VISUALISING PROCESS INDUCED VARIATIONS IN THE MANUFACTURE OF TUFTED SANDWICH PANELS

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Abstract

Tufting is a promising through-thickness reinforcement (TTR) method for composite sandwich panels but is still under-used. In order to better understand the formation of the tuft and the influence of different processing parameters a test bed was designed to make visible the quality implications of needle and thread insertions. The forces required to insert tufts were measured in sandwich structures of NCF carbon and foam core alongside the visual effects of the needle on the assembly. The results provide more detail on the process and will help to identify the process parameters that limit tufting quality and therefore its repeatability and mechanical performance.

1. Introduction

Composite laminates are known to have desirable properties in the fibre-plane loading directions (x and y) but they have poorer properties through the thickness (z) due to the laminae being held together only by the strength and interfacial adhesion of the resin matrix; it is clear that further reinforcement in this third direction would be desirable. Tufting is the use of yarn loops as microfasteners for such through-thickness reinforcement (TTR), as well as being a means of joining parts in dry fibre preforms which are then infused by resin transfer moulding (RTM). Tufting offers a viable means of combating the limitations of composite sandwich structures which otherwise offer improved stiffness and strength for a relatively small increase in weight. Their poor resistance to inter-ply delamination and the debonding of the skins from the core reduce energy absorption in failure. Tufting technology has certain advantages over other commercially available TTR techniques such as z-pinning and stitching. The simplicity of the process is attractive and requires only minimal access to the preform surfaces, which facilitates the manufacture of complex shapes. The low tension of the tufting thread also minimizes disruption of in-plane filaments [1] which is often observed in stitched panels and can reduce the in-plane properties. The process uses a similar set-up to stitching with a needle and presser foot (as shown in Figure 1). A sacrificial backing such as foam is required if a loop is to be formed on the reverse of the panel, though partial insertion is also possible.

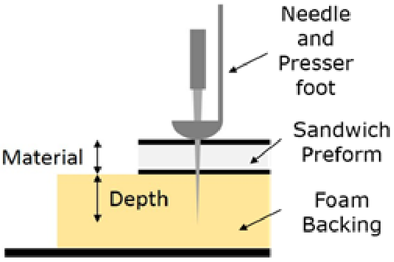

Figure 1: Tufting head components

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Past research has gone some way to optimising the process parameters of tufting [2,3] but little work has been done regarding the influence of these parameters on the quality of the tuft. Indeed quality is difficult to quantify, particularly as the region of interest is embedded within the laminate core. Features that can be assessed in terms of quality are likely to have an impact on the failure mode of the tufted component. When considering edgewise crushing of sandwich panels, such assemblies can buckle causing the skins to debond from the core [4]. This means this failure mode is inefficient in terms of energy absorption, something that would be a critical property if a part were to be used in automotive structures, for example. Tufting can arrest the debonding and delamination of the skins and so influence failure in such a way to absorb a greater level of energy. In order to achieve this, better understanding of tufting is needed [2,5].

Insight into the process may be gained by studying the forces required for insertion and retraction of the needle and the physical attributes of the resulting tuft. In order to understand the requirements of the needle and tufting yarn as they undergo loop formation, Chehura *et al.* applied fibre Bragg grating sensors around the circumference of the needle to measure the strains that develop during insertion and retraction [6]. They found that the strains experienced by the different sides of the needle are affected by the geometry of the needle and the bending moment induced by these is influenced by the inclusion of a thread or wire. That work did not investigate the force required for needle insertion and how this may vary depending on the material choices. Carvalho *et al.* [7] note that in stitching of textiles the parameters which must be measured are thread tension, presser foot force and force on the needle bar. The presser foot pressure is important as it varies with the movement of the stitched material and may cause uneven stitches. If the force used to insert the needle is too high then the yarn may break and it should also be noted that if the force is too great then the needle may break. In a later paper Carvalho *et al.* [8] determined that sewing speed has the greatest effect on the penetration forces. They had hoped to monitor the generation of defects, for example when a damaged needle was used, by comparison of the needle penetration forces, but concluded that the force measurements did not vary sufficiently for a distinction to be visible. Aktas and Potluri [9] developed an analytical model for prediction of needle penetration forces into a foam core requiring only compressive strength and frictional resistance of the foam as inputs. The model showed similar trends to the experimental data, but underestimated the actual forces recorded.

To date there has been little work published regarding what level of variation in the tufts would be permissible. Indeed, what might be deemed a ‘defect’ in tufted sandwich panels has yet to be determined and this lack of understanding is a barrier to the development of the technology. In the case of tufting it is not immediately clear which aspects of the process and tuft would be identified as defining and limiting features. This research provides a framework to determine the nature of tufting and develop a vocabulary to assist in discussion as well as identification and measurement of the aspects of tufting. A preceding project provided some detail on the tuft formation using a transparent tufting bed [10] and has contributed towards a better understanding of the attributes of the completed tuft. Observed physical attributes caused by the needle insertion into the core and skins are used to create ‘quality matrices’, establishing a potential ideal tuft, i.e. uniform with minimal preform disruption. This work suggested that there was some correlation between the as-measured quality (in relation to an ideal tuft) and the rate of needle insertion.

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2. Method

2.1 Methodology

A test bed was designed to make visible the quality implications of the process parameters on sandwich panel reinforcement, with a view to later informing their manufacture. Parameters such as tuft spacing, insertion speed, length of loop, *etc.* were identified from a commercial TTR module, and these were recreated in the test rig by constraining a compacted preform in a transparent holder (Figure 2). Two lines of holes were made in the top of the box along one edge and at half the width of the box to permit the needle to pass into the preform. This perforated lid acted in the capacity of a presser foot, holding the panel in place as the needle retracts. In this set-up (Figure 3) the tuft is visible while it forms *in situ*. Initially the needle was observed alone, inserting into, and retracting from, the preform using a test machine to control the rate and was recorded by imaging techniques. Thread was then included so that loop formation could be observed.

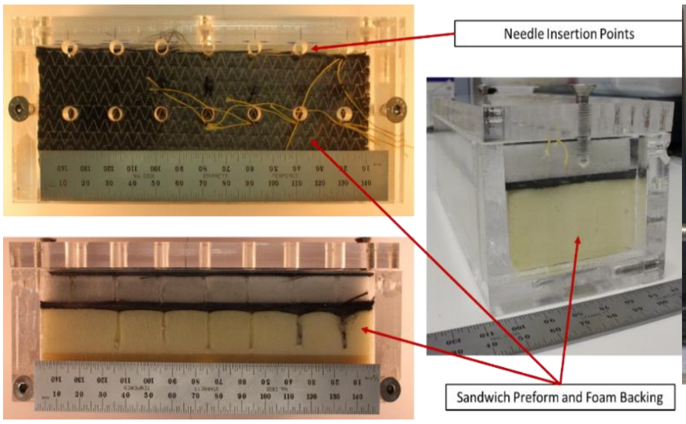

Figure 2. Tufting unit design

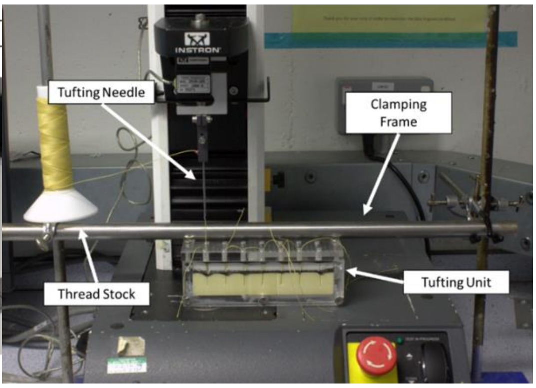

Figure 3. Test set-up

2.2 Procedure

The sandwich preforms consisted of uniweave carbon fibre fabric skins from SGL Automotive (300 gsm) and a Rohacell 110 IG-F closed-cell foam core of 10mm thickness by Evonik. Each of the skins was a hand lay-up of six plies, with a unidirectional and quasi-isotropic ply orientation. The 0° fibre direction was parallel to the long edge of the preform. The total preform thickness was approximately 14 mm which was positioned on top of a backing material with a sheet of vacuum bagging film in between the preform and the backing. Backing materials investigated here were closed-cell polystyrene foam and a closed cell PVC foam from Airex®. The plies were pre-consolidated before being placed in the test rig by being held under vacuum pressure at 1 bar, at 90°C for 2 hours in order to prevent unwanted movement of the plies during needle insertion. The tufts were formed of aramid thread (Tkt-20 Kevlar®, supplied by Somac Threads).

An Instron 3343 (electromechanical test machine) equipped with a 1 kN load cell was used to control the needle insertion. The tufting needle was attached to the test machine and the acrylic box was positioned below. A frame clamped the box to the platform preventing movement as the needle was retracted (Figure 3). The needle was inserted at rates up to the maximum that the Instron could achieve (1000 mm/min). The box was manually positioned so that insertions would occur at both the edge of the preform where it could be captured by video imaging and in the centre of the preform to obtain measurements with more realistic boundary conditions.

3. Results and discussion

Figure 4 shows the evolution of the tuft as seen in the test bed with the needle passing through preform and the loop being formed.

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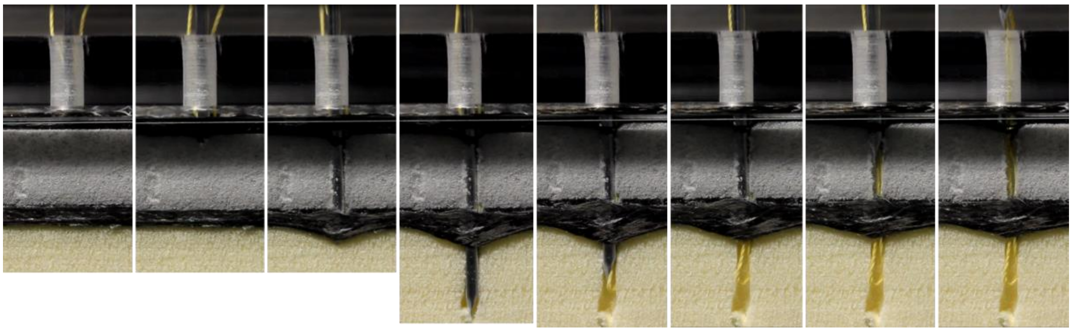

Figure 4. Thread loop formation on the edge of the preform

3.1 Needle penetration force

The force data recorded by the Instron provide some detail of how the total force acting on the needle varies as a result of the material through which it is passing. Below the x-axis is the compressive force acting on the needle due to the insertion and above the axis the force is positive as the needle retracts from the preform.

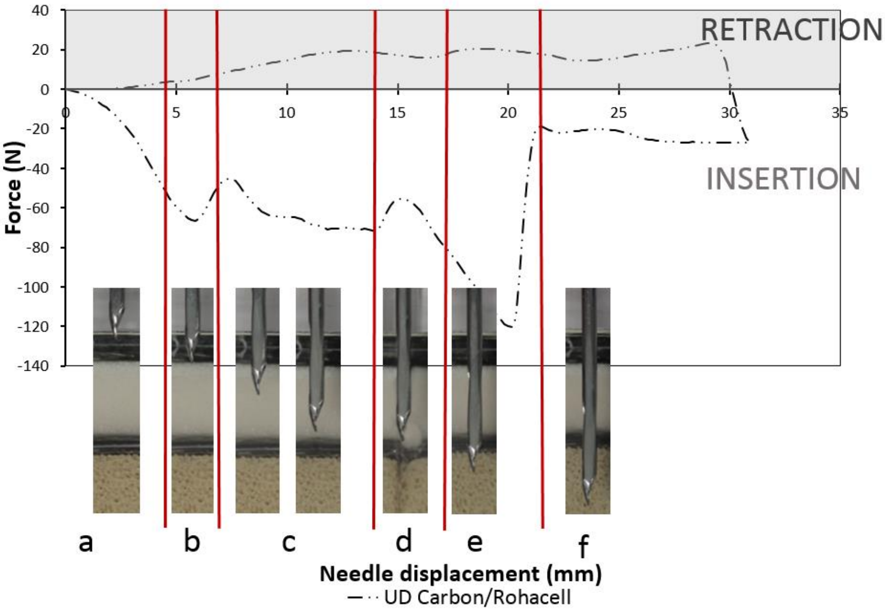

Figure 5. A typical force plot showing which part of the preform is responsible for the behaviour

It was seen that the forces reach local maxima as the widest part of the needle reaches the interfaces between the skins and the core (Figure 5). The force then becomes linear as the needle moves through the backing foam, before retracting and the forces become positive, though they are much lower as the damage caused to the preform decreases the frictional resistance.

Figure 6 shows the differences between the forces measured when just a needle is inserted at the edge of the box and in the centre of the preform and when a thread is inserted in the centre of the preform all at 1000 mm/min.

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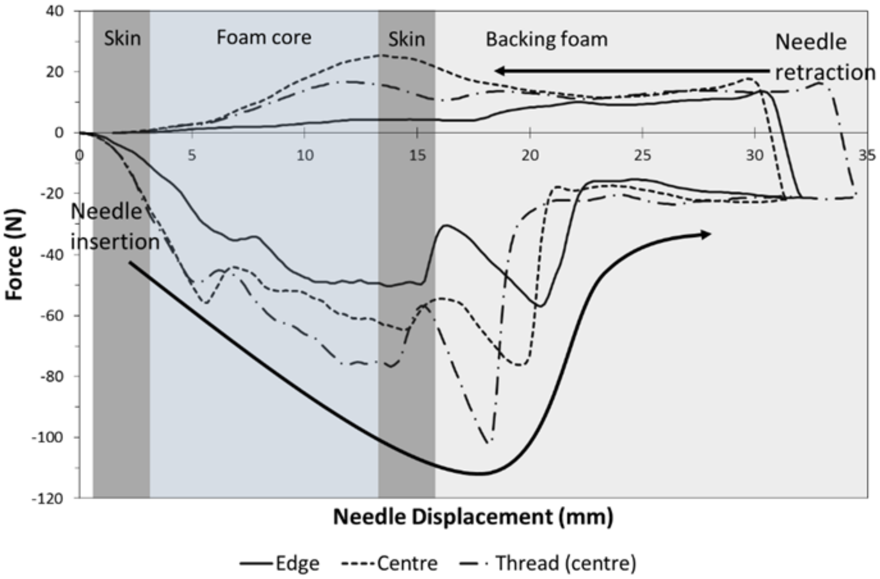

Figure 6. Forces acting on the needle passing through the preform into the polystyrene backing foam at 1000 mm/min

The pattern of the forces is very similar between the edge, the middle and when a thread is included, though their peak insertion forces vary between each case by around 25 N. It is to be expected that the force measured at the edge of the box would be lowest as only half of the needle is in contact with the preform, and the frictional resistance would increase further when a tufting thread is used with the needle. That the forces act on the needle in the same way but at different magnitudes suggests that the experimental test rig offers a visualisation the tuft formation within the panel.

3.2 Quality

The method described here allows the nature of the tuft to be recorded and preserved in the dry preform, allowing it to be assessed qualitatively. Previously, variations in tufts have only been analysed after infusion [11]. Henao *et al*. [12] x-rayed their samples after infusion but that method does not permit damage to the foam core to be seen. Images of the needle channels were taken to analyse and identify the common features (Figure 7) that may be used to discuss and rank the attributes of the tufts to provide a guide for acceptability. The common features identified were carbon fibre fragments, core fragmentation and the width of the channel opening.

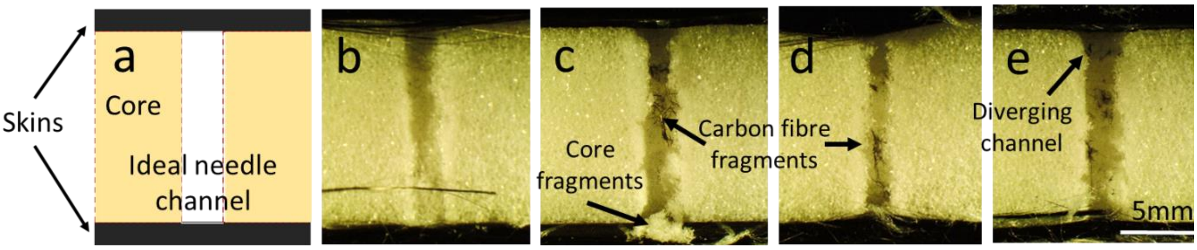

Figure 7. Needle channel features; a: theoretical, b: near ideal needle channel, c: carbon fibre and core fragments, d: carbon fibre fragments, e: divergence of the needle channel

The features of the needle channels that are observed can be used as a basis for rating the success of tufting and can be used to assess the consequences of different process parameters. The three features

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described above were quantified and ranked on a scale of 0-1 where 1 represents an ideal tuft, as in Figure 7a. This ideal channel would be clean without carbon or core debris and be the diameter of the needle, *i.e.* not vary along its length. If the column is non-uniform there is potential for resin rich areas. Debris in the column could prevent even distribution of resin during infusion and increase the likelihood of voids. The total of these ratings were then plotted against the insertion speed.

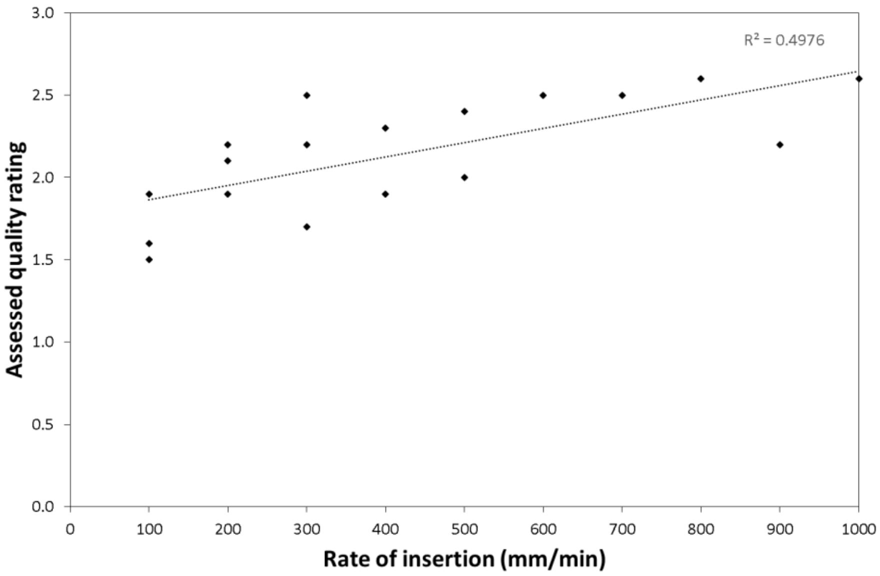

Figure 8. Graph showing trend of quality *vs*. insertion rate

The initial results from the use of the quality attributes (Figure 8) suggested some correlation between increasing tuft speed and an improvement in tuft quality.

5. Conclusions

Until now assessment of control in the tufting process could not be made until after infusion and cure. The test bed described in this paper has successfully recreated in the lab the variation of the commercial tufting process and has permitted the tuft to be viewed as it forms and allows the researcher to better understand loop formation. The bed highlights the quality attributes of the needle channel and tuft. The suggested method of analysis indicates that there is a possible trend seen in the quality of the needle channel with increased insertion speeds.

6. Future work

From these initial investigations the importance of understanding the variation in the tufting process is clear. There is a need to extract a greater number of process parameters and determine their influence over the process induced variation. A test bed with greater control is required along with a mechanism for extracting intact tufted samples for analysis. The rate of insertion must be increased to meet industry requirements as these investigations suggest there is a connection between rate and quality and so this should be investigated to that limit.

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