NOVEL HEAD CONTROL ALGORITHM FOR 3D CONTINOUS TOW SHEARING

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Keywords: Continuous tow shearing (CTS), Automated fibre placement (AFP), tow steering, defects.

ABSTRACT

It has always been challenging to manufacture a composite structure with complex geometry using automated fibre placement (AFP) process. Typically, the tool surface is difficult to be tessellated using fibre tapes with a finite width, without producing gaps and overlaps, and requires fibre steering along non-geodesic fibre paths, which produces defects such as tape buckling and pull-up. In this work, a defect-free fibre-steering process on a complex doubly-curved surface was demonstrated by realising the continuous tow shearing (CTS) process in three dimensions. A new head control algorithm was developed, which defines the head orientations and trajectories based on a pin-jointed strip (PJS) model, to manipulate the fibre tow using both in-plane shear and out-of-plane twisting deformations. Fibre steering process using this new algorithm was tested on a doubly-curved surface, using an industrial robot arm with a CTS prototype head, and its lay-up quality and accuracy were assessed by using a three-dimensional laser scanner. The new control algorithm enables defect-free fibre steering on complex 3D surfaces allowing for simplifying the design and analysis of novel composite structures.

1 INTRODUCTION

The use of automated fibre placement (AFP) has been increasing exponentially in different industries, especially in the manufacture of large composite aircraft and spacecraft structures. Since the AFP process was first developed in the 1970s, it has been extensively studied and the productivity aspects such as lay-up speed and the number of tows simultaneously laid per course have significantly been improved. This progress has made the AFP the most cutting-edge technology for manufacturing carbon fibre composites [1].

However, although AFP has shown high efficiency for straight lay-ups on flat or low-curvature surfaces, it is well known to produce various defects especially when laying-up on doubly-curved surfaces. In most cases in industry, the tool surface has curvatures in three dimensions (3D), which results in the need to steer the tows following non-geodesic paths on the surface for its full coverage. Fibre steering is also required to realise novel variable stiffness (also called fibre-steered, tow-steered, curved fibre or variable angle tow) structures. Steering tows using the conventional AFP process always produces various defects depending on the tool geometry and the curvature of the lay-up path, as well as the manufacturing process parameters such as lay-up temperature, head speed and compaction force. The fundamental cause of such steering-induced defects is the material manipulation mechanism of the AFP utilising the in-plane bending deformation of the tow, which makes it impossible to avoid fibre length difference within the tow in steering. Many research works have evaluated the effects of fibre-steering induced defects in the AFP processes and their negative influence on the structural performance of the manufactured composite parts [2,3].

To address the fundamental limitations of the AFP in fibre steering, a novel process called continuous tow shearing (CTS) was developed by Kim et al. in 2012 and has demonstrated its advantages in manufacturing fibre-steered flat-laminates [4,5]. Differently from AFP, CTS utilises in-plane shear deformation of the tow, fundamentally changing the way the tows are manipulated for steering. In theory, the CTS mechanism allows all the fibres within the tow to be realigned along the same reference steering path without causing length difference, which enables defect-free fibre steering even with an extremely small steering radius compared to the AFP (~50 mm). Furthermore, the CTS mechanism makes it possible to avoid gaps and overlaps between the steered tows realising a perfect tessellation of the tool surface. However, achieving in-plane shear deformation of the tow on a 3D surface requires more complex and sophisticated head movements, which is fundamentally different from that in the AFP process, as the orientation of the CTS head must change according to the curvatures of the tool surface and the tow paths while maintaining the fibre lengths the same across the tow width.

In this work, a new head control algorithm to realise the CTS process on complex 3D surfaces was developed. This new algorithm discretises the target 3D surface by creating a pin-jointed net (PJN) in a specific way. It allows for tessellating the surface with pin-jointed strips (PJSs) arranged along the reference path approximating the continuously sheared tows. Then the local CTS head orientations and coordinates are found from the tow width vectors along each PJS. To demonstrate the potential of this method, a fibre-steering test was carried out on a doubly-curved surface using the CTS prototype head mounted on an industrial robot and the quality and accuracy of the lay-up were assessed with a high-resolution laser scanner.

2 CONTINOUS TOW SHEARIGN (CTS) IN 3D

2.1 Geometrical consideration on 3D tow deformation

As is well known, in the conventional AFP the defects are mainly originated by in-plane bending deformation of the tow, which makes the fibres inside and outside of the tow path inevitably buckle and stretch, as shown in Fig. 1(A). In the case of CTS, in-plane shear deformation of the tow is used where the tow is sheared along a shifting direction or the initial tow width direction, as shown in Fig. 1(B), causing no fibre length difference across the tow width. When the CTS head steers a tow on a flat surface or in 2D following the reference path (RP), the head does not rotate but only translates in the shifting direction (i.e. the transverse direction of the unsheared tow). However, to realise the CTS mechanism on a non-flat surface, as shown in the Fig. 1(C), the tow needs to be twisted as well as sheared ensuring that the two tow edges (ideally all the fibres within the tow) have the same length. Therefore, the calculation of local tow width vectors should be fundamentally different from the AFP process, where those vectors are simply perpendicular to the tangent curve of the RP.

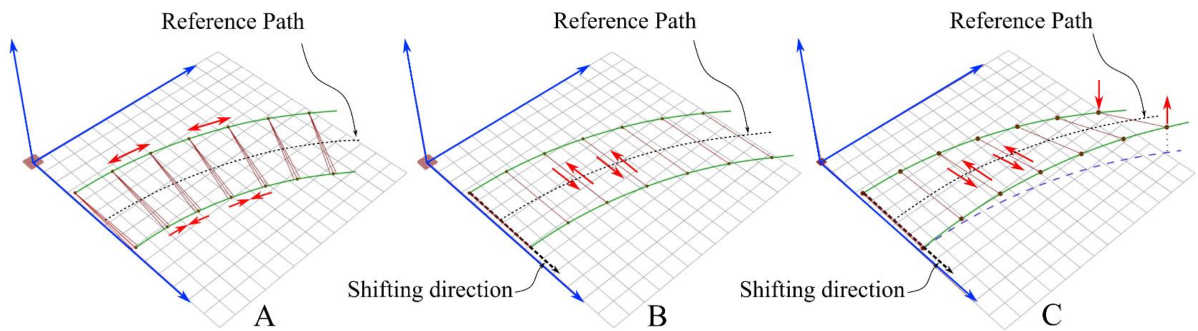

Figure 1: Tow deformations: A) AFP using in-plane tow bending deformation, B) 2D-CTS using only in-plane tow shearing, and C) 3D-CTS using both in-plane shearing and out-of-plane tow twisting.

Fig. 2 shows how the tow element edges of a PJS can be calculated on a doubly-curved surface. Considering an initial shifting direction curve at the start point O of a RP on a free-from surface $S(u,v)$, the tow can be modelled as a PJS formed by a chain of tow elements (i.e. four-bar linkages) consecutively connected. The distance between point P_i and Q_i is equal to the tow width, w, and the distance between P_i and P_{i+1} (or Q_i and Q_{i+1}) corresponds to d, which is the strip segmentation length as an input parameter. All the points P_i and Q_i lies in the surface domain $S(u,v)$, while the points Q_i generate the second edge of the PJS.

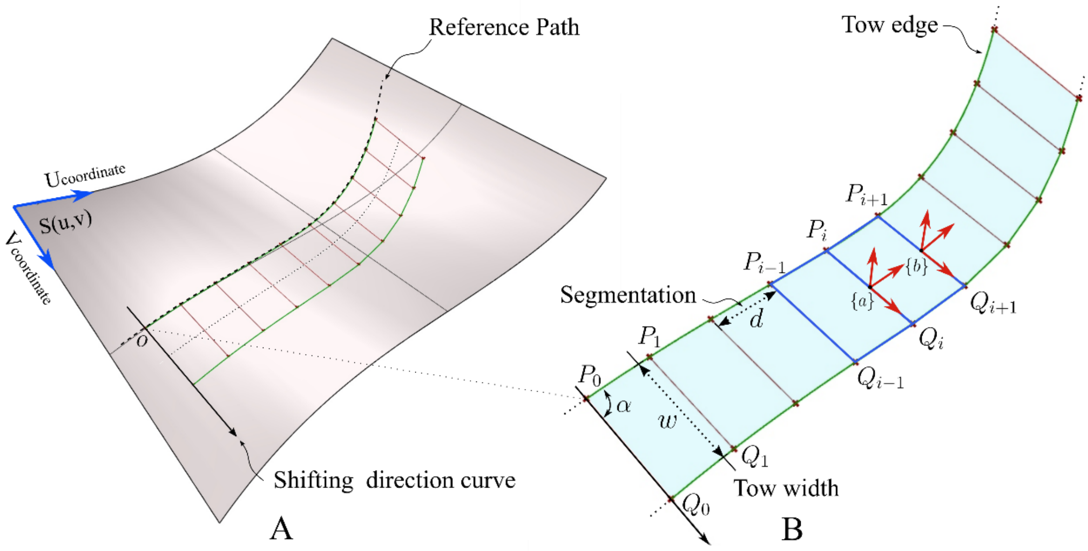

Figure 2: A) Tow shearing on a doubly-curved surface *S(u,v)*, B) a pin-joined strip, PJS, comprising sheared tow elements propagating along the reference path.

It should be noted that in the geometrical consideration made in Fig. 2, the RP coincides with one of the tow edges. However, the PJS could be created in such a way that the RP passes through the mid-points of the tow width elements, as shown in Fig. 1; this method could be more useful when tow paths need to be independently defined without considering gaps or overlaps in the overall lay-up.

2.2 Path planning and propagation

The path planning algorithm developed in this work starts from defining a RP and a shifting direction curve on an input 3D surface. As shown in Fig. 3, to define a reference fibre path, an in-plane RP is first defined on a plane, and then the curve is projected to the tool surface. For the shifting direction curve, a curve that crosses any point on the in-plane RP is defined on the same plane and projected onto the tool surface. Although there is no restriction on the shape of the shifting direction curve, the angle α between both curves at their intersection point, I_0, impacts the shear angle distribution as well as the arrangement of the individual tow edges (consequently all the fibres) when the strips are fully propagated on the tool surface. Furthermore, the distribution of the shear angle affected by α determines the thickness distribution, as the tow thickness is coupled with the tow shear angle [4]. α can be a design parameter that the user can set according to certain design requirements, e.g. to minimise the overall thickness variation of the layer, α could be chosen to minimise the maximum tow shear angle.

Given a RP and a shifting direction curve projected onto the tool surface, the intersection point between both curves set the start point denoted by P_0, for propagation of the tow elements creating PJSs on the surface *S(u,v)*. The RP and the shifting direction curve are segmented by the path segmentation length, *d*, and the tow width, *w*, respectively, as described in Section 2.1; the value of *d* can be adjusted to increase the accuracy of the surface approximation. As shown in Fig. 2, from the intersection point P_0, the next point P_1 on the RP and Q_0 on the shifting direction curve can be calculated. A geometric approach is used to find the last hinge point of the first tow element, Q_1, which is located on the tool surface at the distance of *w* from the P_1 and the distance of *d* from the Q_0. By repeating the calculation with P_i, a set of Q_i points can be calculated to create the next tow edge from the PR (i.e. in this case the RP represents one edge of the tow), while generating a PJS. By repeating the same calculation by taking the generated tow edge points Q_i as new inputs until the boundaries of the surface are fully covered, the surface can be fully tessellated with a series of PJSs creating a PJN. The propagation process is carried out along the -U and -V directions to fully discretise the four quadrants around the P_0 on the surface *S(u,v)*.

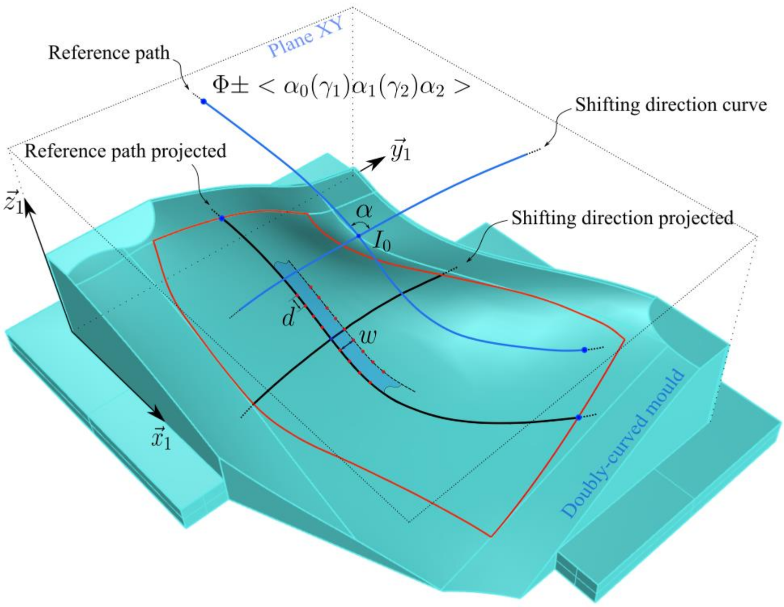

Figure 3: Reference path and shifting direction curve created on a plane and projected onto the doubly-curved surface *S(u,v)*.

2.3 CTS head orientation calculation

During the AFP process, at any point along the tow path, the head keeps the axis of the compaction roller perpendicular to the tangent line of the RP and rotates proportionally to the curvature change of the RP [6,7]. In contrast, during the CTS process, the CTS head should keep the width direction of the compaction shoe parallel to the local tow width direction (i.e. $\overrightarrow{P_i Q_i}$ or shifting vector in Fig. 2). The CTS head is shifted between each target nip point, while maintaining its vertical axis always normal to the surface. The nip point coordinates and head orientations are calculated by taking the mid-point between P_i and Q_i using the closest-to-surface point algorithm [8] as well as the tow width vectors.

3 3D CTS LAY-UP TEST AND INSPECTION

3.1 Target 3D surface

To evaluate the accuracy and quality of the new head control algorithm, a lay-up test was carried out on a doubly-curved mould using an industrial robot with 6 degrees of freedom (IRB 6640-180/2.55, ABB, DE), as shown in Fig. 4(A). The mould tool with a negative gaussian curvature (i.e. saddle-like shape) was manufactured by machining a 150 mm thick epoxy tooling board using a 3-axis CNC machining centre, as shown in Fig. 4 (B). The mould was clamped on a fix workbench close to the robot base and sealed with a flexible vacuum bag to improve the bonding of the tow during the deposition and avoid any damage of the mould for reuse.

A local reference frame was assigned at one corner of the mould and for improved positioning accuracy of the tool, a 3D touch-probe sensor was used for accurate coordinates transformation between the global reference frame located at the robot base {a} and the local reference frame {b} for the mould as shown in Fig. 4(A). Essentially, the frame {b} determines the position and orientation of the mould with respect to {a}. Additionally, a tool-frame named head frame {c} was set at the rear end of the compaction shoe of the CTS head (i.e. nip point), where the tow is deposited onto the surface. The robot was programmed to move the CTS head in such a way that {c} frame aligns with the tow width vector (or shifting direction vector) of the PJSs described above.

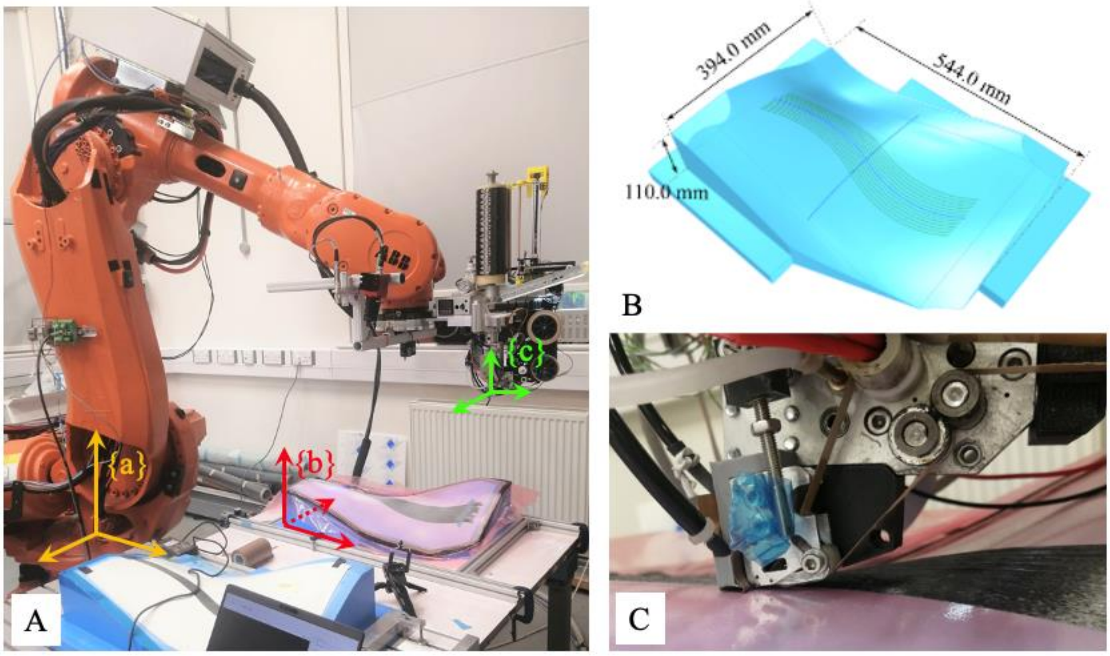

Figure 4: A) CTS head prototype mounted on the industrial robot arm and the mould tool on a table, B) dimensions of the mould tool with the tow edges, reference path, and shifting direction curve displayed on its surface, C) CTS tow deposition unit depositing the tow.

3.2 CTS head on a robotic platform

For the lay-up trial, the single-tow CTS head prototype built in the previous work [4] was improved and used on the robot. A 24K dry carbon tow (Tenax-E IMS65, Toho Tenax Co. Ltd., DE) and an epoxy resin film tape (MTM49-3, Solvay) were fed into the in-line impregnation device to produce an impregnated tow within the head on the fly [4]. Fig. 4(C) shows the tow deposition unit at the tip of the CTS head, and its working mechanism of the CTS prototype head is described in detail in [4,5].

To operate the mechanical parts in the CTS head, a programmable logic controller (PLC) was used and the communication between the robot controller and the head unit was established; the operations of the pneumatic actuators and motors attached to the head, which control the compaction force and tow feeding and tensioning, were through the PLC directed by the output from the robot controller.

3.3 Lay-up and quality inspection

As shown in Fig. 4(B), the RP had a total length of 393.3 mm and its steering radius along the curve after its projection onto the mould was within a range of 183 mm to 700 mm, whilst the minimum steering radius was reached at the crest of the projected RP. 12 tows were laid at the speed of 10 mm/s, and the tow impregnation temperature was about 80ºC. The nominal tow width was 6.5 mm, and the shifting distance along the shifting direction curve was 6.25 mm, which was slightly smaller to allow a small overlap eliminating gaps. The shifting direction curve before projection was chosen to be straight for simplicity, and the angle between the RP and it was 72º. The maximum local shear angle was 30º.

The lay-up accuracy and quality were evaluated using a bespoke 3D laser triangulation surface scanner (C5-2040-GigE 3D scanner, Automation Technology, DE) mounted on the robot close to the CTS head. The scanner was triggered using a digital signal from the robot to get a profile at intervals of 0.1 mm along the longest edge of the mould. To quantify and evaluate the defects, the thickness profile of the laid tows was obtained by consecutively scanning the same surface area before and after the lay-up. Both scans were overlapped in a point cloud analysis software (CloudCompare v2, GNU GPL) to calculate the offset distances of the points on the tow surface from the mould surface and obtain the thickness distribution.

4 RESULTS AND DISCUSSION

Fig. 5 shows the photo of the laid tows and its thickness distribution measured by the laser surface scanner. AFP processes typically produce significant wrinkling defects at a steering radius over 500 mm when using ¼ inch wide tows [9,10]. Although the minimum steering radius of the path trialled in the lay-up test was much smaller, 183 mm, the 3D CTS head control algorithm allowed for almost defect-free fibre steering. As shown in Fig. 5(C), there was no sign of wrinkling, and the thickness variation was minimal. Furthermore, the deviation of the edges of the laid tows from those of the propagated PJSs was about 0.2 mm, demonstrating high lay-up accuracy.

The method of discretising the tool surface using PJSs approximated the tows sheared on a 3D surface in a high degree of accuracy. Although there must have been a subtle difference in fibre lengths within the tow due to the surface curvature, its impact was minimal due to the narrow tow width and the short discretisation length (~1.5 mm).

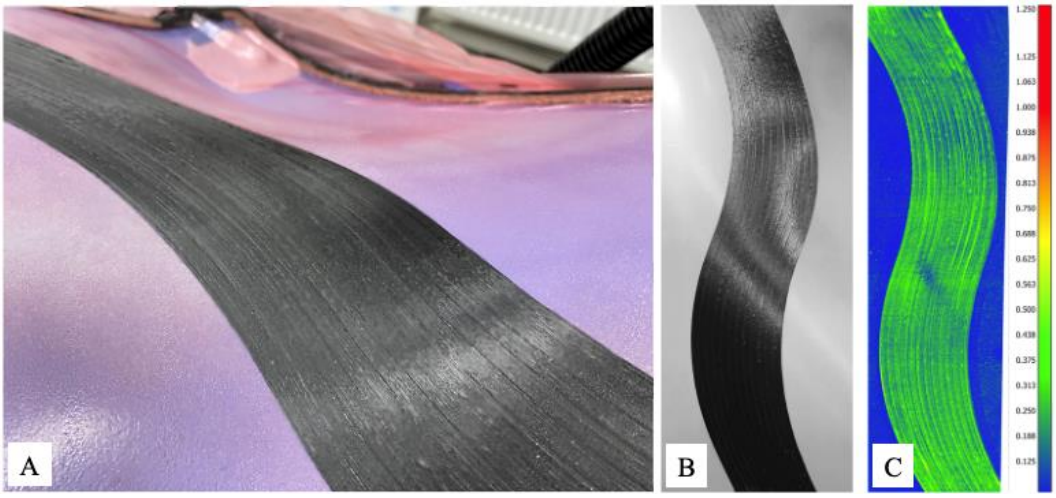

Figure 5. A) Photo of the laid tow surface, B) top view, C) thickness distribution calculated from the surface scan results.

5 CONCLUSIONS

In this work, the world's first defect-free automated tape placement on a doubly-curved surface was experimentally demonstrated. To enable the CTS process on complex three-dimensional surfaces, a new head control algorithm was developed, which allowed for using both in-plane shear and out-of-plane twist deformation of the tow to perfectly tessellate the tool surface using pin-jointed strips. Lay-up trials on a small-scale doubly curved surface demonstrated the feasibility of 3D CTS process. Despite high surface curvature and small steering radii of the lay-up paths, the tow shearing achieved in 3D caused almost no length fibre difference within the tow and eliminate any defects such as tow wrinkling and pull-up that are unavoidable in the current AFP fibre steering process. The result showed that 3D CTS has great potential to produce high-quality fibre-steered composite structures requiring minimum inspection effort. Furthermore, it could significantly simplify the design process by eliminating the necessity of considering the effects of defects.

ACKNOWLEDGEMENTS

This research was conducted with the support of the EPSRC (Engineering and Physical Sciences Research Council, UK.) under the project EP/R023247/1 ACTS3D Advanced continuous tow shearing in 3D. The authors would like to thank Bristol Composites Institute Laboratory (BCI Lab) for the facilities provided for carrying out the experimental work.

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