Advanced Automated Tape Laying with Fibre Steering Capability Using Continuous Tow Shearing Mechanism

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ABSTRACT

Advances in automated material placement technologies have enabled the production of fibre-steered composites, which allow for improved structural performance and expand the overall design space for composite structures. It has been demonstrated that the Continuous Tow Shearing (CTS) mechanism significantly improves the fibre steering capability of modern automated fibre placement machines. While the CTS was originally developed for use with semi-impregnated tows and dry fabrics, in this research the process was improved to realise fibre steering with wide prepreg tapes. The results from the feasibility study showed that the CTS process can achieve steering radii as low as 50 mm with 100 mm wide prepreg tapes, without generating significant manufacturing defects, making CTS the world's first automated tape laying technology with fibre steering capability.

1 INTRODUCTION

Recently, a composites design approach, which optimally distributes the structural loads through curvilinear fibre paths, in order to improve the structural efficiency of modern aircraft, is gaining attention thanks to advances in automated fibre placement technologies [1]. For example, a composite wing skin with optimally steered fibre paths could distribute the load directly onto the wing stiffeners and thus achieve a significant weight reduction, while maintaining the same stiffness and strength (Figure 1) [2]. Also the fibre steering designs make it possible to tailor the stiffness of a structure locally, allowing for aeroelastic tailoring of aircraft structures [3]. Such designs could play a vital role in the future as more flexible wings are under consideration for future aircraft programmes. Overall, fibre steering can significantly expand the design space for composite structures, allowing for more radical and optimised designs and shapes that were not possible before.

Figure 1. Examples of fibre steered designs of a wing skin and a fuselage section [2]

The current state-of-the-art technology enabling such designs is the automated material placement process, where carbon fibre tapes are laid up on a mould surface using a robotic material deposition head. Although these machines are excellent at laying straight paths, their fibre steering capabilities are extremely limited as they bend the tapes to steer the fibre paths, which inevitably leads to significant defects such as fibre buckling and resin pockets. Furthermore, as the minimum steering radius is dependent on the tape width, the automated tape laying machines laying more than 100 mm wide tapes have almost no steering capability.

In order to address this manufacturing issue, a novel fibre steering concept, named Continuous Tow Shearing (CTS), was developed at the University of Bristol [4-6]. The CTS can align fibres along a curved path without causing buckling and defects, by shearing continuously-fed tapes. The main advantage of this technology is that the material width no longer affects the minimum steering radius since it relies on the shear deformation of the tape, which means that much wider tapes can be employed, significantly boosting the productivity of the process.

The CTS mechanism was originally designed for use with semi-impregnated tows and dry fabrics. In this research, the CTS head mechanism was modified to expand its capability to shear wide prepreg tapes, which are the most common materials in the aerospace industry. This paper presents preliminary lay-up test results, which highlight the fibre steering quality that can be achieved with the process.

2 MATERIALS & METHODS

2.1 WIDE TAPE CTS HEAD

One of the differences between the wide tape CTS developed in this research and the commercial Automated Tape Laying (ATL) machines, is that the CTS employs a PTFE compaction shoe to press the laid tape material on the substrate instead of using a roller. In the CTS process, the trailing edge of the compaction shoe acts as a shearing boundary, sliding on top of the tape, and is part of the key shearing mechanism of the CTS head (a detailed explanation can be found in [6]). The materials used previously, such as semi-impregnated tows and unidirectional dry fabrics were suitable as they have low friction surfaces, due to the exposed dry carbon fibres. However, most prepregs exhibit high surface tack and would inhibit the sliding of the shoe on top of the tape. In this research, to enable use of prepreg tapes with the CTS, phenoxy powder was spread on the surface of the material, in order to reduce its tack (white powder in Figure 2). Phenoxy was chosen as it acts as a toughener [7] and thus it is expected that it will not degrade the interlaminar properties.

An additional requirement to enable use of prepreg with the CTS technology is that the individual fibres within the B-staged resin matrix slide against each other exhibiting a global shear behavior without developing shear buckling which occurs when the prepreg behaves like a rigid tape. Unlike fabric materials, the shear deformation characteristic of unidirectional prepreg materials has not been widely studied. Most notably in [8], Potter investigated the shear behaviour of cross-plied unidirectional prepreg during bias extension tests. It was found that the shear deformation was not uniform and that most of the strain develops in the regions of low fibre content between the tows. In-

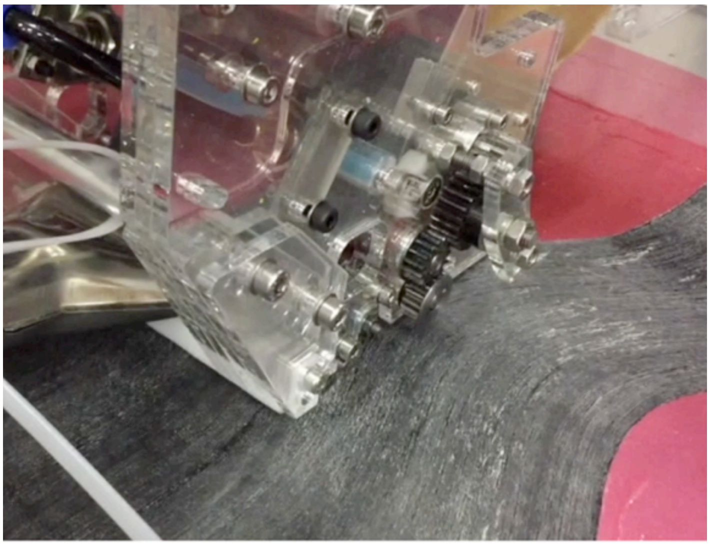

Figure 2. Wide tape CTS head continuously shearing 100 mm wide prepreg tape.

plane wrinkling was also observed and a hypothesis was formed that it is driven by tow misalignments, where essentially a few misaligned tows that come under tension cause the rest of the tows to come under compression and thus wrinkle. This highlights the fact that inherent defects in the prepreg material significantly affect the development of wrinkling and buckling during shearing. An extensive study concerning the sources and measure of misalignments in prepreg can be found in [9].

Furthermore, the shear response of prepreg is highly affected by temperature and shear rate due to the viscoelastic nature of the material [10]. In order to control the temperature of the prepreg tape within the shearing stage, the wide tape CTS head that was presented in [6] was further modified by adding a hot air blower prior to the shearing mechanism, offering control over the surface temperature and flow rate of the hot air (Figure 2). The surface temperature of the incoming prepreg tape was monitored by using an infrared thermal camera.

2.2 EXPERIMENTAL CONDITIONS

In order to assess the fibre steering quality that can be achieved with the CTS process, a preliminary set of experiments was conducted. Since the most common measure of steering performance of an automated material placement machine is the minimum steering radius that it can achieve without introducing significant defects, the main processing parameter under investigation here was the steering radius and its effect on the fibre steering quality.

Paths with three different fixed steering radii (50 mm, 100 mm, 200 mm) and the same maximum shear angle (40°) were laid up (Figure 3). The 100 mm wide tape material was slit from a standard unidirectional carbon/epoxy prepreg (MTM49-3/T800, Cytec, US) with a fibre areal weight of 140 g/m^2. The lay-up conditions are summarised in Table 1 and remained fixed except the steering radius and the lay-up speed for the experiments presented here. In order to ensure that the shear rate ($\dot{\theta}$) was the same for the different paths, the lay-up speed (v) was adjusted accordingly, using equation (1).

$$v = R\dot{\theta} \tag{1}$$

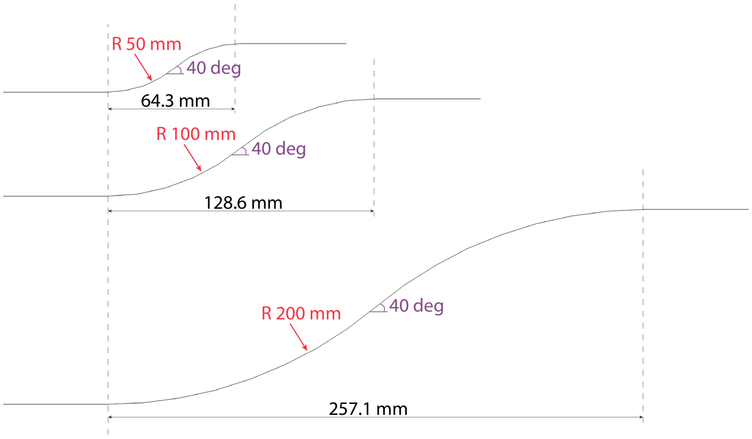

Figure 3. Steered Paths

Steering Radius (mm)	Speed (mm/s)	Shear Rate (s^{-1})	Temperature (°C)	Maximum Shear Angle	Compaction Pressure (MPa)
50	2	0.04	50	40°	37
100	4	0.04	50	40°	37
200	8	0.04	50	40°	37

Table 1: Lay-up conditions.

3. RESULTS & DISCUSSION

The tapes, which were laid on a acrylic plate, were scanned using a high-resolution image scanner (Figure 4) and a qualitative analysis was performed. Figure 5 (a) shows the straight part of a path, and Figure 5 (b)-(d) show the magnified images taken near the inflection point of each path where the prepreg tape was sheared at a maximum shear angle (40°). It was evident that the shear angle has an impact on the fibre steering quality, with in-plane fibre wrinkling starting to develop as the shear angle increased. The wrinkling appears to be localised with certain fibre bundles remaining straight. As it was discussed earlier [8], it could be deduced that the wrinkling is driven by the inherent fibre misalignments within the prepreg tape, which can be seen in Figure 5 (a). This means that the shear deformation makes the majority of fibres come under tension subjecting their adjacent misaligned fibres to compression, which leads to localised fibre wrinkling.

It is also evident that the magnitude of the wrinkling increased with a reduction in the steering radius of the path, as the path with a radius of 50 mm exhibited more wrinkling compared to the path with a radius of 200 mm (Figure 5). It could be inferred that some degree of tow bending was introduced; the material was not deformed under pure intra tow shear, but the deformation was a mixture of intra tow shear and inter tow shear. In the inter tow shear tows or fibre bundles slide against each other, whereas in the intra tow shear individual fibres slide against each other and rearrange within tows. Such formation of fibre bundles within a unidirectional prepreg material subjected to in-plane shear and their inter tow shear behaviour have been observed in the bias-extension test of cross-plied unidirectional prepreg materials [8]. In addition, in the case of CTS, where shearing is accomplished by two parallel shearing boundaries which move laterally in relation to each other, some degree of tow bending would occur at the shearing boundaries, which could lead to fibre wrinkling. Depending on how effectively the intra tow shearing is generated by process conditions such as temperature and shear rate, the degree of wrinkling could change. Further testing is required to investigate the effect of each parameter. What is also interesting from the lay-up test results shown in Figure 4, is that the developed wrinkles did not propagate forward as the shear angle returned to 0° towards the end of the path, which suggests that the quality produced by the CTS is related only to local material and process parameters.

4. CONCLUSIONS

In this work, the feasibility of shearing a wide unidirectional carbon/epoxy prepreg material using the Continuous Tow Shearing mechanism was studied. A series of lay-up tests was carried out in order to highlight the fibre steering quality that can be achieved with this process. Although some degree of in-plane fibre wrinkling was observed in the steered specimens, the steering quality was superior to that of state-of-the-art processes; such as automated fibre placement (AFP) and automated tape laying (ATL). Particularly, the CTS process could reach a minimum steering radius as low as 50 mm for a 100 mm wide prepreg tape without significant defects. This steering radius is remarkably smaller than those of commercial material placement machines, which is approximately 11000 mm for an ATL machine laying up 100 mm wide tapes, and 650 mm for an AFP machine laying up 6.35 mm wide tows. It was demonstrated that the CTS mechanism can realise the world's first ATL process with fibre steering capability, which upon further development can enable the high-volume production of high-quality fibre-steered composite structures.

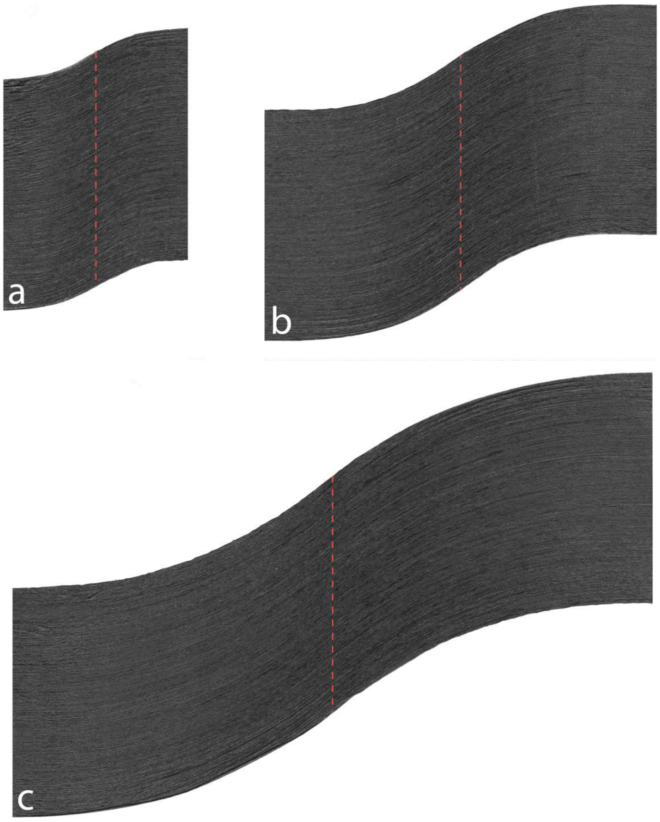

Figure 4. Scanned Steering Samples of 100 mm wide tapes with different radii: a) 50 mm, b) 100 mm, c) 200 mm.

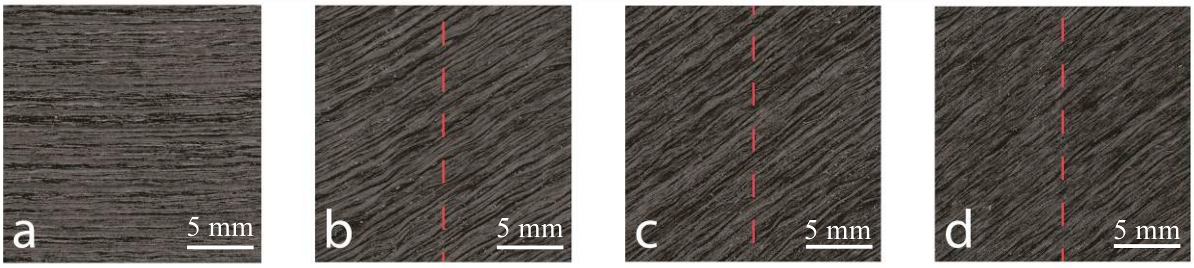

Figure 5. Zoomed images taken from the centerline of the layed paths: a) straight section, maximum shear angle for paths with a steering radius of b) 50 mm, c) 100 mm, d) 200 mm.

ACKNOWLEDGEMENTS

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