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# Investigation of mechanical properties of tufted composites: Influence of tuft length through the thickness reinforcement

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ABSTRACT

In the aerospace, transport and energy industries, laminated composites are widely used to manufacture thicker and more complex composite pieces. Three-dimensional (3D) fabrics have been developed to replace the multilayered reinforcements in some applications to increase performance through the thickness. The present study is dedicated to improving the understanding of the mechanical performances of 3D composite pieces reinforced by tufting. The tufting process and the equipment configuration are described in detail in the present paper. A 3D reinforcement architecture is prepared by the tufting process with varied tuft length, and then resin transfer moulding technology is used to manufacture the composite samples. Tensile tests are carried out to characterise specifically the influence of the tuft length on the tensile performance of tufting threads through the thickness of composites. The tensile results and microscopic analysis on the cross section of the 3D specimens show that the tuft length strongly influences the mechanical properties of tufted composite. Therefore, control of the tuft length is necessary to optimise the tufting process and thus improve the mechanical performance of assembled thick reinforcements and composites.



## 1. Introduction

Laminated composites are widely used in many industrial fields such as transport, construction, energy and defence. Compared to metal materials, laminated composites present better mechanical performances, such as high specific strength and stiffness. However, the lamination of two-dimensional layered fibre structures has shown the limitations, including high cost and some inferior mechanical properties such as interlaminar shear [1,2]. Therefore, a considerable amount of work has been conducted on the development of 3D preforms with reinforcements of high in-plane densities. This work presents the insertion of binding fibres to connect layers, which brings out the excellent mechanical properties of layers to improve the resistance to delamination and the impact resistance [3,4]. Different approaches of 3D preform manufacturing were considered and classified [5,6] according to the through-the-thickness reinforcement (TTR) methods. Thick or multilayered weaving [7,8] and other specific technologies such as stitching [9,10], z-pinning [11–13] and tufting [14–16] were applied to through-thickness insertion of fibrous structures.

The present study is dedicated to tufting and the analysis of the influence on the mechanical properties of tufted preforms and composites. Tufting has emerged as a popular method of localised TTR for dry preforms. The tufting process involves inserting a single threaded needle through a preform, where friction within the preform is responsible for holding the thread in place as the needle is retracted [17]. Tufting can be used to reinforce different types of textiles, such as woven fabric, braided fabric and non-crimped fabric (NCF) [18]. It requires only one side access of thread and does not require the use of a second thread, which makes it simpler and more cost-effective. The influence of reinforcement by tufting during the preforming step has also been highlighted [19]. Hartley et al. [20] have shown recently that increasing the number of tufts significantly increases crash performance (25 %) compared to untufted coupons. Colin de Verdiere et al. [18] have investigated the effect of tufting on the in-plane and out-of-plane mechanical response of NCF. They have shown that tufting considerably increases delamination resistance in mode I but to a lesser extent in mode II.

The present paper outlines the manufacturing of tufted composites and the tensile characterisation of the tufted samples, in particular the influence of the tuft length on the tensile performance of tufting threads positioned through the thickness of composites. Thick assembled reinforcements are prepared by using the

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tufting process. Microscopic analysis of the cross section of tufted composite and tensile test results shows the influence of tuft length on the mechanical performance. As a result, it is essential to control the tufting parameters in order to optimise the process of tufting and the mechanical performances of tufted composites.

## 2. Material and methods

### 2.1. Tufting process

Tufting is a relatively novel technique which is based on the ancient methods of carpet making and recently used for achieving through-the-thickness reinforcement in thermoset polymer matrix composites. It is ideally suited to load-bearing structures intended to be made via dry-fabric/liquid resin infusion processes. The tufting technology involves the insertion of yarns in z-direction (through the thickness) in order to strengthen fibre-reinforced plastics or link two fabric preforms together. As presented in Fig. 1, a threaded needle is inserted into a dry-fabric or bound preform and then removed from the fabric along the same trajectory. The "tuft" of thread relies on friction from the fabric itself and/or hold provided by underlying ancillary material (e.g. foam) to remain in place, and the loop of thread, which appears at the bottom of the work piece or hidden in the fabric preform according to different needs [14,21,22], is not locked in place. The tufting process can be used to bind thick structures because of its need for only one side access. Compared with traditional stitching techniques, where two threads are bound by forming a knot in the preform which weakens the performance of reinforcement, tufting applies a tension-free tuft which can reduce the effect of sewing on interlaminar performance and avoid the zone around the tuft being weakened [15–18,20–22].

In order to carry out the tufting process, automated tufting equipment has been designed and developed using a CAD software. Fig. 2 presents the equipment design. This equipment consists of four parts: the tufting system, the presser foot system, the feeding system and the frame. The tufting system carries a hollow needle which is controlled by a pneumatic cylinder to insert tufting yarn with different tuft lengths. Another pneumatic cylinder is linked with the presser foot and is installed alongside to adjust the pressure. The feeding system carries the tufting thread bobbin and provides tufting thread with a set length and pre-tension. With this equipment, the important tufting parameters such as tufting density, tuft length, tufting direction and pressure of presser foot can be controlled. The maximum tuft length is determined by the range of the pneumatic cylinder controlling the needle. The main parameters of the tufting equipment are shown in Table 1.

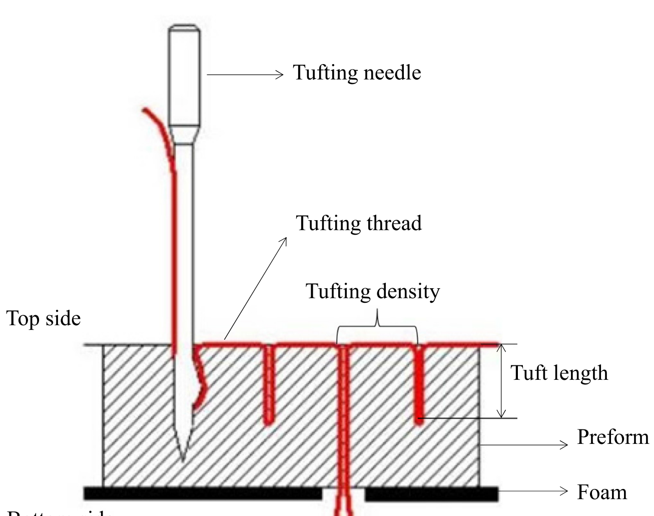


**Fig. 1.** Schema of tufting process.

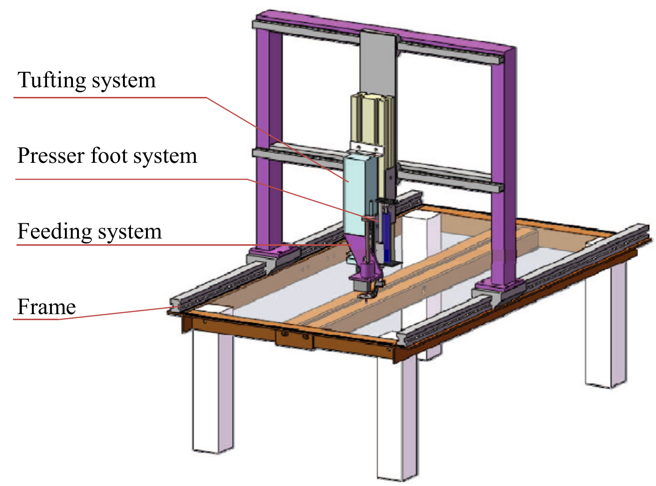


**Fig. 2.** CAD image of the tufting equipment.

### 2.2. Material

As the aim of the present study is to investigate the influence of tuft length on the mechanical properties of tufted composite pieces, thick tufted specimens need to be prepared. Thirty-four plies of plain woven E-glass fabrics (HexForce™ 1064) with an area density of 927 ± 10 g/m$^2$ are stacked. A thin release film with a thickness of 50.75 µm (Cytec E2760, red color) is placed between the 24th and 25th layer to separate the stack into two parts (upper and lower parts) (see Fig. 3). This release film can avoid extra adhesive effects after the vacuum infusion process. Consequently, the tensile test in the thickness direction will be applied only on the inserted tufting threads. The preform is tufted using a TORAYCA® FT300 3000-59A twisted carbon thread (Table 2) with different tuft lengths and a permanent tufting density of 5 mm. The twist of carbon thread is 194 ± 18 T/m. In order to control the tufting quality, it was decided to tuft carbon yarns into a glass-fibre-reinforced fabric. After the liquid resin infusion with an epoxy resin, the glass fabric becomes translucent, which makes possible to conduct the observation/micro-observation of the tuft length and tufting yarn loop (carbon yarn loop). The dimensions of the preforms are 250 × 150 × 25 mm$^3$. Fig. 4 shows one of the preforms after tufting. In order to study the influence of the tuft length on the mechanical properties of tufted composite pieces, the Desired Tuft Length (DTL) is changed during the preparation of the tufted reinforcement (from 16 to 22 mm) for every three lines presented in Fig. 4. This tufted preform is one of the samples tested. The DTL relating to the stroke of the tufting needle is not the final tuft length observed in the tufted composite piece. The DTL is modified

**Table 1**
Main parameters of tufting equipment.

| Parameters | Values |
|---|---|
| Size of tuft machine | 700 × 400 mm$^2$ |
| Needle inserting speed (after optimisation) | 60 mm/s |
| Needle retreating speed (after optimisation) | 60 mm/s |
| Needle diameter | 2 mm |
| Maximum needle stroke | 50 mm |