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# Steering of Carbon Fiber/Thermoplastic Pre-preg Tapes using Laser-Assisted Tape Placement

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**The weight saving benefits of fiber-reinforced composite materials in structural applications are well established. However, there is an increasing requirement to develop processing techniques that can produce highly repeatable and accurate components more efficiently than using autoclave processing; Laser-assisted Automated Tape Placement (LATP) in-situ consolidation of thermoplastic composites has significant potential to fulfil this requirement. In addition, LATP can process layers with Variable Angle Tow (VAT), an advanced tailoring option that allows modification of load paths within the laminate to result in more favorable stress distributions and improved laminate performance. Studies of VAT laminate manufacture using dry fiber placement and thermoset pre-preg tape placement have been previously reported. This work examines the ability to produce VAT laminates from carbon fiber/PEEK pre-preg tapes using LATP. A VAT laminate was successfully manufactured which had three steering radii of 800 mm, 600 mm and 400 mm with little defects. Characterization and mechanical testing were completed on steered samples to examine the effect of lay-down speed and radius on bond strength of steered tapes. Measurements showed that the width and thickness of the carbon fiber/PEEK tapes were changed during steering. Mechanical testing showed that bond strength was a function of lay-down speed, yet the effect of steering radius was inconclusive due to undesired failures.**

## I. Introduction

There is an increasing demand for advanced composite processing systems that can produce highly repeatable and accurate components more efficiently than conventional autoclave processing techniques. Recently it has been shown that laser-assisted automated tape placement (LATP) in-situ consolidation of fiber-reinforced thermoplastic composite material has the potential to produce high quality components without the requirement for a secondary consolidation processing step.[1] Large complex parts can be produced using this process without the need to use large, high cost autoclaves.[2]

In addition, LATP allows the control of the fiber orientation in a ply with high precision, enabling the manufacture of Variable Angle Tow (VAT) laminates.[3] VAT allows the alignment of fibers to the desired structural load path, providing improved performance without increasing weight. Tailoring the in-plane stiffness improves compressive buckling and first-ply failure.[4] Also, stress concentrations around cutouts on composite plates, for example fuselage windows, can be relieved by fiber steering.[5]

VAT laminates are prone to a number of common defects which include gaps, overlaps, tow buckling, tow pull-up and tow misalignment.[6, 7] These defects are caused by the matrix of the pre-preg tape confining the fibers and preventing them from freely conforming to the change in lay down length as the tape is steered. Lozano *et. al* (Ref. 6) state that gaps and overlaps, caused when a tape is not laid parallel to an adjacent one, creates resin rich (thermosets) or resin poor (thermoplastic) areas that are susceptible to stress concentrations and damage, reducing laminate strength. Also, overlaps create relatively large voids and act as initiation sites for delamination. Tow buckling occurs on the inside radius of a tow if compressive forces are too high, conversely tow pull-up occurs on

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the outside of a tow due to excessive tensile forces.[6] Tow buckling and pull-up result in poor bonding between the steered layer and substrate, as well as local thickness variation. Techniques have been implemented to reduce the effect of gaps and overlaps, including tow drop which prevents overlap regions[8]; tows can be cut individually by the tape laying machine to reduce thickness build-up, resulting in panels that contain small wedge-like areas free of fibers due to dropping of the individual tows. Continuous Tow Shearing (CTS) is a fiber placement technique using the shear deformation characteristic of dry tow to reduce defects such as fiber wrinkling, gaps, overlaps, resin rich areas, and fiber discontinuity.[9] However, CTS induces thickness variations.

There are currently two known Automated Fiber Placement (AFP) manufacturing methods that have the capability to produce VAT laminates; thermoset pre-preg tape placement and dry fiber placement. Several studies have manufactured VAT laminates using thermoset tape placement. However, thermoset tapes are prone to processing defects due to the resin of the tape confining the movement of the fibers as it is steered. Hence, thermoset tapes are limited to a minimum turning radius, which is dependent on the width of the tape and material properties.[10] Research has shown that minimal curvature radius ranges from 635 mm to 2000 mm. In addition, thermoset tapes require a secondary processing, such as autoclaving, to ensure adequate consolidation after being laid, increasing processing time and cost. Dry fiber is easier to steer as there is no matrix confining the fibers, allowing the tow to bend or shear.[11] This reduces defects such as buckling and wrinkling, allowing a minimum curvature radius of 400 mm.[12] However, dry tows do not have tackiness, so a fixing method, such as tailored fiber placement is required to allow lay-up of the tows. This is an embroidery technique in which dry fibers are stitched onto a surface to keep them in place. In order to avoid using a fixing method partially impregnated fibers have been used, but this reverts to the previous issue of the matrix confining the fibers and limiting the minimum radius of curvature. Additional to this, dry fiber placement requires post resin infusion, which reduces the efficiency of the process.[13]

To date there is limited research completed on VAT laminates manufactured using in-situ consolidated thermoplastic pre-preg tapes. The capability of being able to steer with thermoplastic tapes is beneficial as they have many advantages over thermosets. These include recyclability, rework ability, higher temperature performance, high impact resistance and frozen storage is not required. Fraunhofer IPT developed a process to manufacture VAT laminates,[14] which enables the placement of curved paths without warpage and distortion of the tape. However, this method relies on a pre-conditioning of tapes and therefore cannot in-situ manufacture VAT laminates. Another study showed a successful result of a tow steered panel completed with in situ consolidation of carbon fiber/thermoplastic tows. A minimum radius of 1270 mm was achieved by laying twelve 6.35 mm tapes at one time with a hot gas torch ATP machine.[15]

This work investigates the ability to produce VAT laminates with Carbon Fiber/Poly Ether Ether Ketone (CF/PEEK) pre-preg tapes using LATP in-situ consolidation. In Section II, initial trials which were completed to steer thermoplastic tapes by hand, to examine the proof of concept, are detailed. In section III programming steps for the LATP Kuka robot are outlined. The effect of the steering radius on defect propagation is examined. Basic characterization is also carried out to study the change in geometry of the tape as it is steered and the bond strength, section IV describes the materials and the manufacturing method used to produce characterization samples. Finally, Section V describes the characterization tests, while in section VI the results are presented and discussed.

## II. Proof of Concept

Initial tests were carried out to investigate the possibility of steering thermoplastic tapes. This consisted of laying a single steered CF/PEEK tape onto a 0° uni-directional laminate. The thermoplastic tape was heated above its melt temperature (343 °C) using a heat gun. As the tape began to melt it was steered by hand, then consolidated onto the substrate using a steel roller, the test set up is shown in Fig. 1. Three different tape widths were tested; 3 mm, 6 mm and 12 mm. The 12 mm wide tapes were most susceptible to fiber wrinkling and fiber pull-up during steering which resulted in a weak bond between the steered tape and the substrate.

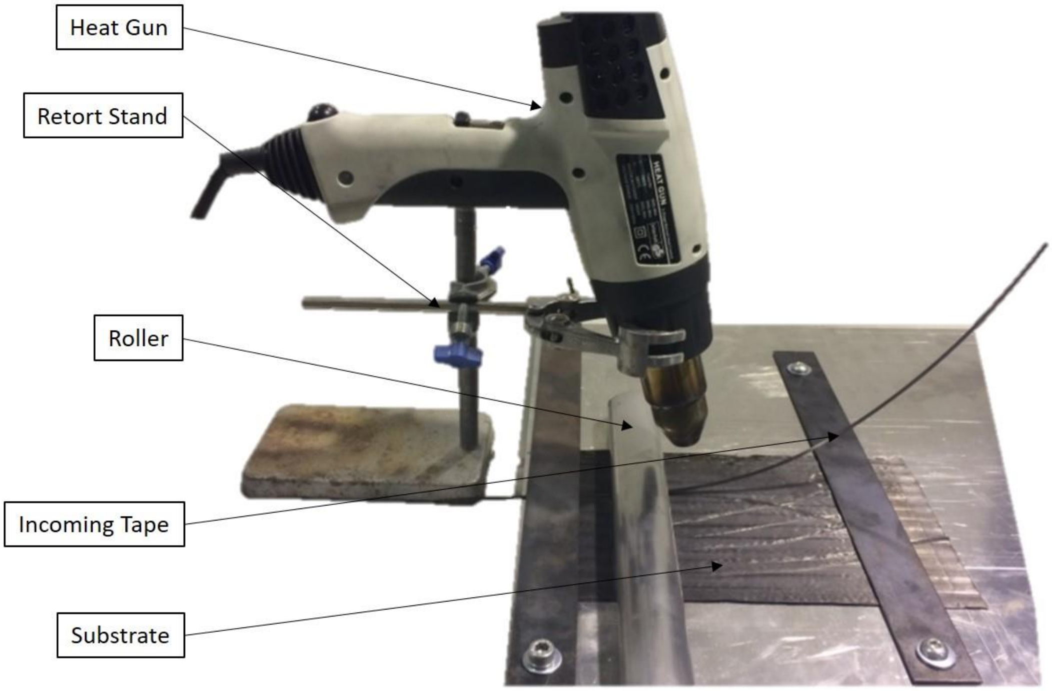

**Fig. 1 Experimental set up for manual steering of thermoplastic tapes.**

The 3 mm and 6 mm tapes also showed some fiber wrinkling and fiber pull-up, this can be seen in Fig. 2a, however this may be due to inconsistent roller pressure and heating during hand lay-up. It was noted that pull-up was avoided if pressure was kept constant after the tape was heated, while pull-up resulted if it was removed immediately after heating the tape. To investigate this possibility, after individual steered tows were laid down onto the uni-directional substrate they were then processed by the LATP machine. The head of the machine would pass over the steered tapes with the laser on and the roller applying pressure to the steered tows, but not laying tape. In this process the LATP machine applies a constant source of heat (approx. 375 °C, which is above melting temperature of PEEK) and pressure onto the steered tapes, which resulted in improved consolidation of the steered tapes with little fiber wrinkling and lower amounts of fiber pull-up, as shown in Fig. 2b. From completing these trials, it was evident that it was possible to complete in situ consolidation of thermoplastic tapes while steering. A further step was taken to steer thermoplastic tapes using the LATP machine to process the tapes.

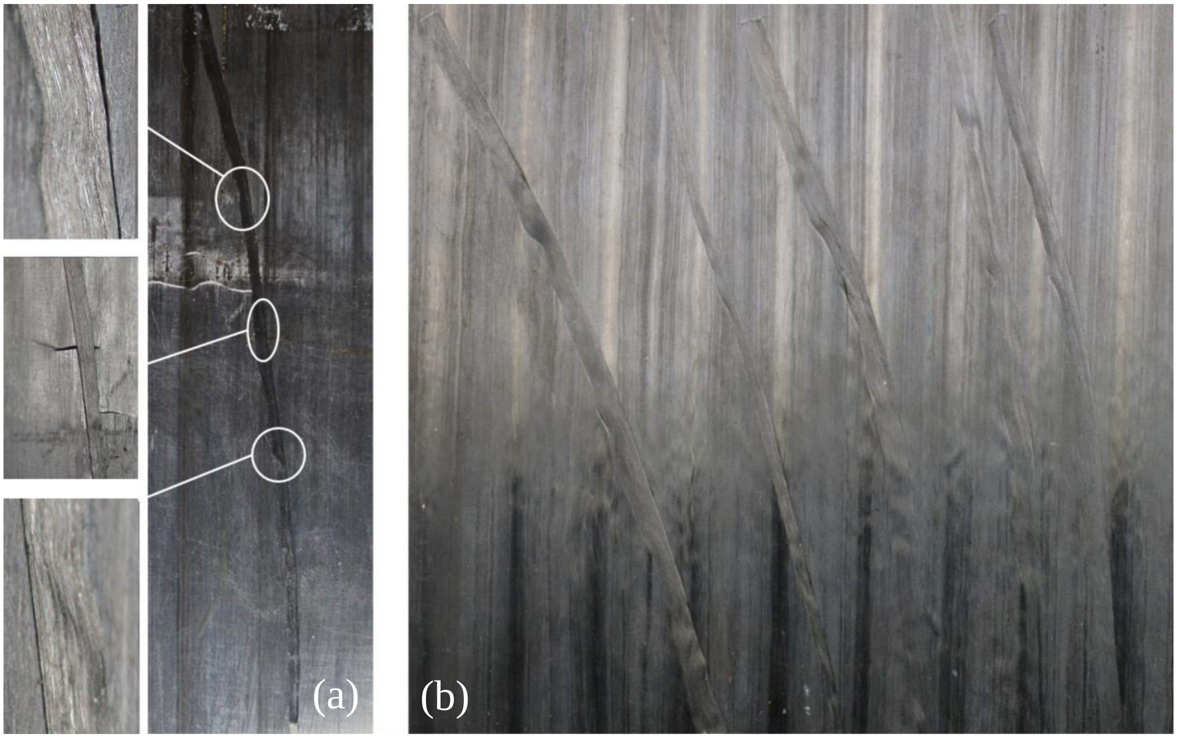

Fig. 2 a) Steered fibers showing fiber wrinkling, pull-up & buckling, b) Steered fibers after being processed by the LATP machine.

## III. Steering using ATP machine

Steering trials were completed using the LATP system at the University of Limerick consisting of the LATP head (AFPT, GmbH) attached to a robot arm (Kuka, KR240 L210-2) as shown in Fig. 3a. The tape head consists of an optic lens connected via a fiber optic cable to a remotely located 3 kW diode-laser heat source, a tape feed, guidance, tensioning and cutting system, a consolidation roller and a thermal camera. The setup and process is shown in Fig. 3b. The lens causes the laser beam to diverge providing a range of spot sizes at the nip point depending on the focal length of the optical lens. Current optics installed allow the tape placement head to process tapes between 6 mm and 25 mm. Hence, for this investigation steered tapes are limited to 6 mm tape.

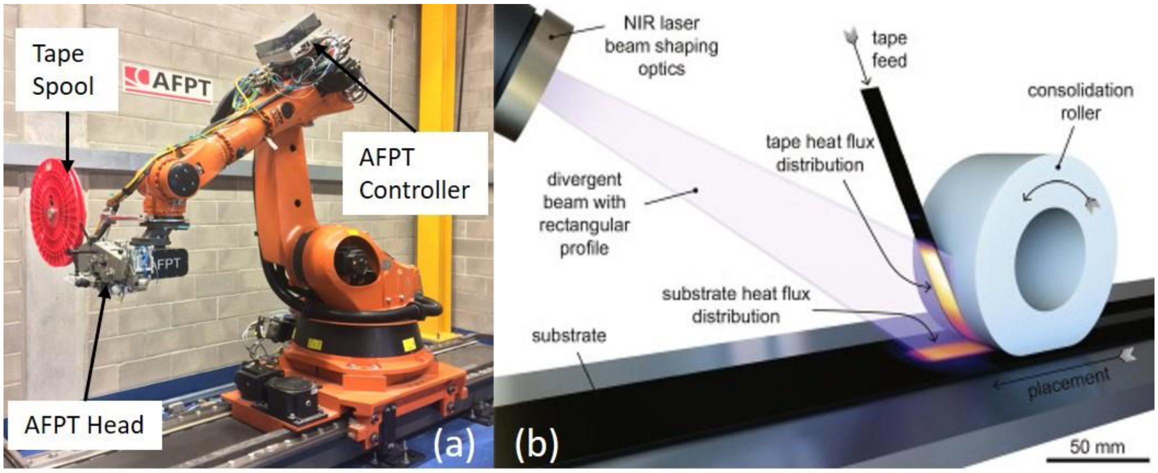

Fig. 3 a), LATP head & Kuka Robot b), LATP process showing laser, tape feed, substrate & roller.[16]

Prior to steering, the Kuka robot and LATP code had to be programmed to move the tape placement head in a curved motion. All the robotic arm movements, as well as all the operations completed by the LATP head are processed by two controllers. Both the controllers throughout the KUKA System Software (KSS), execute the commands defined in the scripts files written in the proprietary Knowledge Representative Language (KRL). Using this programming language, the user can program the desired successions of operation and movements that the robot must execute during the manufacturing process. To program a steered pattern, a circular motion is used. For this, three points are required; the start point, end point and a point in between, then to finish the endpoint of the tape.

Initial tests of steering with the LATP machine consisted of placing a PEEK substrate on a tooling surface. On top of this steered layers are laid down. For this study carbon fiber (Hexcel IM7) /PEEK (Victrex 150 UF10) pre-preg material supplied by Suprem (Switzerland) was used. To investigate the limitations of steering with thermoplastic tapes, a number of different steering radii were used; 2000 mm to 200 mm. At each of these radii three steered tapes were processed to assess repeatability. Tapes were processed at a linear rate of 3 m/min. The test piece can be seen in Fig. 4. From initial observation, the steered layer bonds well to the substrate. Visually, the steered fibers showed no wrinkling, buckling or pull-up at steering radii of 2000 mm to 800 mm. At 600 mm there are visual signs of wrinkling and pull-up, while at 400 mm there is an increased amount of fiber wrinkling, fiber pull-up and the introduction of the fibers folding under each other. Finally, at a steering radius of 200 mm, the defects became more significant, fiber buckling and wrinkling became more pronounced, also it saw an increased amount of fiber folding. Fiber folding is when the tape folds over itself due to high stresses in the tape when steering at small radii, as can be seen in Fig. 4.

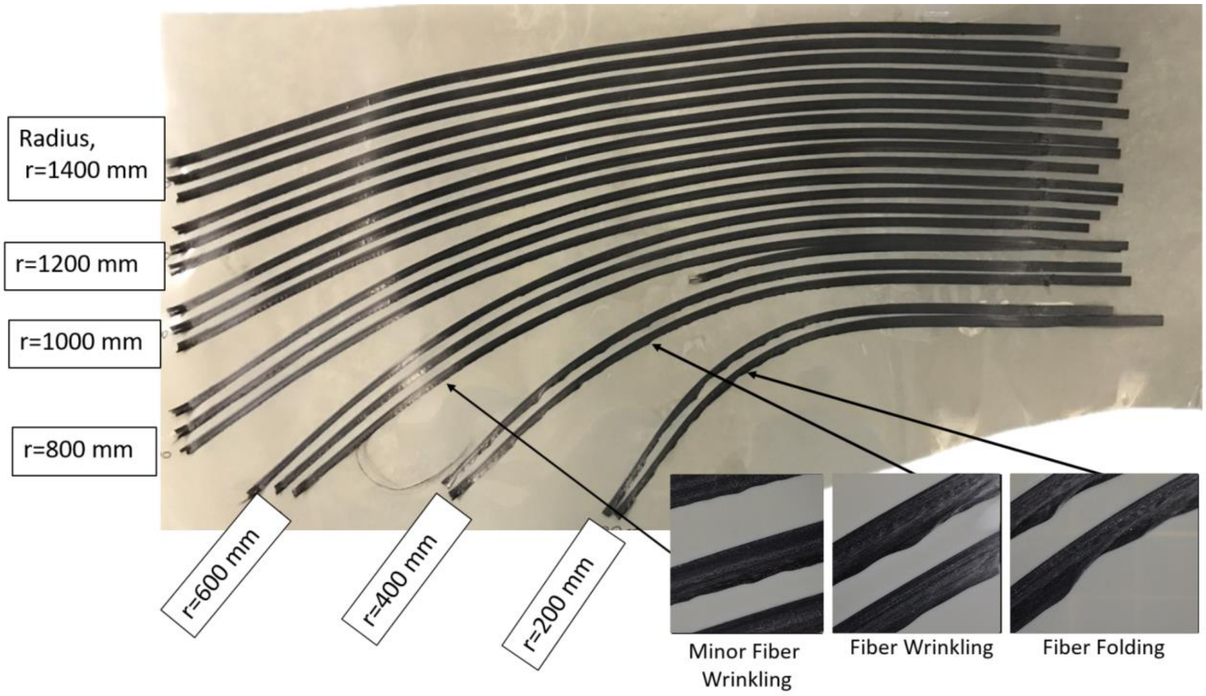

**Fig. 4 Initial trials of Steering on to a PEEK substrate,with fiber wrinkling and folding highlighted.**

Further steering trials were carried out to manufacture a composite laminate with steered layers; three different laminates were manufactured using three different radii: 800 mm, 600 mm and 400 mm. First a 0° layer was laid down to act as a substrate, then a layer which started at 55° steered along a 400 mm radius to 37° and back to 55°. For the 600 mm and 800 mm radii, the angles consisted of 55°, 43°, 55° and 55°,45°, 55° respectively, as shown in Fig. 5. The linear lay down rate was 3 m/min; 6 m/min was initially attempted, but at this rate the laser power does not stabilize sufficiently quickly over a relatively short lay down path and poor bonding between the incoming tape and substrate was observed. It was noted that defects such as fiber wrinkling, fiber pull-up and fiber folding were not as pronounced for the 400 mm steering radius onto the laminate, as they were when laid onto the PEEK layer. The CF/PEEK substrate is significantly stiffer than the PEEK substrate preventing the tape from folding under itself.

Also, the tape was steered over a shorter length than on the PEEK substrate meaning defects were prevented as the stresses at the edges were not able to build up over a short distance.

The gaps between adjacent tapes began to increase with decreasing steering radius, agreeing with previous VAT studies. [10, 12] The gaps between the adjacent layers in the 400 mm radius section is much larger than those in the 800 mm radius section, as shown in Fig. 5. For the 400 mm radius section gaps accounted for 16.8 % of the area, while the 600 mm and 800 mm radii sections were 12.7 % and 10.2 % respectively. Varying the steering radius of adjacent tapes as they are laid to achieve a better fit can eliminate gaps or overlaps, as shown in Fig. 6. However, in this case the fibre angle is no longer constant in y-direction.

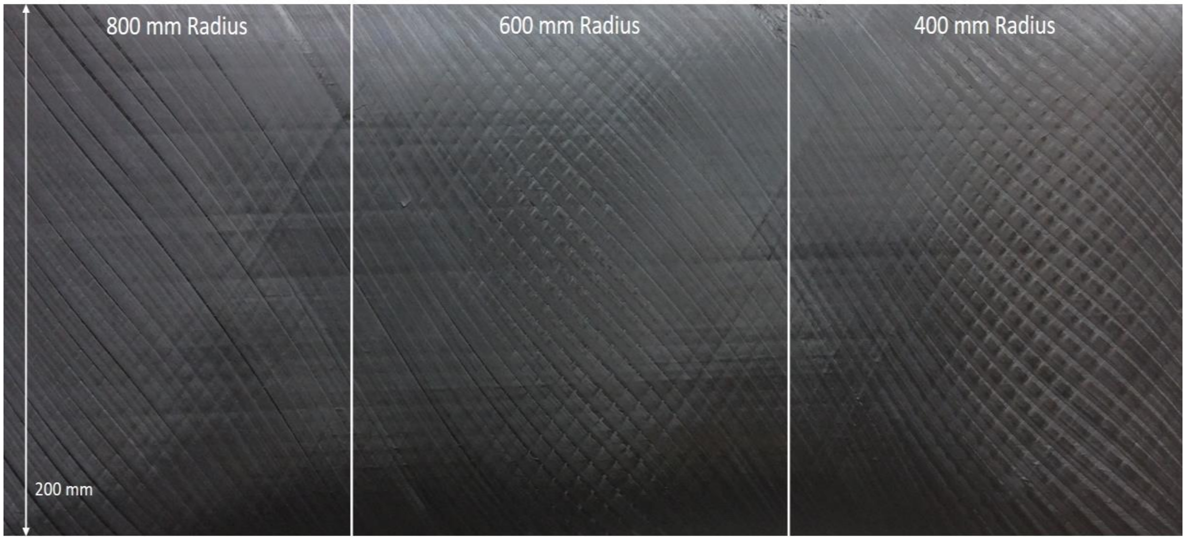

**Fig. 5  Steered laminate manufactured using LATP with 3 different radii – 800 mm, 600 mm, 400 mm.**

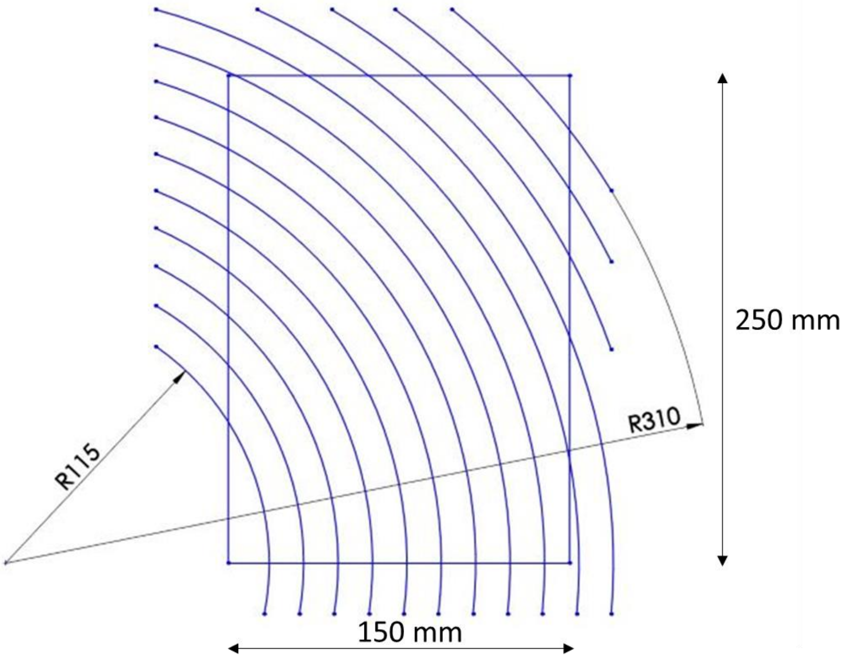

**Fig. 6  Varying steering radius to eliminate gaps and overlaps.**

## IV. Materials and Manufacturing of Test Samples

Initial trials show it is possible to manufacture laminates with steered thermoplastic tapes, however it does not show the effect steering has on the geometry and the mechancial performance of thermoplastic tapes. To investigate this, test samples were manufactured. The geometrical changes and bond strength were examined. Two different parameters were examined while steering thermoplastic tapes. First, the lay down speed; steered samples were manufactured with a radius of 400 mm with varying laydown speed of 1.5 m/min, 3 m/min, 6 m/min and 10 m/min. Second, the steering radius; using a different CF/PEEK pre-preg tape, samples were manufactured with a constant lay down speed of 3 m/min and varying radii of 200 mm, 600 mm and 800 mm.

### A. Materials

Two different types of carbon fiber/thermoplastic pre-preg tapes were used to manufacture the test samples. Suprem tapes (carbon-fiber (Hexcel IM7)/PEEK (Victrex 150 UF10)) were used to manufacture tests at 400 mm radius and varying lay down speed. Suprem is an ATP grade tape which is 12 mm (+ 0.0, - 0.1) wide, composed of 4 x 12 k tows. Initial proof of concept trials showed that it is difficult to steer 12 mm wide tapes, however Suprem tapes are possible to split along the 12 k tow lines. For this study 12 mm tapes were split into 6 mm tapes. Suprem tapes have a nominal thickness of 0.144 mm before processing.

Toho Tenax tapes (carbon fibre (Tenax -E IMS65 24K)/PEEK) were used to manufacture test samples at varying steering radii and lay down speed of 3 m/min. Toho Tenax tapes used had a nominal width of 6.35 mm and thickness of 0.1875 mm before processing.

### B. Manufacturing

Test samples were manufactured using the LATP system described in section III. Two laminates were manufactured, the first with constant radius of 400 mm and different lay down speed, the second laminates with constant laydown speed of 3 m/min and varying radii. Both laminates were manufactured on a cold flat tool with the following layers; a layer of PEEK under vacuum, a 0° layer of straight fibres, followed by steered layers spaced out at intervals. Images of both laminates are shown in Fig. 7 & Fig. 8. The layer of PEEK acts as an initial substrate that keeps the 0° layer in place, as this is difficult to achieve directly onto a cold tool. The initial section of the steered tapes are straight, to ensure a good bond with the 0° sub rate before steering the tape.

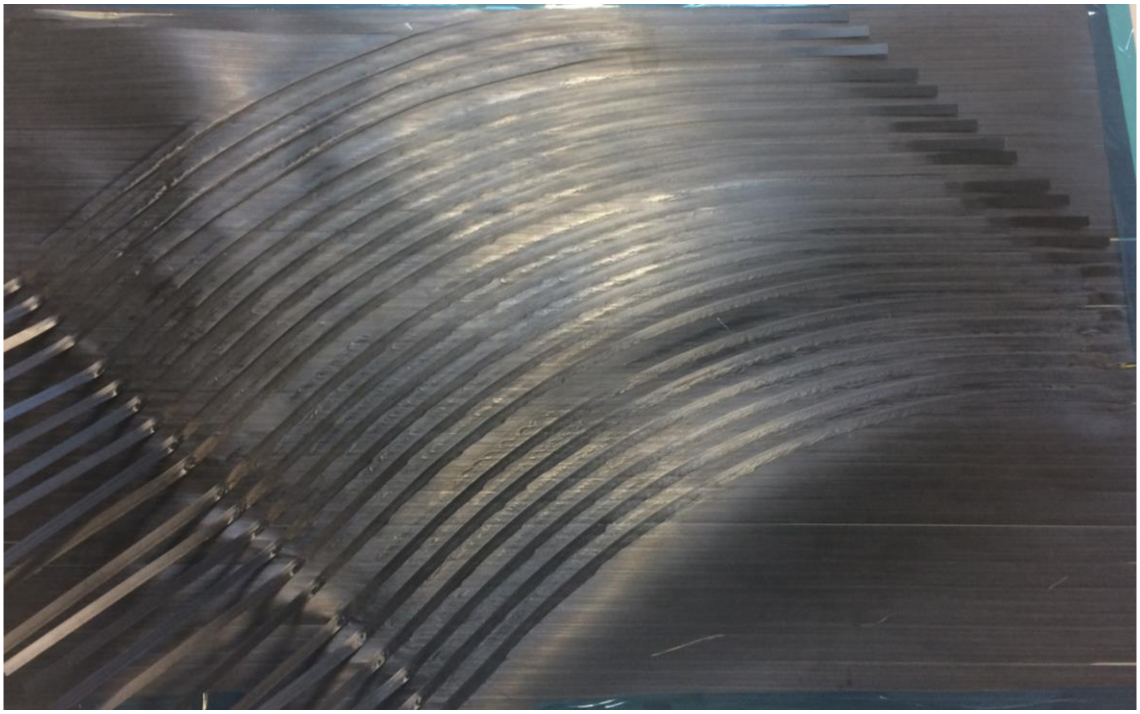

**Fig. 7 Suprem Carbon Fibre/Thermoplastic laminate with steered fibres at 400 mm radius and laydown speed of 1.5 m/min, 3.0 m/min, 6.0 m/min, 10.0 m/min.**

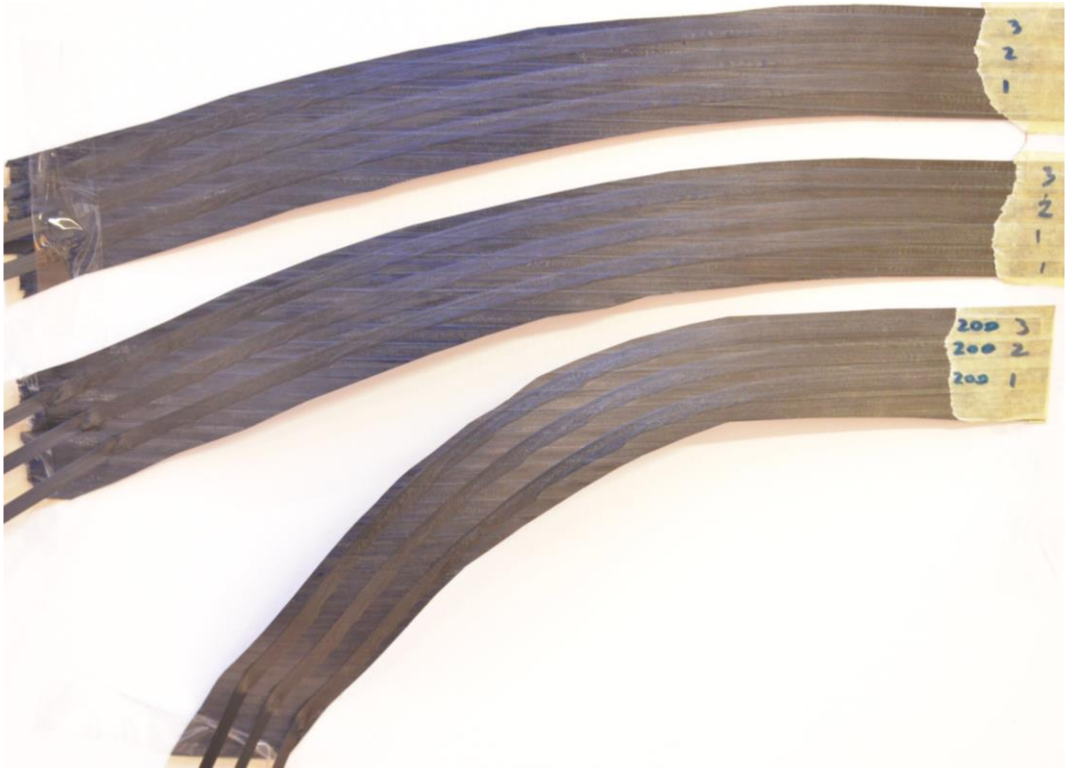

**Fig. 8 Toho Tenax Carbon Fibre/Thermoplastic laminate at radii of 200 mm, 600 mm and 800 mm with a laydown speed of 3 m/min.**

## V. Characterization Tests

To investigate if steering of thermoplastic tape is beneficial in composite structures, it is important to analyze if the mechanical properties are affected detrimentally. Three methods of analysis have been selected to evaluate the effect of steering CF/PEEK; geometrical analysis, optical microscopy and mechanical testing.

### A. Geometrical Analysis

Geometrical analysis examines the changes in the tape after steering, this is done by measuring the thickness and width of the tapes of straight sections and comparing them to steered sections. A Mitutoyo Series 500 Vernier calipers with a resolution of 0.01 mm was used to measure the width of the tapes. A Mitutoyo Series 293 Micrometer with a resolution of 0.001 mm was used to measure the thickness of the tapes. The initial material of each sample is straight for 100 mm then it is steered. Therefore, a number of measurements were taking for the straight section and then these were compared to the steered section. For the straight section 10 measurements for width and thickness were taken, for the steered section 40 measurements for width and thickness were taken. It is important to note that the thickness measurement includes the thickness of a steered layer plus 0° layer and layer of PEEK.

### B. Optical Microscopy

Samples were extracted from the steered layers and were mounted, ground and polished. Microscopy, along with image capture was completed to examine the effect of steering on the bond between the substrate and the steered layer. Three samples were taken for the steered layers at different speeds and two were taken for the steered layers at different radii. These were then compared to straight samples to visually examine the effect of steering on CF/PEEK pre-preg tapes.

### C. Mechanical Testing

To examine the bond strength between the steered layer and substrate a wedge peel test was completed. The wedge peel test is a simplified version of a double cantilever beam which is a standard test method for fracture toughness. Wedge Peel tests have been previously used to measure the bond strength of straight CF/PEEK samples processed using LATP. [2, 17] The difficulty in completing a bond test on steered tapes is that the delamination line must remain perpendicular to the fiber for the test, in doing so ensuring an accurate measure of bond strength and providing samples at different radii that are comparable. To keep the delamination line perpendicular to the fiber direction, a test rig was manufactured which is shown in Fig. 9. The sample is adhered to a semi-circular plate that has the same radius as the steered layer. The semi-circular plate is then connected to a pivot point, a steel cable is attached to a point on the curve and is guided along the semi-circular plate with pins. The cable is pulled by the crosshead of a tensile tester, the load required to pull the steered tape through a wedge is measured. For samples with different radii, a circular plate with the corresponding radius was used. The wedge that creates the delamination is 1 mm thick. The test was completed at a rate of 20 mm/min.

**Fig. 9  Wedge Peel Test.**

## VI. Results and Discussions

### A. Geometrical Analysis

Table 1 and Table 2 summarize the results obtained from the geometrical analysis completed on both laminates. Table 1 shows the change in width and thickness of the Suprem tapes due steering at different lay-down speeds with constant radius. Table 2 shows the change in width and thickness of the Toho Tenax tapes due to steering at a constant speed with different radii.

**Table 1 Dimensional changes in Suprem tape while steered at 400 mm radius and various lay-down speeds.**

| Measurement | Lay-down speed (m/min) | Straight (St. Dev.) [mm] | Steered (St. Dev.) [mm] | Difference (St. Dev.) [mm] |
|---|---|---|---|---|
| Thickness | 1.5 | 0.432 (0.0034) | 0.503 (0.0150) | + 0.071 (0.013) |
| | 3.0 | 0.431 (0.0019) | 0.473 (0.0084) | + 0.042 (0.012) |
| | 6.0 | 0.431 (0.0081) | 0.506 (0.0160) | + 0.074 (0.019) |
| | 10.0 | 0.431 (0.0262) | 0.802 (0.0587) | + 0.371 (0.075) |
| Width | 1.5 | 6.44 (0.37) | 5.94 (0.45) | - 0.503 (0.17) |
| | 3.0 | 6.39 (0.34) | 5.65 (0.26) | - 0.744 (0.16) |
| | 6.0 | 6.67 (0.27) | 5.85 (0.17) | - 0.821 (0.23) |
| | 10.0 | 6.47 (0.27) | 4.70 (0.32) | - 1.769 (0.34) |

Table 1 shows that lay down speed does affect the width and thickness while steering. It is important to highlight that normally pre-preg tapes would get wider and thinner when processed in a straight line. This can be seen in Table 1 as the width of processed Suprem straight tapes ranges from 6.39 – 6.67 mm, while unprocessed Suprem tapes are nominally 6 mm in width. However, when steered the tapes experience the opposite effect, they get thicker with a decrease in width. This happens due to shear of the soft matrix under bending and is somewhat analogous the CTS technique (Ref. 9) described earlier. At 10.0 m/min samples experience the biggest changes. The compaction roller would then pass over the tape while it is still above its glass transition temperature of PEEK and as a result does not achieve a good bond with the substrate. This in turn leads to a large pull-up force on the outer radius. The fiber pull-up largely affects the geometrical shape as the tape is much narrower and thicker[18].

An additional point to note is that the thickness of the Suprem tape at 1.5 m/min increase by 0.071 mm, while 3.0 m/min only experiences 0.042 mm. A possible explanation is, while steering at 1.5 m/min it was observed that the laser was degrading the roller; a white residue from the roller was deposited on the steered fibers. This degrading of the roller may have affected the compaction force that the roller applies, thereby reducing the consolidation of the steered tape at 1.5 m/min. Alternatively, another cause is at 1.5 m/min the heat from the laser is transferred over a longer length of the substrate and steered tape and after the roller passes over the tape, the tape has not cooled and is still able to expand.

**Table 2 Dimensional changes in Toho Tenax Tape while steered at various radii and lay-down speed of 3 m/min.**

| Measurement | Radii (mm) | Straight (St. Dev.) [mm] | Steered (St. Dev.) [mm] | Difference (St. Dev.) [mm] |
|---|---|---|---|---|
| Thickness | 200 | 0.539 (0.0129) | 0.631 (0.0085) | + 0.091 (0.0067) |
| | 600 | 0.514 (0.0051) | 0.564 (0.0123) | + 0.050 (0.0155) |
| | 800 | 0.531 (0.0120) | 0.560 (0.0048) | + 0.029 (0.0127) |
| Width | 200 | 7.36 (0.13) | 6.15 (0.09) | - 1.22 (0.20) |
| | 600 | 7.24 (0.20) | 6.45 (0.14) | - 0.79 (0.12) |
| | 800 | 7.07 (0.07) | 6.73 (0.02) | - 0.48 (0.07) |

Table 2 shows that steering at different radii influences both width and thickness. At 200 mm the largest change in dimension is observed; there is a 0.091 mm increase in thickness and a 1.22 mm decrease in width. As steering radius increases, the geometrical changes are less, as 800 mm only sees a 0.029 mm increase in thickness and 0.48 mm decrease in width. This is important to take into consideration when designing a laminate with steered fibers. One of current major issues with steering fibers is that there is an unavoidable issue with gaps and overlaps. If this issue was to be solved it would be important to take into consideration that the gap would increase as the steering radii decreases, as seen in Table 2 the width reduces with reduction in steering radii.

Figure 10 gives examples of how the width and thickness of CF/PEEK tapes can change due to fiber wrinkling and fiber pull up. Figure 10 (a) shows an extreme case of how fiber buckling on the inside edge of the steered tape can cause a decrease in width and an increase in thickness, as the steered fibers bunches up. Figure 10 (b) shows the side profile view of a sample steered at 10 m/min; it highlights how extreme fiber pull-up causes a large increase in thickness as the outside of the tape does not bond to the substrate and folds over on itself. Figure 10 (c) and Fig. 10 (d) show less severe fiber wrinkling, however they are still a cause for reduction in width and increase in thickness. Figure 10 (d) also highlights how width varies in a steered tape. During steering compressive stresses build up on the inner radius which facilitates a periodic folding (buckling) deformation on the inner radius. This behavior could be explained by a shear crimping type instability most commonly observed in shear-compliant sandwich columns under compression loading, yet here has been localized to the surface regions of highest compressive stress.[19]

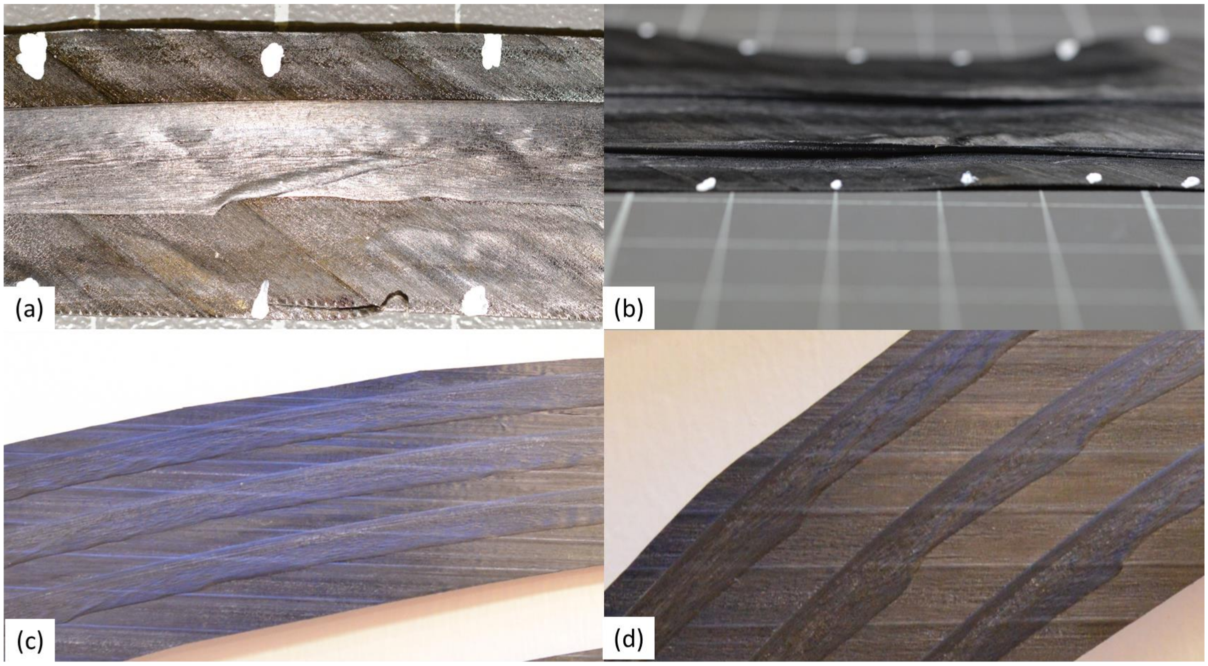

**Fig. 10 Examples of varying width and thickness while steering due to fiber wrinkling, fiber buckling and pull -up.**

### B. Optical Microscopy

In this section, images of the optical microscopy study are shown. The microscopy images show the cross section of the laminate perpendicular to the direction that the steered tape was laid down, focusing on the bond between the steered tape and the substrate. Images consist of a layer of PEEK with a 0° direction layer, then a steered layer. Images of straight tapes of both Toho Tenax and Suprem tapes are shown in Fig. 11 for comparison purposes. Figure 12 displays images of the bond between tapes steered at 400 mm radius but with varying lay down speed. Fig. 13 shows optical microscopy of tapes that were steered at different radii but constant speed. Finally, Fig. 14 shows a number of images of the outer and inner curves of the steered tapes.

Figure 11 highlights the difference between Toho Tenax tapes and Suprem tapes. Supreme, an ATP grade tape, shows higher fiber volume fraction. However, the bond between the top tape and substrate tape of Toho tape is difficult to discern in comparison to the Suprem tapes, indicating that there may be a better consolidation. A possible reason for this is that Supreme tapes are an ATP grade and have a resin rich layer at top and bottom surface to improve bonding when processed.

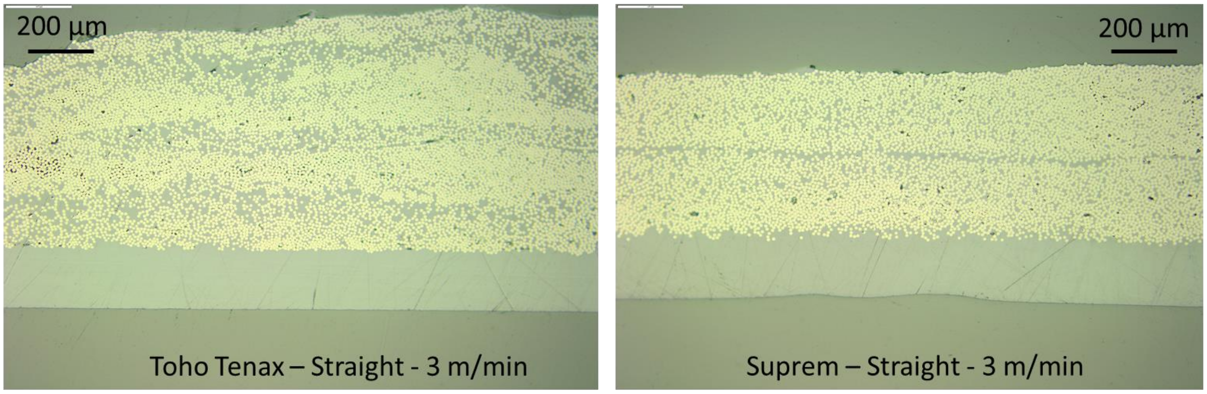

**Fig. 11  Optical microscopy images X20 comparing Straight Toho Tenax Tapes with Suprem Tapes.**

Figure 12 shows the optical microscopy images of the center of Suprem tapes processed at 400 mm radius and at different lay down speeds. On visual inspection there does not appear to be an obvious difference in the bond of tapes processed at different speeds. All the steered tapes appear to have a similar bond, at the center of the tape, with the substrate. However, as seen in Fig. 11 straight Suprem tapes show a visible bond line, as previously mentioned a possible reason is that Suprem tapes has a resin rich layer top and bottom to improve bonding.

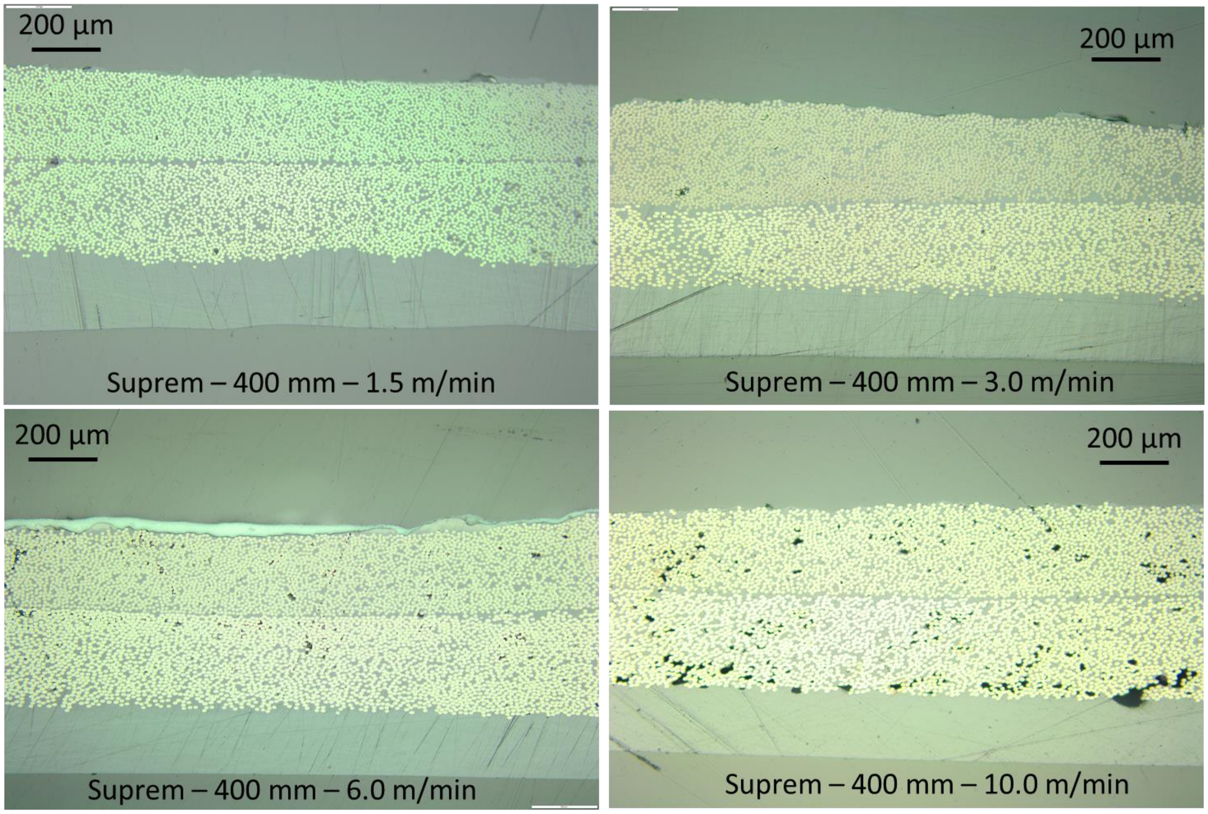

**Fig. 12  Optical microscopy X20 of bond between steered tapes at 400 mm radius with laydown speeds of 1.5 m/min, 3.0 m/min, 6.0 m/min and 10.0 m/min.**

Figure 13 shows the bond between the steered tapes and 0° substrate for radii of 200 mm, 600 mm and 800 mm, and these are compared to a straight tape. The straight tape acts as the benchmark, and from Fig. 11 the bond between the straight fiber and substrate is not well defined, this is an indication that there has been good consolidation between both layers. When the 200 mm radius steered tape is compared to the straight tape, the bond between the steered tape and substrate is visible, meaning that the consolidation between both layers may not be of the same quality. For the 600 mm steered tape the bond is similar to that of the 200 mm tape, meaning that there may being a reduction in the quality of consolidation. Finally, the 800 mm steered tapes show similar consolidation to that of the straight tapes, meaning that the consolidation does not appear to have experienced a reduction. However, this is inconclusive as only two samples for each radii were examined, the visible bond line in the 200 mm and 600 mm samples may be due to the lower geometrical tolerances (compared to Suprem) of the Toho Tenax tapes.

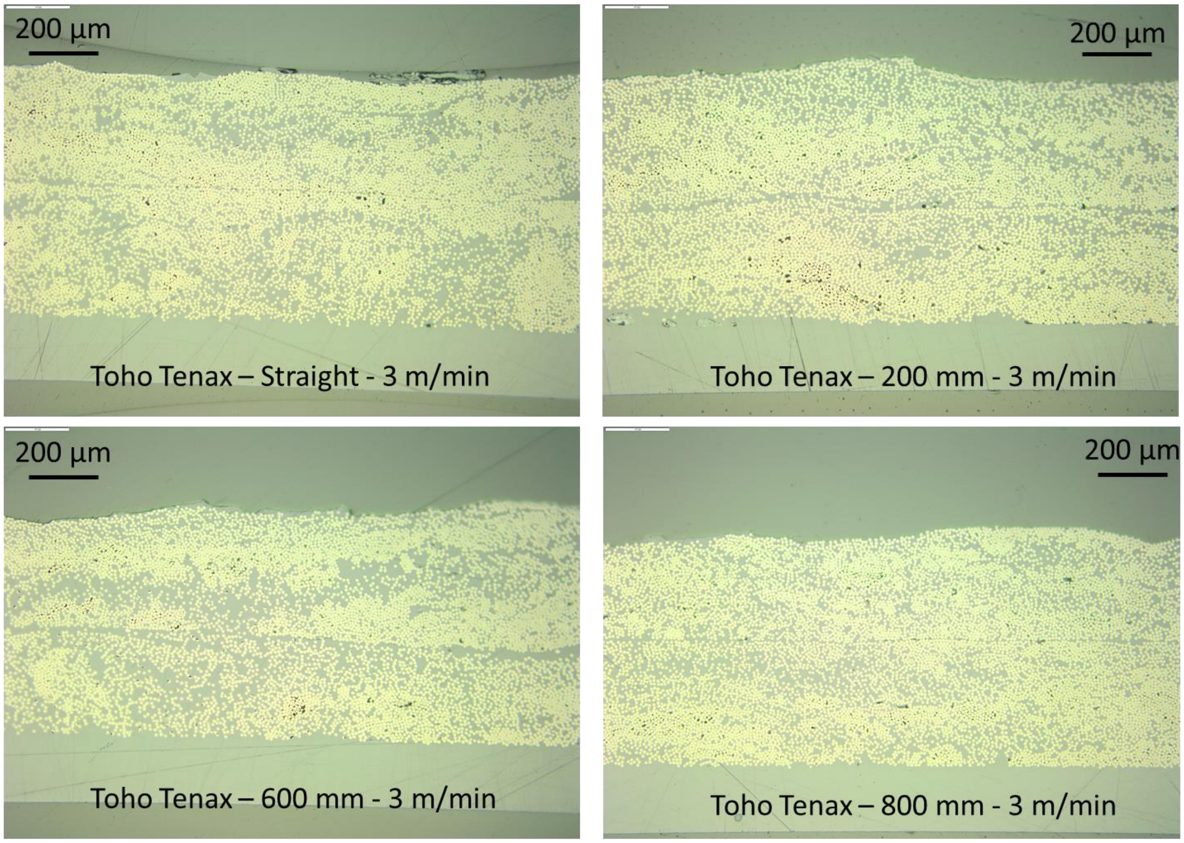

**Fig. 13 Optical microscopy X20 of bond between steered tapes at 200 mm, 600 mm, 800 mm radii with a laydown speed of 3.0 m/min.**

Figure 14 shows the effect that steering has on the edge of a tape. Examples of both good and bad bonds are shown. For both 1.5 and 3.0 m/min there are examples of good and bad bonds. The location where the sample was taken has a big influence: if this is taken at a wrinkle the bond is bad, else the bond is good. By viewing all microscopy images there is no obvious relationship between lay down speed and effect of bond at the edge. What is evident is that there is an effect on bonds at the edge of the tape due to steering because reducing the steering radii increases the severity of wrinkles and defects, which subsequently causes poor bonds. Reducing steering radii does appear to increase the frequency of defects, as the laminates at 200 mm, 600 mm and 800 mm have the same number of defects, however the size of defects is larger for the 200 mm. The Suprem tape at 10.0 m/min gives a good indication of how fiber pull up affects the steered tape.

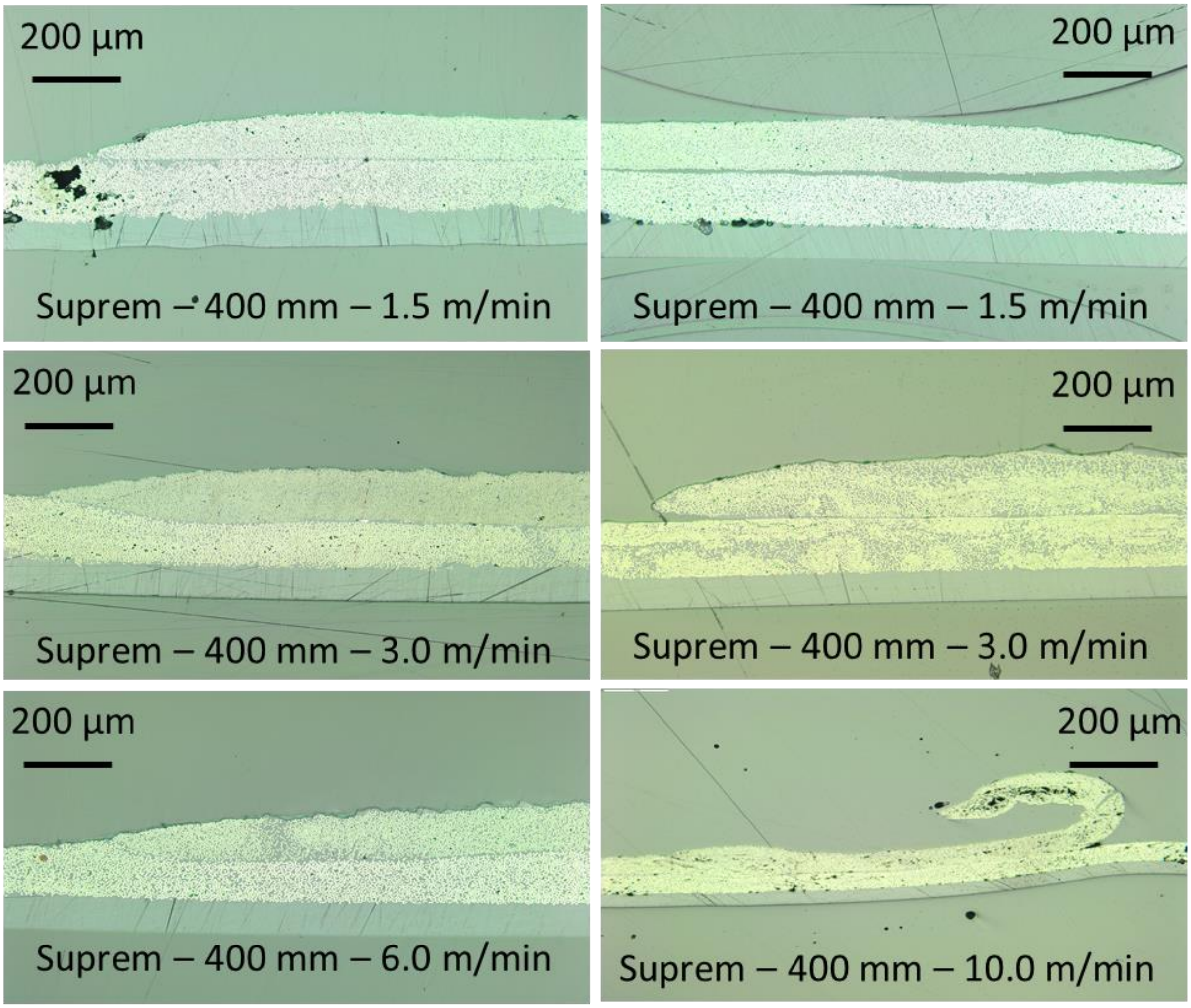

**Fig. 14 Optical microscopy of edges of steered tapes, examining good and bad bonds.**

### C. Mechanical Testing

The result of the Wedge peel tests for Suprem samples, manufactured at varying lay down speeds, are shown in Fig. 15 and Table 3. The results for Toho Tenax Tapes are shown in Table 4. During testing of wedge peel samples, a number of samples experienced undesired failures. These failures involved either slicing of tapes or partial tearing of tapes, where the size of the tear increased as the test progressed until the tape tore fully. However, slicing of tapes is an indication that the bond between the steered tape and substrate is strong as fibers are cut before the bond fails. A second indication that slicing is a sign of a good bond is that no tapes at 10 m/min experienced slicing and all samples had severe fiber pull up on the outer edge which would have reduced the bond strength.

Figure 15 shows wedge peel vs extension for samples successfully tested. The graph shows that samples did not experience stable delamination. During tests it was observed that at locations where fiber wrinkling occurred (Fig. 10 (a)) the load experiences a large increase, then decreases once it delaminates. In other cases, at locations where fiber wrinkling occurs, the tapes partially tear.

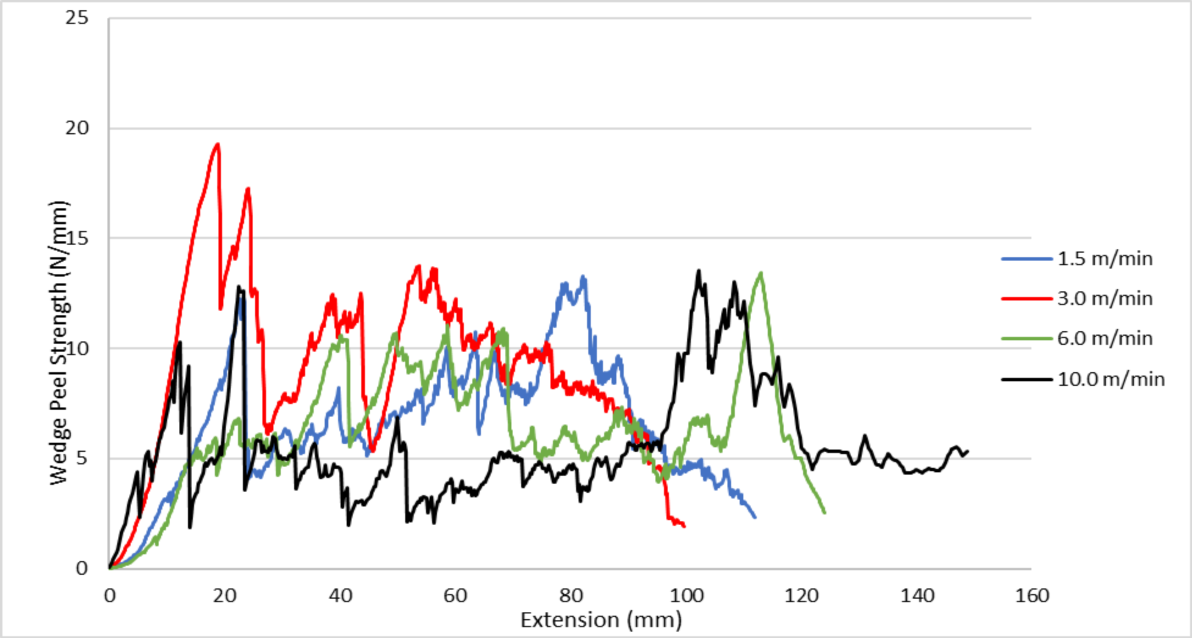

**Fig. 15 Wedge Peel Strength Vs Extension of Suprem Tapes with varying lay-down speed.**

Table 4 gives a summary of test results for Suprem Tapes. For each of the lay-down speeds five samples were tested, bar 10 m/min, four were tested. Before examining the values of wedge peel strength, it is important to highlight that a large number of samples experienced undesirable failure of slicing or tearing. Samples at 3.0 m/min and 6.0 m/min had the highest number of undesired failures which highlights there was good bond strength. This is further supported by the single successful wedge peel test at 3.0 and 6.0 m/min, as the values for wedge peel strength are the highest. At a lay-down speed of 1.5 m/min undesirable failure also occurred, but not at the same frequency as 3.0 & 6.0 mm/min, which indicates its bond may possibly be weaker. This is also endorsed by a lower wedge peel strength. This lower value further supports the point raised in the geometrical analysis, that the 1.5 m/min tapes have a larger thickness than 3.0 m/min tapes, meaning that its consolidation was less.

**Table 3 Wedge Peel Strength of Suprem Tapes.**

| Lay-down Speed | 1.5 m/min | 3.0 m/min | 6.0 m/min | 10.0 m/min |
|---|---|---|---|---|
| No. of samples successfully tested | 2 | 1 | 1 | 4 |
| Wedge Peel Strength (N/mm) | 6.4 | 9.3 | 7.1 | 5.4 |
| Standard Deviation | - | - | - | 0.87 |
| No. of samples sliced | 1 | 3 | 2 | - |
| No. of samples that tore | 2 | 1 | 2 | - |

Table 5 summarisies the results of wedge peel tests for Toho Tenax steered tapes. Toho Tenax tapes were more succesful, as there were less undesired failures. Three samples were tested for each radius, and only one sample for both 600 mm and 800 mm expereinced undesired failure. Wedge peel values for 200 mm were the highest, which was not expected as from visual inspection prior to the tests, the 200 mm samples had more severe defects (fiber wrinkling & fiber buckling) However, by examining the samples after they were tested, the 200 mm samples experienced interlaminar delamination while 600 mm and 800 experienced intralaminar delamination. This is shown in Fig. 17 (a) where a 200 mm sample is shown and there are no remains of the steered tape, Fig. 17 (b) shows that there are remains of a 800 mm steered tape on the substrate, meaning intralaminar failure occurred. In correlation with the optical microscopy images in Fig. 13, the images visually show an excellent bond between the two layers but show locally low fibre volume fraction in the tow, which would help initiate intralaminar delamination.

**Table 4 Wedge Peel Strength of Toho Tenax Tapes.**

| Radius | 200 mm | 600 mm | 800 mm |
|---|---|---|---|
| No. of samples successfully tested | 3 | 2 | 2 |
| Wedge Peel Strength (N/mm) | 5.3 | 5.0 | 5.44 |

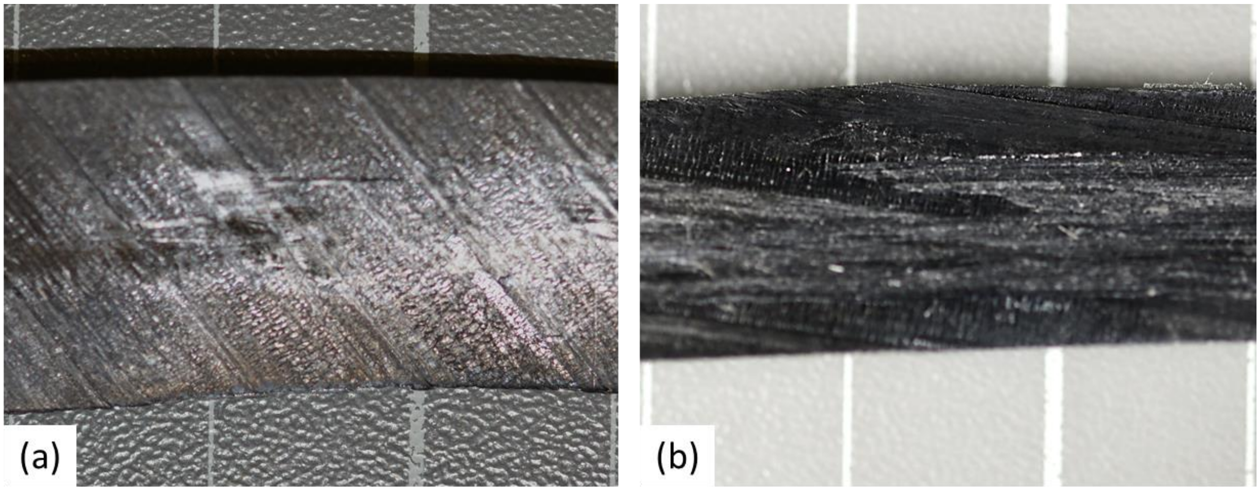

**Fig. 17 a), Interlaminar failure at 200 mm radius b), Intralaminar failure at 800 mm radius.**

## VII. Conclusion

From initial tests, it is possible to produce VAT components with thermoplastic material processed using LATP. VAT can produce higher performance laminates without increasing weight; producing VAT laminates from LATP in-situ consolidation of thermoplastics composites can potentially be more efficient than steering with thermoset tapes or dry fiber placement, which require a secondary processing step. Trials successfully showed that a steering radius of 400 mm is achievable with CF/PEEK, (which is equivalent to that done previously with thermosets), with few defects.

When the effect of steering on CF/PEEK tapes was examined it was found that the dimensions of tapes are affected by lay down speed and steering radius. A fast lay-down speed of 10.0 m/min leads to fiber pull-up due to poor consolidation, at a slow lay-down speed of 1.5 m/min, the tapes do not cool sufficiently and is allowed to expand once the roller has passed over the tape. Varying steering radius leads to a proportional change in tape dimensions. At a radius of 200 mm the largest decrease in width was found and the largest increase in thickness was also experienced, while the opposite effect occurred at a radius of 800 mm.

Optical microscopy showed that the biggest effects on the bonds due to steering was observed at the edges of steered tapes, this is where compression and tensile stresses are highest.

Wedge peel tests were inconclusive as many samples experienced undesirable failures such as slicing, tearing and intralaminar failure. Such defects are indications of good bond strength as the samples failed by other means before delamination occurred. Suprem tapes at 3.0 m/min & 6.0 m/min experienced the highest number of undesirable failures, and results from successful tests showed the highest values for wedge peel strength.

Future work will include double cantilever beam tests on steered samples to achieve more conclusive results for measurement of bond strength. Also, further investigation will be completed to improve understanding why fiber wrinkling, buckling and pull-up occur. The use of narrower tapes may also be investigated to examine if defects are reduced while steering.

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