EFFECT OF MATERIAL CHARACTERISTICS ON THE LAYUP QUALITY OF THE CONTINUOUS MULTI-TOW SHEARING (CMTS) PROCESS

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Keywords: Automation, Fibre Placement, Continuous Multi-Tow Shearing (CMTS), Tow Steering

Abstract

The aerospace industry has pioneered the use of automated material placement machines, which excel in placing fibres in straight lines on large-scale moulds. Nonetheless, their ability to produce curved paths, which are required for complex doubly curved shapes and more efficient load distribution, is extremely limited. In order to overcome this limitation, the Continuous Multi-Tow Shearing (CMTS) process was developed, where in-plane shear deformation is employed in order to steer the tow path. The CMTS utilises unidirectional (UD) carbon fabric with multiple tows in the form of a tape.

In this paper two different materials were tested with a CMTS prototype head and a qualitative analysis was performed in order to give insight into the effect of material parameters on the quality that can be achieved with the process.

1. Introduction

Automation is a highly sought-after property in composites manufacturing and especially in the aerospace industry. Recently there has been great interest in expanding the capabilities of automated material placement machines into more complex parts. In order to lay up a tape or tow on a complex doubly curved mould and maintain a constant fibre orientation, steering of the fibre paths is required. Furthermore fibre steering has allowed for the production of Variable Angle Tow (VAT) panels where the structural loads can be optimally distributed through the curvilinear fibre paths, creating a new field of research in structural engineering [1]. The biggest limitation of modern placement machines is that they utilise the in-plane bending deformation of the tows/tapes (by rotating the placement head) in order to steer the fibre path, introducing several defects such as tow/tape buckling. A common measure of performance for the steering capabilities of a machine, is the minimum steering radius that it can achieve without the introduction of significant defects. This is approximately 6000 mm for ATL layup, using 150 mm wide tape [2], and 650 mm for AFP layup using 6.35 mm wide tow [3]. As the tows/tapes are bent, the minimum steering radius is dependent on the width of the tows/tapes, with smaller widths offering better steering capability.

Excerpt from ISBN 978-3-00-053387-7

2. Continuous Multi-Tow Shearing (CMTS)

In order to overcome this limitation, the Continuous Tow Shearing (CTS) process was developed, where in-plane shear deformation is employed in order to steer the tow path [3]. A minimum steering radius of 50 mm using an 8 mm wide tow can be achieved using the CTS, which is more than 10 times lower than conventional AFP. Furthermore, as CTS utilises the shear deformation of the tow material the tow width no longer affects the steering capability of the placement machine. To fully exploit this feature and boost productivity, the concept of Continuous Multi Tow Shearing (CMTS) was developed, that can lay up a unidirectional (UD) carbon fibre fabric with multiple tows in the form of a wide tape [4].
CMTS is a dry fibre placement process, where a resin tape is attached to the bottom side of a UD carbon fabric tape prior to the shearing stage. The semi-impregnated material is separated from the backing paper at the end of the pinch device (Figure 1) and is pressed by the compaction shoe onto the substrate. The whole dispensing system in the CMTS process is powered by a DC motor which pulls the backing paper of the resin tape by rotating two rollers. The current prototype can accommodate tapes up to 100 mm width. For more information concerning the operating mechanism of the CMTS prototype, the reader is referred to previous work [5].
In this paper, the effect of material characteristics on the CMTS lay-up quality is investigated. Although the shear behavior of woven fabrics has been extensively studied (a concise review can be found in [6]), there are few papers concerning the behavior of UD fabrics under shear deformation [7]. Nonetheless, it has been reported that the “shear locking” mechanism in UD fabrics is different from that of woven materials [7]. In UD fabrics, an increase in the shear angle causes the tows to come into contact, due to an increase in the lateral compressive force and further shear deformation causes out-of-plane tow buckling. Also, in contrast to woven fabrics, in UD fabrics the weft yarn has reduced stiffness and can accomodate large strains. It has been also found that the weft yarn pattern of a UD fabric highly affects the shear behavior and the onset of wrinkling during shearing [8, 9]. There are multiple parameters related to the weft yarn (e.g. pattern, yarn thickness, material etc.) and in [8] a modeling approach is presented in order to predict their effect during shearing of a UD tape. Furthermore, it is also stated that the sizing of the fibres also has an important role in the behavior of the material and can significantly increase the shear resistance of a UD tape.

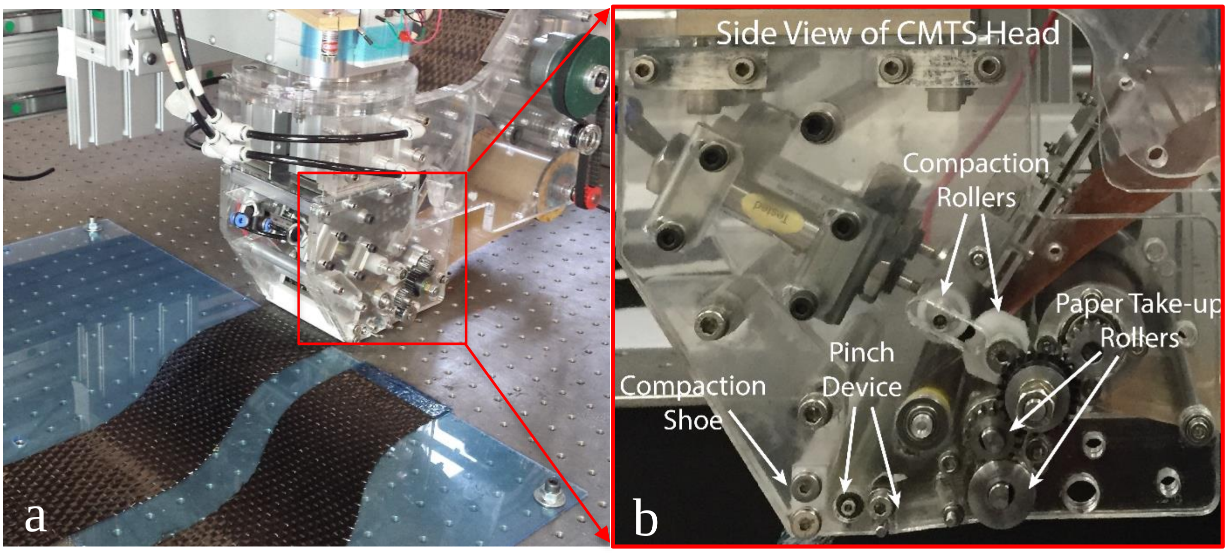

Figure 1. CMTS prototype head: (a) lay-up on a CNC gantry platform, (b) side view of the deposition head.

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3. Experimental Method

In order to investigate the effect of material characteristics on the lay-up quality, two different UD carbon fabric materials have been tested (Table 1). The width of both materials during the layup process was 90 mm. Material A, which has thermoplastic fusible weft yarns, was cut to this dimension from a 500 mm wide roll, while the width of the material B, which has glass fibre weft yarns, was reduced to 90 mm from its original width of 100 mm, in order to remove the inherent gaps between tows. Before the material was sheared in the shearing gap (between the pinch device and the compaction shoe), a 125 gsm B-staged epoxy resin film (913, Hexcel, US) was transferred to the bottom of the material within the CMTS head.

Table 1. Material Specifications of Selected UD Carbon Tapes

	Material A		Material B	
Areal weight (g/m^2)	218		225	
Weave	Plain		Plain	
	Warp	Weft	Warp	Weft
Thread Count (ends/cm)	2.5	1.6	5	3.5 x 2
Fibre Description	12k Carbon Fibre	Thermoplastic Yarn 110Tex	6k Carbon Fibre	Glass Fibre
Weight Distribution (%)	92	8	88	12

Fig. 2 shows the tested tow steering paths with the so-called linear angle variations [3]. Within the 200 mm wide steering region, the fibre angle was a function of the horizontal distance from the start point of the steering. Each path had a maximum fibre angle ranging from 10° to 50° at the inflection point, with 10° intervals between the paths. The minimum steering radii were 130.5 mm, 155.5 mm, 200 mm, 292 mm and 576 mm, respectively.
The materials were laid up on a transparent acrylic plate, and then the top surface was scanned using a high-resolution image scanner (1200 dpi).

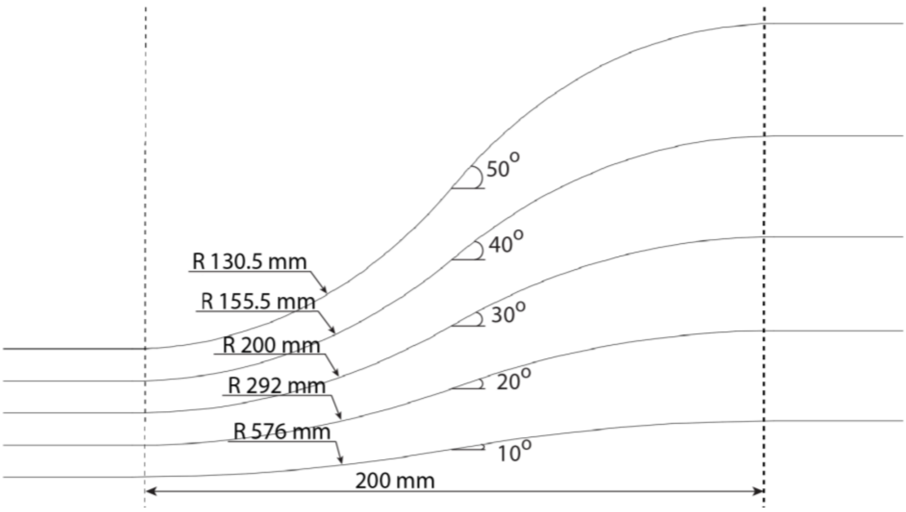

Figure 2. Tested tow steering paths.

4. Results

Based on the scanned images of the sheared fabrics (Figure 3), the effect of material characteristics on the lay-up quality was evaluated qualitatively.
Material A had a better material handleability, due to the fusible weft yarns that could keep the original tow arrangement. The material stability was helpful to improve the reliability in a straight lay-up as well

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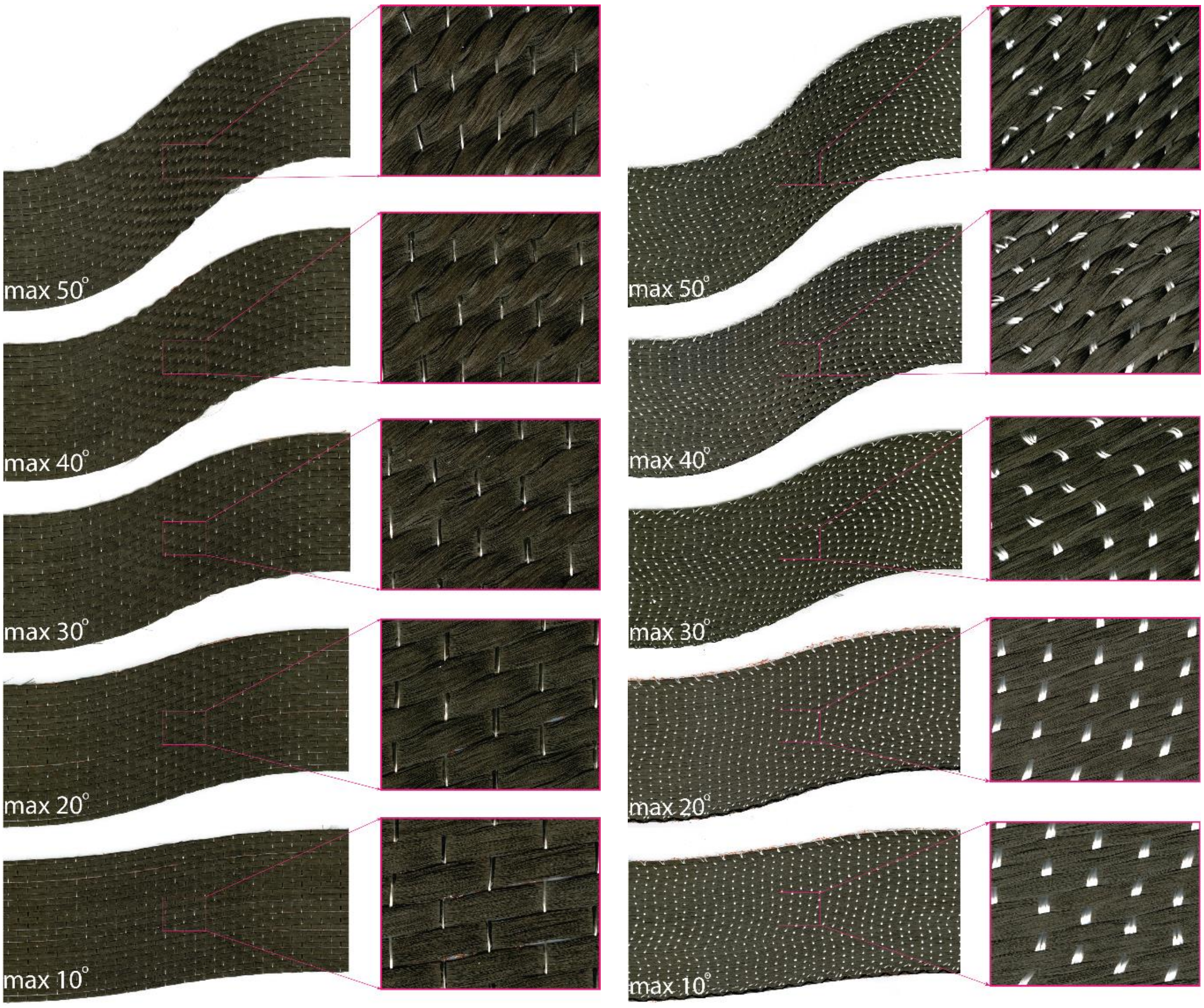
as in a steering process with small steering angles. However, the fact that the fusible yarns locked the inherent tow gaps, negated the advantage. Furthermore, it negatively affected the steering quality as follows.

This material exhibits severe wrinkling in the highly-sheared region and there was a clear correlation between the extent of the wrinkling and the shear angle as shown in Fig. 3a. The main reason for the development of these wrinkles is the fact that the thermoplastic resin, coated on the fusible weft yarn, penetrates through the tow surface and locks the fibres. This means that the fibres near the weft yarns could not be rearranged by shear deformation, thus producing in-plane wrinkles. It is reasonable to deduce that the pitch of the fusible weft yarn could highly affect the areal density of the in-plane wrinkles, with shorter pitch leading to more severe wrinkling. However, the locking effect of the fusible yarns was useful to induce the intra-tow shear when the steering angle was low, as the tows were heavily sized and behaved almost like tapes.

It was also observed that the tows near the tape edges were slightly bent rather than sheared. This might be related to the fact that the weft yarn had a free end at the edge of the tape and therefore it could no longer resist the tow bending. Due to this bending effect, in-plane wrinkles were generated along the edges of the tape.



(a) (b)

Figure 3. Scanned steering samples tested for different maximum steering angles: (a) Material A, (b) Material B.

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In terms of the wrinkling generation mechanism, material B behaved differently as the weft yarns were not able to constrain the fibre arrangement to such an extent as with material A. While mainly in-plane wrinkles were produced for material A, in-plane and out-of-plane wrinkles were generated for material B, as shown in Fig. 3b. This is related to the lateral compaction of the fabric. According to the working principle of CMTS, as the shear angle increases, the tape width needs to be reduced keeping the width along the original tape width direction (shift-width) the same during the shearing process [4]. During shearing, once the tows come into contact, due to the lateral compressive force, out-of-plane wrinkles begin to generate [7]. Furthermore, the tow thickening due to the lateral compaction and some level of intra-tow shear and tow rotation increased the weft yarn tension, which led to the formation of tow necking at the crossover points of the weft yarns with the tows. This phenomenon seemed to be similar to the shear locking of woven fabrics, but further investigation is required in order to unravel the exact underlying mechanism of this complex tow deformation at high shear angles.
The lateral compaction of the tape could be relieved by allowing for some inherent gaps of the tape. Gaps between the tows would increase the shear limit of the material, as the point where the tows come in contact could be delayed. However this would also lead to the development of resin pockets, for the straight parts of the tape trajectory, after curing. It would be worth investigating the relationship between the initial width reduction ratio of the tape and the shear limit.

5. Conclusions

In the CMTS process, which uses UD carbon fabric tapes, the weft yarn has two very important functions; first of all it maintains the straightness and alignment of the tows as they are being fed within the machine and more importantly it prevents the out-of-plane shear deformation of the tow as the compaction shoe slides on top of it. However the weft yarn also highly affects the shear behavior of the UD tape.
In this work, a qualitative analysis on the effect of the material characteristics of the UD carbon fabric tape on the CMTS lay-up was carried out, employing two materials with different weft yarn formats. Wrinkling defects were developed for both materials, when the rearrangement of the fibres within the tow was constrained, but this happened for different reasons for each material. In material A the fusible weft yarns locked the fiber orientation and width at the crossover points, not allowing for shear deformation of the tow and thus leading to severe wrinkling at high shear angles. In material B, the glass fibre weft yarns could slide on top of the tows and lead to less extensive in-plane wrinkling, but developed tow necking and tow out-of-plane wrinkling at the crossover points. The wrinkling that both materials exhibit at high shear angles would have a detrimental effect on the mechanical properties of a cured part.
It was evident that the weft yarns affected the shear behavior and the defect generation mechanisms of the tapes. Further study on this issue is required, in order to improve the lay-up quality of the CMTS process.

Acknowledgements

This work was supported by the Engineering and Physical Sciences Research Council through the EPSRC Centre for Doctoral Training [EP/G036772/1].

Excerpt from ISBN 978-3-00-053387-7

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