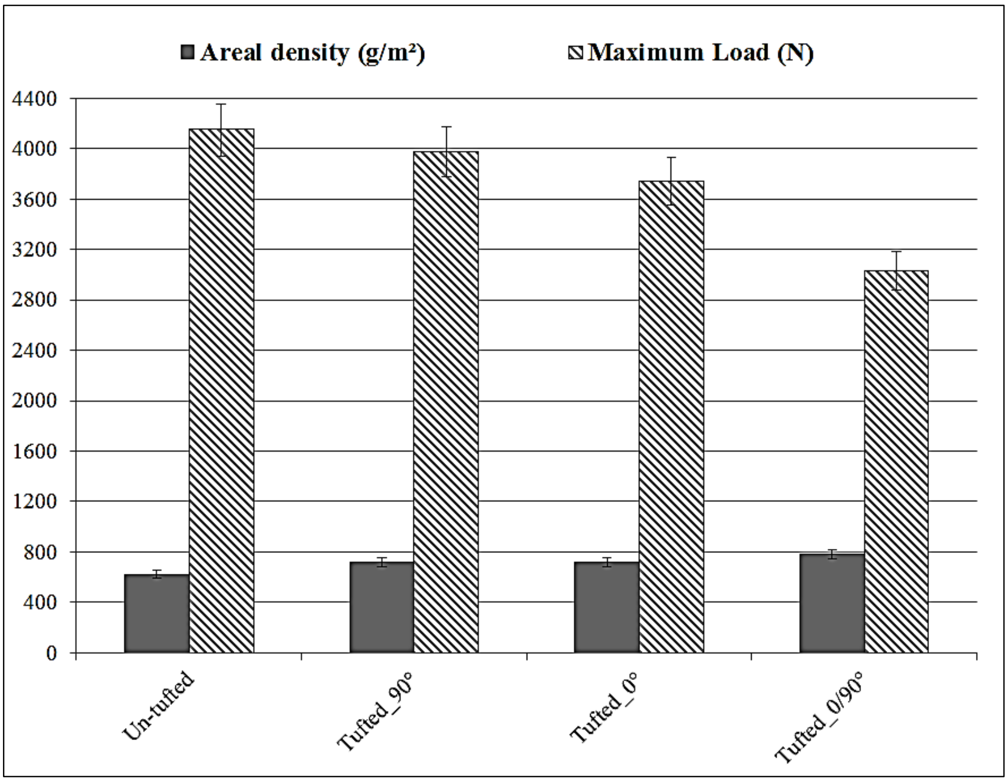


Fig. 10 Areal densities against the maximum tensile load

preforms appears, characterized by an increased slope, when the strain increased. This phenomenon is due to the highly stretched fibers in the loading direction.

After the peak point, the load is reduced in a non-linear behaviour as the strain is increased. In this section, the loops separate from the preform without generating the breakage of tufted thread. The results indicate a dissimilar behaviour in the post failure region where the specimens tufted at 0° and 90° present a similar failure section, however, the un-tufted and tufted at 0/90° samples show a uniform phenomenon.

For more understanding of the mechanical behaviour of tufted preforms, an investigation of the tensile strength and the areal density of tufted and un-tufted structures were performed and illustrated in Fig. 10. From the extracted date, it is obvious to notice that the maximum load is inversely proportional to the evolution of the areal density where the increase of the mass per unit area leads to a reduction of the strength. The un-tufted preform shows a higher tensile load with a lower areal density in comparison to the tufted preform, this can be explained that the addition of tufts through-the-thickness of the laminate may damage the in-plane mechanical properties due to fibre breakage and misalignment. Therefore, the manufacturing of the preform should be carried efficiently.

Added to the tensile properties, the flexural behaviour of the same specimens was performed in the present work. Fig. 11 outlines the flexural characteristics of the dry tufted and the un-tufted preforms. The following data show that through-the-thickness reinforcement affects significantly the bending behaviour where all tufted specimens, independently of the tufting orientation, present

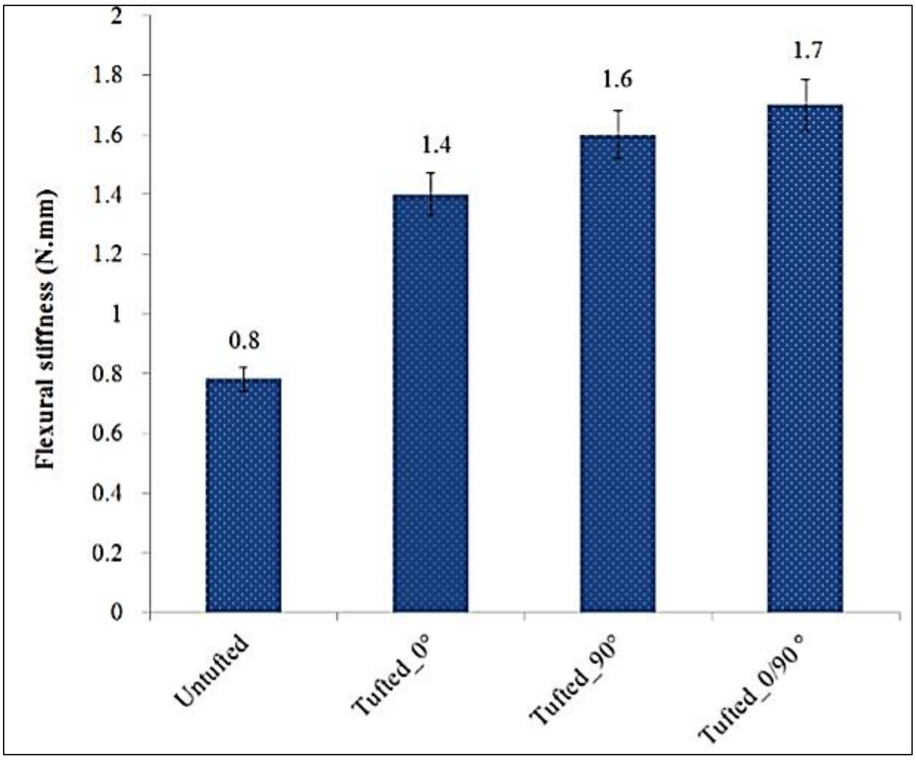


Fig. 11 Flexural stiffness of tested preforms

a higher flexural stiffness than the un-tufted preform. Flexural strength and material stiffness are mainly controlled by the evolution of the areal density where the stiffness increases as the mass per unit area is increased. As can be seen in Fig. 11, the orientation of tuft yarns influences the flexural behaviour where the preform tufted at 0/90° presents the highest value of stiffness, this can be explained by the impact of carbon tuft yarns.

5. Conclusions

Tufting is a promising through-the-thickness reinforcement technology due to its ability to bind several layers together by only one side access to the preform. However, the addition of threads in the Z-axis may reduce the in-plane performance of the final structure where a detailed study about the manufacturing process as well as the parameters involved is suggested in order to improve the in-plane performance.

In this work, tufted preforms with different tuft threads orientation (0°, 90°, 0/90°) were manufactured. In fact, an experimental investigation was performed in order to highlight the influence of the tufting technology on the mechanical behaviour of tufted textile reinforcements. Depending on the tufting parameters such as the tuft threads orientation, tufting shows different effects on tensile behaviour where the un-tufted structure presents the highest tensile load. The presence of through-the-thickness yarns leads to a lower tensile load and higher strain where the tuft threads make the breaking phenomenon slower. Regarding the stiffness, the addition of yarns through-the-thickness affects significantly the flexural behaviour of the final structure. It has been shown that tufting improves the flexural strength and material resistance where the flexural stiffness is higher, for all tufted specimens, than the untufted sample. The evaluation of the preform drapability is highly suggested in order to highlight the impact of enhanced bending stiffness.

In the future work, the studies about the in-plane shear are quite necessary to understand the forming behaviour which represents our next main work. The preforming behaviour will be carried out by using different punches (hemispherical, square box, tetrahedral…) to predict the feasible forming conditions. Also, a deep study using the Scanning Electron Microscope (SEM) is highly recommended in order to assess the fiber misalignment.

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