Literature review of tufted reinforcement for composite structures

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Abstract. In order to minimize the damage caused by the 2D structures, several research have been done on more complex structures (3D-preforms) which have more interesting mechanical characteristics. Divers textile technologies are used to manufacture 3D preforms such as weaving, knitting, stitching, z-pinning, tufting… This kind of reinforcement aims to achieve a balance between the in-plane and out-of-plane properties. Recently, the tufting technology shows more opportunities to develop 3D reinforcements especially with the advances in robotics. The present paper focuses not only on the various technologies of reinforcement through the thickness but also on the mechanical behaviour of a tufted preform in a stamping process.
Keywords: Composite material, 3-Dimensionnal reinforcement, Tufting, Forming

1. Introduction

Composite material are widely used especially in the aeronautics, space and defence sectors where the need to manufacture a lighter pieces with a rigidity control. 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 (3D) preforms with reinforcement through-the-thickness, thus making it possible to combine good mechanical properties while improving the resistance to delamination and resistance to impact.

Various technologies were developed in order to manufacture 3D preforms such as weaving, stitching, Z-pinning, tufting… 3D structures show a major challenge in many fields due to their reinforcement through the thickness (in Z direction).

However, this kind of reinforcement presents a compromise where a bad manufacture of 3D preforms obviously generates a fall in the mechanical behaviour of the final structure. That’s way a detailed study of the manufacture process as well as the parameters involved are quite required to ensure a 3D structure with better mechanical properties.

The present work focuses on the various technologies of reinforcement through the thickness, and it presents in detail the preforming behaviour of tufted 3D reinforcement as well as the various parameters involved.

2. Reinforcement technologies

This section highlights the most widely used technologies of reinforcement through the thickness namely, weaving, Z-pinning, stitching and more in detail the tufting process. These kinds of reinforcement have the potential to develop, at lower cost, structures with great mechanical performance.

2.1. 3D weaving technology

3D fabrics are generally characterised by a stacking of several layers and a binder thread. This binding is done by the addition of a binder yarns in the Z direction, making it possible to link the various layers together. There are several studies that focus on the classification of 3D woven structures [1-4]. Different weaving architectures are developed according to the interlacing and orientation of the yarns within the structure as well as the weaving pattern.

At this level, three main categories of 3D weaving categories can be distinguished:
-Layer-to-layer angle interlock: the interlacing takes place only between two successive layers where the binding thread returns to its initial position (the first layer) after the binding of these two layers. This architecture is characterised by an undulating interlacing where the warp yarns keep an undulating shape between two layers of stacking. This category of interleaving is presented in figure 1 (a).
-Through-the-thickness angle interlock: during the weaving process, the binding thread passes through the entire thickness of the preform through more than two columns of weft threads as shown in figure 1 (b).
-Orthogonal interlock: this type of weaving requires the passage of binding thread not only throughout the thickness of the preform but also for each column of the weft yarns. The layers are assembled by means of binding threads. Figure 1 (c) illustrates the orthogonal weaving structure.

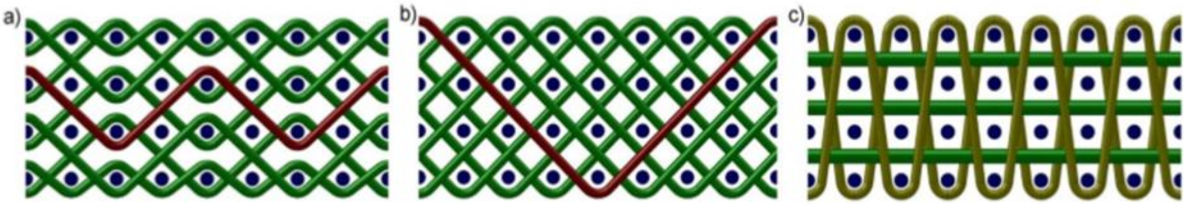

Figure 1. 3D woven architectures: (a) layer-to-layer angle interlock, (b) through-the-thickness angle interlock, (c) orthogonal interlock. [5]

3D weaving process does not require a special looms to produce 3D structures. It is possible to use standard weaving looms for 2D laminates with some simple modifications.

Regarding the several studies [6-8] show a better resistance to interlaminar shear and obviously a greater resistance in the thickness. **Mouritz** *et al.* [6] highlight not only a high damage resistance to ballistic impact for 3D fabrics but also a low-velocity impact damage tolerance. The greater resistance to impact of 3D weaving structures is guaranteed by the binder yarns (yarns inserted through the thickness) which can stop or slow the growth of delamination cracks.

Expect all these advantages of 3D woven fabrics, it cannot ignore the in-plane properties which are generally lower than the 2D preforms as well as the failure characteristics [5, 6].

In the following part, the three main technologies of reinforcement through-the-thickness are represented.

2.2. Z-pinning

The Z-pinning technology (also known under Z-fibres reinforcement) consists on the insertion of rigid rods called “pins” in the Z-direction. Z-pins are made with high stiffness and high material strength such as carbon, titanium and steel with a diameter between 0.2-1mm [9]. The Z-pinning process is a simple and reliable method where it requires the placement above the stack of foam containing the pins as shown in figure 2. The upper face of the foam is then swept by an ultrasonic impactor which provides the well insertion of pins into the laminate and then it remains to remove the collapsed foam and to cut the protruding. It is necessary to mention that the pins inserted in the foam, act as a fine nails that intertwine the laminate layers together. [9]

The most important advantage of Z-pinning technology is the high delamination toughness which increases damage tolerance and impact resistance as well as the joint strength [9-11]. In addition, Z-fibres process requires just one-sided access to the preform unlike the weaving or stitching process.

Several research [9-26] have been carried out on the Z-pinning technology shown that this kind of reinforcement improves the interlaminar toughness under different shear modes (I, II, mixed mode). Mouritz *et al.* [9] assert that Z-pinning technology leads not only to an increase of through-thickness elastic properties of laminates but also to higher impact strength due to its low damage rate.

However, the insertion of pins through laminates thickness may generate a reduction of the in-plane mechanical characteristics. This reduction is due to microstructural damage owing to fibre crimp and waviness which reduces the fiber volume content and obviously the presence of resin-rich zones [9, 27]. Figure 3 illustrates some microstructure damages caused by pins insertion.

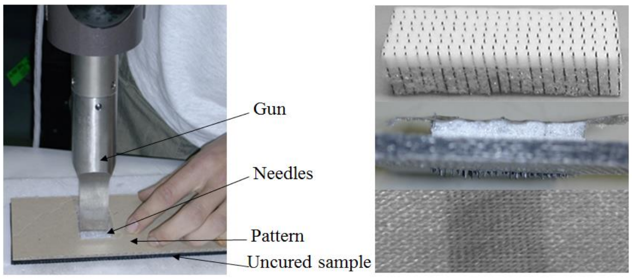

Figure 2. Z-pinning technology [28].

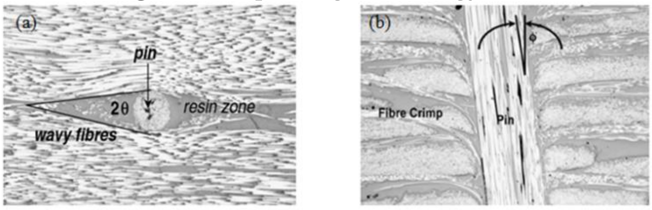

Figure 3. Microstructural damages caused by Z-pinning (a) Fibre waviness and creation of resin-rich zones (b) Fibre crimp [9].

2.3. Stitching technology

Stitching technology is one of the most effective technology through-the-thickness reinforcement that has been widely reviewd by **Mouritz** *et al.* [27], **Tong** *et al.* [29] and **Dransfield** *et al.* [30]. It is based on the sewing process where a dual-threading system (bobbin & needle threads), as shown in figure 4 (a, b), makes the seam by forming loops and knots through laminates or fabric plies. Stitching involves the insertion of high performance yarns, such as carbon, glass, Kevlar or any other high strength fibrous, through the laminate thickness in order to improve the interlaminar and delamination properties. Typically, there are three different types of stitching techniques:

- ***Chain stitch:*** the binding of the loops is carried out at the surface laminate via a single thread. The principle of the chain stitch is summarized in figure 4 (a).
- ***Lock stitch:*** it enquires a double access to the laminate (both bottom and top). The bobbin and needle threads are linked inside the preform which may generates a high stress concentration and resin rich areas. Figure 4 (b) illustrates the principle of the lock stitch technique.
- ***Modified lock stitch:*** it is well known as the stitching type which causes the least damage and stress concentration of the laminate. The intersection is carried out at the top of the preform by varying the tension between bobbin and needle threads as shown in figure 4 (c).

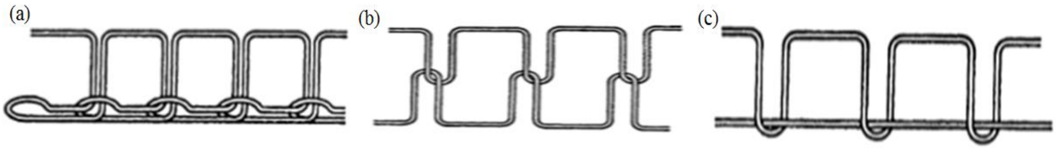

Figure 4. Illustrations of (a) chain stitch (b) lock stitch (c) modified lock stitch [31].

One of the advantages of the sewing technology is the possibility to stitch both dry and prepreg fabric. Stitching can also be used to manufacture complex three-dimensional shapes which increase through-the-thickness strength of the final structure. Moreover, the stitching technique presents a great deal of flexibility in the arrangement of through-the-thickness reinforcement by varying sewing parameters such as stitching density, pattern and the fibre thread. [29]

One of the most effective benefits is that stitch laminates have shown significant improvements in interlaminar fracture toughness [30, 32], fatigue resistance [33] and impact damage resistance [30, 34].

In the other hand, the main disadvantage of stitching technology is the reduction of the in-plane mechanical performances such as tension, compression and shear properties due to the needle penetration. In particular, the insertion of the needle may generate fibre breakage, misalignment and fibre crimping, hence, a creation of resin-rich pocket within the composite. **Mouritz** *et al.* [27] and **Tong** *et al.* [29] have summarized these damages (figure 5). The fact that the stitching technology enquires a dual-threading system in order to make loops and knots which begets a significant weakness in the mechanical properties of the final structure.

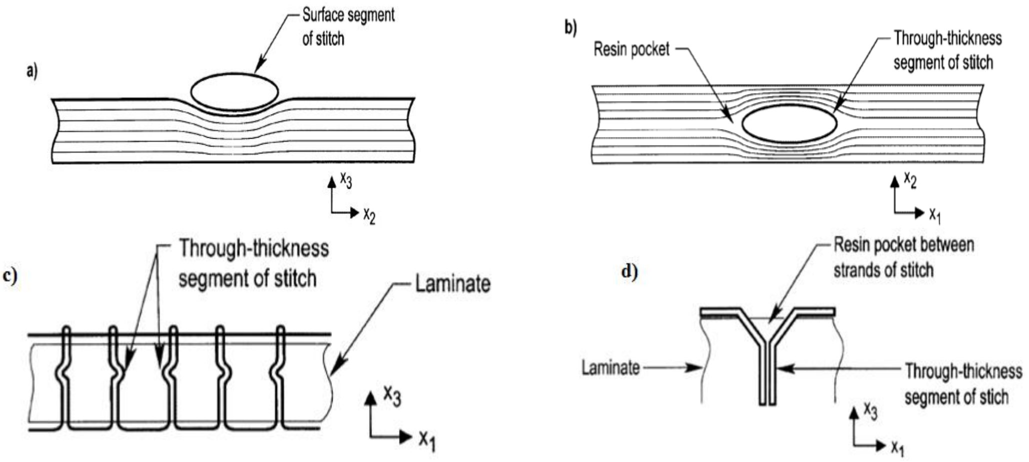

Figure 5. Illustrations of stitching damages (a) crimping of in-plane threads (b) misalignment of in-plane fibres around a stitch in the interior of the laminate (c) distortion of through-thickness segments of stitches (d) creation of resin pocket between two strands of stitch. x_1, x_2 in-plane laminate directions and x_3 through-thickness direction [31].

2.4. Tufting technology

Previously, the tufting technology was used only for carpet and warm garments 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 figure 6 (a). However, this one requires only one-sided access to the preform. The insertion of tufts is carried out via a hollow needle without generating any tension at the surface of the laminate which avoids the shearing and crimping aspects. This kind of reinforcement is more efficient and easier than the stitching technology which requires a second thread as locking thread. In fact, loops are created with simple friction of the tufting thread, which is maintained inside the preform, during the retraction of the needle. Obviously, the tufting process is quiet similar to z-pinning principle, but used to reinforce dry fabrics. Furthermore, the tufting process can be carried out in two different ways. The first one is called ‘Global-tufting’ where the tufts exceed the depth of the preform and the loops are visible at the bottom of the fabric. The other one is called ‘Partial-tufting’ where the tufts are fully retained within the laminate. Figure 6 (b) shows the difference between these categories of tufting. In this context, **Préau et al.** [35] assert that ‘Partial-tufting’ is an efficient technique since it makes it possible to avoid the creation of resin pocket and makes mechanical modeling much simpler.

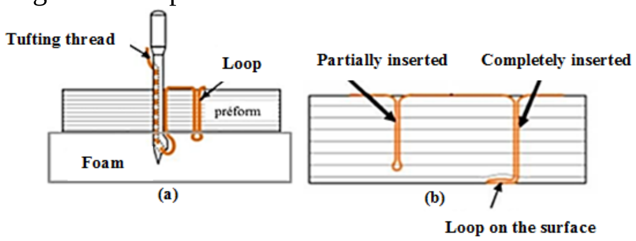

Figure 6. Illustrations of (a) tufting technology (b) partial & global-tufting [36].

Several works [37-39] have been carried out in order to automate the tufting device. Figure 7 presents the automatic equipment developed in our laboratory in order to handle tufting structures. The present device is equipped with the following elements [40]:

- ***Tufting device*** can move along the x and y axes. It is made with a tufting needle which is 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 characteristics 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*** provides the tufting thread with a certain length and tension.
- ***A mobile framework*** allowing the movement of the various equipment.

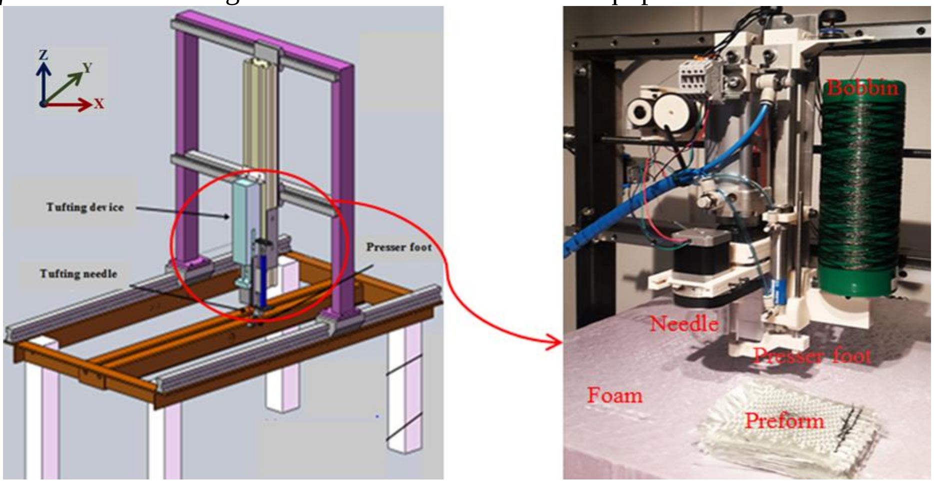

Figure 7. Tufting device (ENSAIT) [40].

In the case of a global-tufting, it should be noted that the choice of the most suitable foam is an essential parameter for the proper handling of the tufting procedure. However, a bad choice of the support generates an irregular formation of the loops and subsequently a complete damage of the loops. Polypropylene or silicone foams are the most widely used [41]. There are several parameters which can influence the final structure such as tufting density, loop length, tufting direction, tufting deepness and pressure of the presser foot.

The next paragraph is related to the mechanical properties of tufted structure at the dry reinforcement (especially forming test) as well as the composite scale.

3. Mechanical characterisation

The present section concentrates firstly on the mechanical properties of tufted composites and then, it highlights the mechanical behaviour at the dry reinforcement notably the forming behaviour.

3.1. Dry scale

The mechanical behaviour at the dry scale has a significant influence on the processing parameters such as porosity, permeability and obviously the mechanical properties of the final composite. Therefore, a detailed study of the preform performance leads to a good understanding of the mechanical behaviour of the final structure. In this context, **Saboktakin** [42] has studied both tension and compression behaviour of tufted twill woven fabrics. The tension test shows that the tufted preforms present a stronger deformation resistance where the maximum load of tufted structure is greater than the untufted one, contrarily to the failure displacement. The curve Load/Displacement can be divided into four specific regions: firstly, the crimp region where the load increases slightly follows the increase of the displacement due to the fibre breakage, followed by an elastic region where the curve present a linear slope. The tensile behaviour exhibited a nonlinear phase between the elastic region and ultimate strength point (peak point) followed by the post-failure region. However, the compression test shows a similar behaviour of tufted and untufted fabrics where both curves present three regions: a first linear part generated by the fibre crimping and the reduction of porosity within the structure, an exponential part related to the bending of woven fibres and tufting yarns and the final linear zone stand for the total compression of the preform. **Saboktakin** [42] has demonstrated that the compression behaviour is widely influenced by the tufting technology where an increase of the fibre volume fraction was noted due to the augmentation of the compaction load.

As detailed in the introduction, the present paper highlights the mechanical behaviour of tufted structure at the dry reinforcement through the preforming test on the basis of the results presented in [40]. The experimental forming with a hemispherical punch is performed in a specific device as shown in figure 8. This equipment allows to analyse the double-curved shape of manufacturing with a given textile reinforcement in different conditions. The device is equipped with four pneumatic jacks applying an adjustable pressure on the blank-holder. Several parameters can be calculated from the stamping test such as the punch force, material draw-in, inter-layer sliding and wrinkles. It should be noted that the reinforcement fabric was an E-glass plain weave composed of four layers [±45°, 0°/90°]$_2$ tufted with a carbon thread.

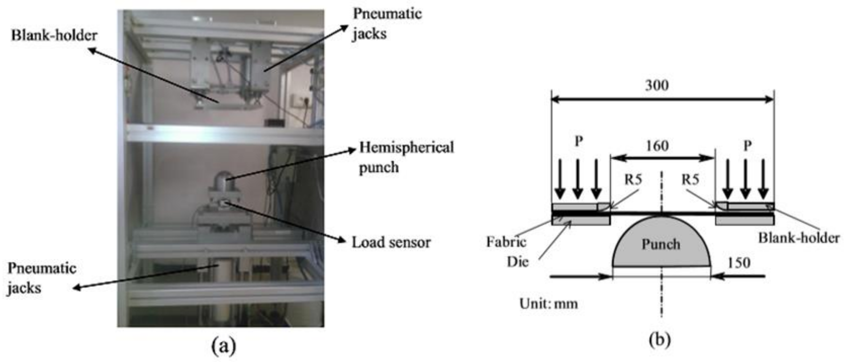

Figure 8. Illustrations of (a) preforming device (b) main dimensions of forming device [40].

The experimental data presented in **Liu** *et al.* [40] show that the punch force increase as a function of the tufting density where they record a significant increase of the maximum punch force (≈ 33%) for a tufting spacing of 5 mm (figure 9 (b)). Thus, the increase of the tufting density may leads to an increase in the rigidity of the preform. However, the graphics of the material draw-in present an extremely different behaviour where it decreases following an increase of the tufting density (figure 9 (a)). Furthermore, they highlight the forming defects following the insertion of tufting yarns, particularly, the wrinkling aspect. It was observed that the preforms having a tufted spacing about 5-10mm present the most regular structure and the fewer number of wrinkles, consequently, the increase of the tufting density may leads to a reduction in the number and the size of wrinkles (figure 10).

One of the most important points studied by **Liu** *et al.* [40] is the influence of tufting density on the inter-layer sliding during the forming process where they notice a big slippage of 19.7 mm for non-tufted structure in comparison to the tufted ones, especially, for the specimen having a tufting spacing about 5 mm, the inter-layer sliding is negligible (≈ 0.2 mm) where the four layers deformed in the same way. Subsequently, the increase of the tufting density generates a reduction in the inter-layer sliding during the preforming test.

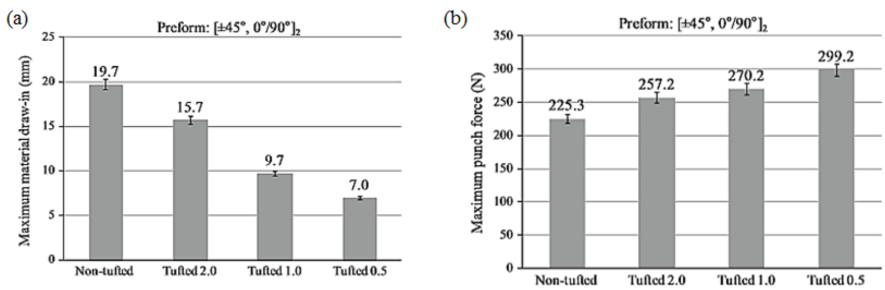

Figure 9. Illustrations of maximum (a) material draw-in (b) punch force [40].

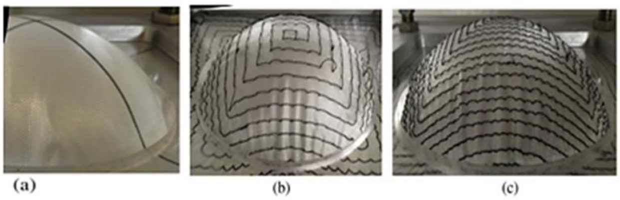

Figure 10. Wrinkling aspect in (a) untufed structure (b) tufted 10mm (c) tufted 5mm [40].

3.2. Composite scale

In terms of mechanical properties of tufted structure, numerous studies have been carried out in order to characterise the mechanical behaviour of tufted composites. For example, **Dell'Anno** *et al.* [38] have tested samples made from woven carbon tufted with glass or carbon thread, using the RTM (Resin Transfer Molding) process for composite manufacturing. They record a reduction of 10% on the tensile strength of the tufted sample where the initial slopes are similar, giving the same Young's Modulus. However, at a strain of 0.35%, they highlight a deviation from the linearity as shown in figure 11 (a). This reduction was explained not only by the fibres breakage and misalignment due to the needle penetration but also to the presence of resin pockets and voids around the tufts (figure 11 (b)). Moreover, **De Verdiere** *et al.* [43] reveal a reduction of the in-plane properties, about 10-15% in both tension and compression behaviour of tufted NCF composites. **De Verdiere** *et al.* [43] assert that the tufting technology reduces the in-plane stiffness of material due to the presence of resin rich zones and fibre crimping. In the other hand, they prove that the presence of tufts leads to an increase of the mechanical properties in the bias direction of NCF composites which they record an increase of both tensile and compressive strength. The main finding of both studies [38, 43] is that the reinforcement through-the-thickness, precisely the tufting technology, presents a compromise. It is quite logic to have a decrease of the in-plane properties due to the presence of tufts and obviously a higher performance on Z direction. Thus, a detailed study of all parameters related to the tufting device, the textile structure as well as the manufacturing of composites will be more efficient to achieve a balance between the in-plane and out-of-plane properties.

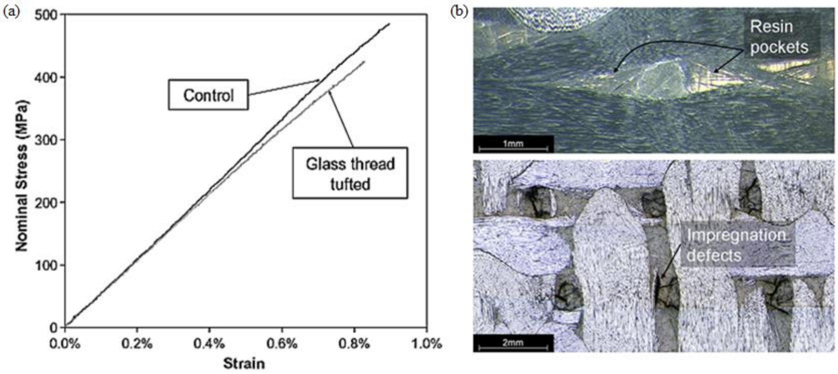

Figure 11. Illustrations of (a) Tensile behaviour of untufted and tufted samples (b) Resin pockets and impregnations defects in tufted composite [38].

Among the most performed tests on the tufted composite is the CAI (Compression After Impact) behaviour where in the papers [38, 43], they assert that the presence of tufts leads to a significant increase in the resistance of delamination which generates a great increase of the CAI performance. For example, **Dell'Anno** *et al.* [38] record a raise in the CAI strength by 25% and 27% in the presence of tufted carbon or glass threads, respectively.

Furthermore, **Préau** *et al.* [35] have studied the mechanical behaviour of tufted composites where they mention a significant decrease of the in-plane characteristics, particularly, the tensile and bending behaviours due to the presence of resin rich area. However, the tufting specimens show a significant increase of the interlaminar fracture toughness (mode I). In addition, the paper [35] emphasises the concept of "Global-tufting" where the tufts are completely inserted in the preform (the loops are visible at the bottom) and "Partial-tufting" where tufts are partially inserted in the structure. The paper [35] indicates that "Partial-tufting" is a very interesting technique since it makes it possible to avoid the creation of resin pocket which allows a better mechanical performance. Moreover, **Treiber** [44] highlighted the mechanical properties of tufted carbon fibre/epoxy composite and the results show a great increase especially in the delamination resistance, by a factor of three, within a laminate. One of the most important points presented in the paper [44] is the concept of the transverse elastic modulus (90) where it shows an increase by 7% and 45% for 0.5% and 2% areal tuft densities respectively for the unidirectional composite. The main raisons of this increase appear to be the locally increased fabric density around the tuft and the addition of tufting thread and loops parallel to the loading direction. In the same context, **Henao** *et al.* [39] have also focused on the compression and bending properties of tufted sandwich where they highlight an increase in both bending and edgewise compression strength as a result of adding a tufted thread. For instance, the increase of the compression strength was about 25.23%, 13.22% and 7.54% for tufting spacing values of 5 mm, 10 mm and 15 mm, respectively. Regarding the bending behaviour, they assert an increase in the failure load for the tufted specimens over 106% in comparison with the non-tufted ones. However, **Hartley** *et al.* [45] have studied the crushing performance of tufted sandwich structures where they reveal an increase in the crush strength between 11-19%. Indeed, the increase of the number of tufts generates a significant enhancement of the crushing performance about 25% in comparison to the untufted sandwich. Nevertheless, the variation of the loop length appeared to have a negligible effect on the loading response.

4. Conclusion

The various technologies of reinforcement through-the-thickness as well as the mechanical behaviour of tufted structure are studied in the present paper. The literature proves that the mechanical behaviour of tufted structure depends strongly on the process parameters and the preform characteristics where the presence of tufted threads generates an increase of the out-of-plane properties. However, a detailed study of all parameters may lead to a balance of both in-plane and out-of-plane performances.

In the future work, the studies about the tension, compression and bending behaviours at different tufting densities as well as the forming behaviour by using various punches (square box, tetrahedral, triangular…) are quite necessary. Indeed, the manufacture and the analyse of the mechanical behaviour of composite tufted structure represent the target of the upcoming work. The correlation between the numerical and experimental modelling of tufted 3D structure is quite necessary to improve the use and the knowledge of the tufting technology.

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