TOW STEERING OF STRETCHABLE TUFF THERMOPLASTIC TAPE WITH LASER TAPE PLACEMENT

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ABSTRACT

Steering of fiber tows using the Automated Fiber Placement process has been shown to increase the versatility of composites design for highly tailored Variable Angle Tow (VAT) laminate structures. Manufacturability is limited to the minimum steering radius which can be placed without defects. A recently developed, highly aligned, short fiber material called Tailored universal Feedstock for Forming (TuFF) allows forming of complex geometries due to its 40 % elongation capability. This paper investigates the steerability of TuFF material made out of 3 mm-long carbon fiber and Polyetherketoneketone (PEKK). An industrial advanced fiber placement system (AFP) by Mikrosam is used to steer a 6.35 mm (0.25 in) tape at different radii in the range of 25 mm to 200 mm. An offset strain is applied to counteract the buckling of the fibers using a differential speed of the feeding and compaction roller. The steering experiments showed that TuFF can be stretch steered to a minimal steering radius (MSR) of 50 mm which is over an order of magnitude smaller than the MSR of conventional continuous fiber tapes.

Keywords: TuFF, short fiber, tape steering, automated fiber placement, thermoplastic

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1. INTRODUCTION

Carbon fiber composites are often used in high performance applications. Traditionally, the laminate stacking sequence is optimized to meet stiffness and strength requirements where the fiber orientation is constant on a ply to ply basis. Recent research has focused to further optimize composite structures by allowing the fiber angle to change within a ply. Those Variable Angle Tow (VAT) laminates first considered in 1987 [1] show promising results for weight reduction. Experimental research of such structures show improvements in buckling loads [2] and aeroelastic tailorable [3,4].

In order to manufacture such highly tailored composites Automated Fiber Placement (AFP) and Automated Tape Laying (ATL) is used. AFP and ATL are similar processes where the prepreg material is placed on a tool or previously placed composite substrate, the backing material is removed and the tape is heated and consolidated under pressure by the compaction roller mounted on the tape placement deposition head. All movements of the machine, such as cut and refeed and placement is predefined in Computerized Numerical Control (CNC). [5]

In order to produce VAT laminates, the prepreg material is steered on a curvilinear path, but the practical implementation is limited due to defects introduced during tape steering. During tape steering of continuous fiber, the inside radius of tape is compressed resulting in tape buckling along the inner radius. The fibers on the outer radius are inextensible and fiber tension is reduced by fiber movement, and tape pull up leading to overall path misalignment. These flaws are magnified for higher tape width over steering

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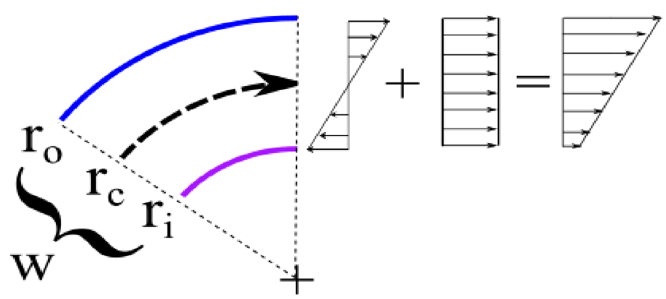
radii ratios limiting the possible MSR for wider tapes. Models to predict the MSR are based on the analytic buckling load of a thin plate with foundational stiffness. This analysis shows that the tape width has a strong influence on the steerable radius and places the MSR of a 6 mm wide tape at around ~600-650 mm [6,7], and was experimentally confirmed in [8].

The Tailored universal Feedstock for Forming (TuFF) material is a novel discontinuous carbon fiber composite developed at the University of Delaware - Center for Composite Materials (UD-CCM). Due to the high degree of alignment, TuFF prepreg can be produced at 60% fiber volume fraction and retain properties equivalent to continuous fiber composites. [9,10] TuFF can be stretched in the fiber direction due to the extensibility of the short fiber material at process temperatures. In this work, thermoplastic TuFF slit tape is used in laser assisted AFP to manufacture highly steered tow paths. By taking advantage of the stretch capability of TuFF, compressive strains during steering are offset by applying axial stretch. The results show that this method is successful at inhibiting tow buckling. Figure 1 shows the conceptional idea of the TuFF stretch steer approach offsetting the inside radius compressive strain with an appropriate tensile strain. For this work the purely kinematic strain during steering is considered and can be calculated with Eq.1. ϵ_e is the strain due to curvature on each edge and w is the width of the tape.



$$\epsilon_e = \pm \frac{w}{2r_c} \qquad \text{Eq.1}$$

2. EQUIPMENT AND MATERIAL

Experiments have been conducted with a single tow laser assisted AFP system by Mikrosam (Figure 2). In order to place thermoplastic slit tape, the AFP robot head is configured with the 3 kW laser for heating and melting the incoming tape and substrate laminate. The laser can heat the material continuously at the nip point up to 500°C at a deposition rate of 7 m/min; however, actual placement speed is limited by part size and robot acceleration. The laser power is PID controlled through a pyrometer measuring the average temperature at the nip point. All experiments were conducted at a setpoint of 450°C, a layup speed of 15 mm/s and a compaction force of 900 N on a ½ in wide roller. Figure 2 shows the setup of the AFP system.

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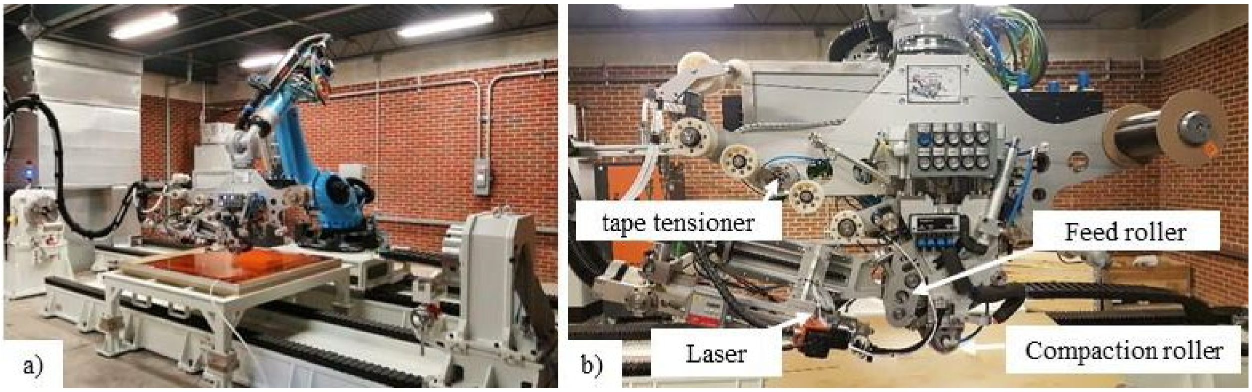
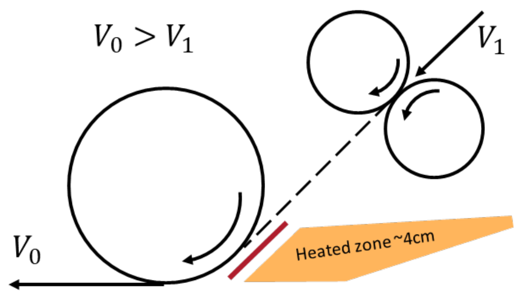


In order to offset the compressive strains during steering, the transport roller feed rate is reduced relative to the placement velocity to continuously strain the material between the rollers. A MATLAB script was written to modify the CNC code text file to accurately control the strain level following Eq.2 where a is the reduction factor to slow down the feed-speed V_1 to achieve a specific engineering strain ϵ that is to be imposed on the system. V_0 is the placement speed of the programmed path. Figure 3 shows a schematic of the velocity difference during stretch steering.



$$\epsilon = \frac{V_0 - V_1}{V_1} \rightarrow a = \frac{1}{1+\epsilon} \qquad \text{Eq.2}$$

Thermoplastic TuFF prepreg was produced with 3 mm IM7 fibers. Two polymer matrices were used in this study. PEKK matrix (Arkema) prepreg was made with 90 gsm fiber areal weight to produce a prepreg with 50 % fiber volume fraction. PEI matrix (Sabic) prepreg was made with 120 gsm fiber areal weight to produce prepreg with 57 % fiber volume fraction. The film infusion process was performed in an autoclave using a cycle that heats to 330 °C and pressurizes to 2.06 MPa (300 psi). The TuFF/PEI prepreg sheets were ~125 µm thick and 406 x 406 mm (16"x16" in) area and the TuFF/PEKK prepreg was ~100 µm thick and 457 x 457 mm (18"x18" in) area. The prepreg sheets were slit to 6.2 +/-0.1 mm wide strips.

3. TOW STRAIN EXPERTIMENTS ON STRAIGHT PATHS

A positive strain has to be accurately imposed during the AFP process to offset the compressive strain component induced during steering. As mentioned in the previous section, this is accomplished via a differential feed speed between the compaction and the feed roller. To characterize the effect of in-situ stretching a series of straight paths were placed with imposed strain in the range from 0-50 %. In order to understand deformations during stretching of the material, measurements of the tape thickness and width along the length were taken before and after placement. Markings were accurately drawn in 1 cm increments on the backside of the tape prior to slitting using a silver marker to measure the longitudinal strain. Post

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placement, the tapes were scanned with a high-resolution scanner at 2400 dpi and the distance between markings were analyzed using ImageJ.

Figure 4 shows the longitudinal strain measurements. The strain measurement of 8 sections of the tow were averaged and the standard deviation is marked in the plot as error bars. The results agree with an average coefficient of variation of 12 % with the imposed strain. There is no evidence of tape damage up to 30 % strain by visual inspection. In the range of 35 % to 50 % strain fraying on the edges is visible in a few regions. The progression of smaller defects with increasing strain is shown in Figure 5.

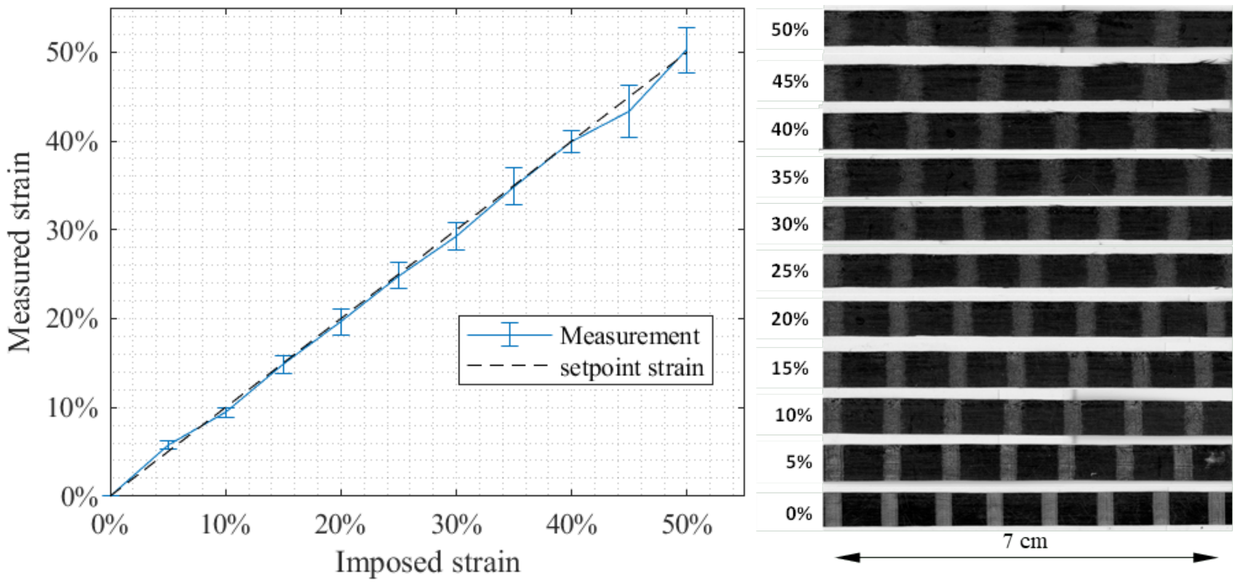

Figure 4: Straight strain comparison for TuFF/PEKK left) measured vs imposed strain right) scans of placed tows at different strains

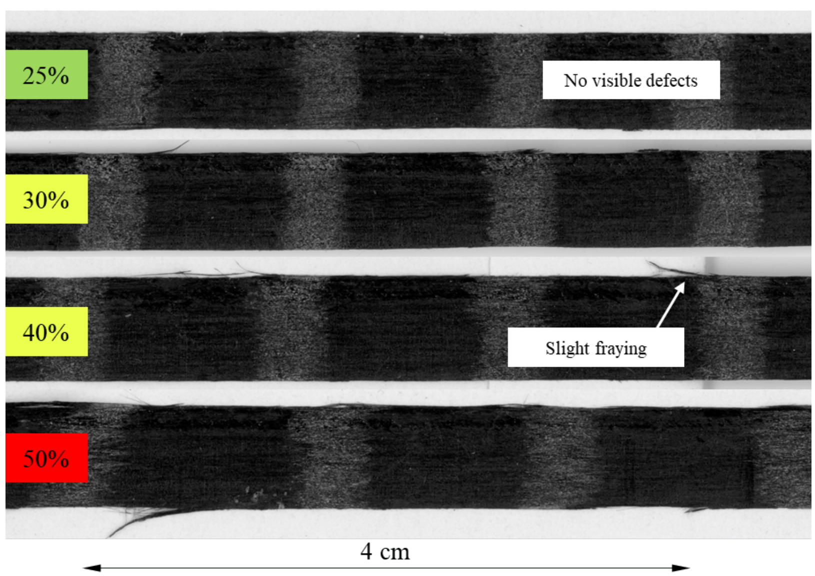

Figure 5: Visible fraying of TuFF/PEKK tape in the strain range of 30-50 %

Micrographs are taken from the stretched samples at a location of 8 cm after placement start, which is in the steady-state process window. This provides insight of the fiber microstructure post placement. Figure 7 shows a side-by-side comparison of the microstructure of the stretched tapes. Porosity is visible throughout all samples to varying degrees. As the material is being stretched, thinning is prominent. The increase in waviness of the top surface could indicate necking of the material with increasing strain, or a side product of the compaction roller surface and is at this point unexplained and subject to further investigation.

The micrograph images were segmented using ImageJ and the masks were analyzed for their width and average thickness utilizing a MATLAB script. Figure 6 compares the thickness change to the original material thickness of 109.6 µm with a coefficient of variation of 8 % (width is measured using a micrometer). The average tape thickness decreases as the tape stretch is increased. Tape thinning can arise from in-plane stretch at process temperature and during consolidation under the compaction roller. Thinning becomes apparent as greater axial strain is applied to the tape. A linear fit of final thickness strain (ε_3) to axial strain (ε_1) is shown in Figure 6. Strain is defined using the initial average thickness of the tape. The results yield a slope of -.64. The increasing standard deviation in the range of 35-50 % longitudinal strain is an indicator that the surface non-uniformity increases. This increasing standard deviation further evidences the 30 % strain limit for the AFP process as mentioned previously. The width strain shows a minimal increase and is therefore reported as a total average of ε_2=5.5 % with a standard deviation of 5.54 %. Width increase may result from squeeze flow under the consolidation roller. The magnitude of the width change might be influenced by the consolidation roller (surface has a compliant coating that deforms under compression). Additional experiments to better understand this behavior are planned in future studies. Changing the process conditions such as increasing roller pressure and heat input will affect the microstructure and will need to be optimized for the process to reduce porosity.

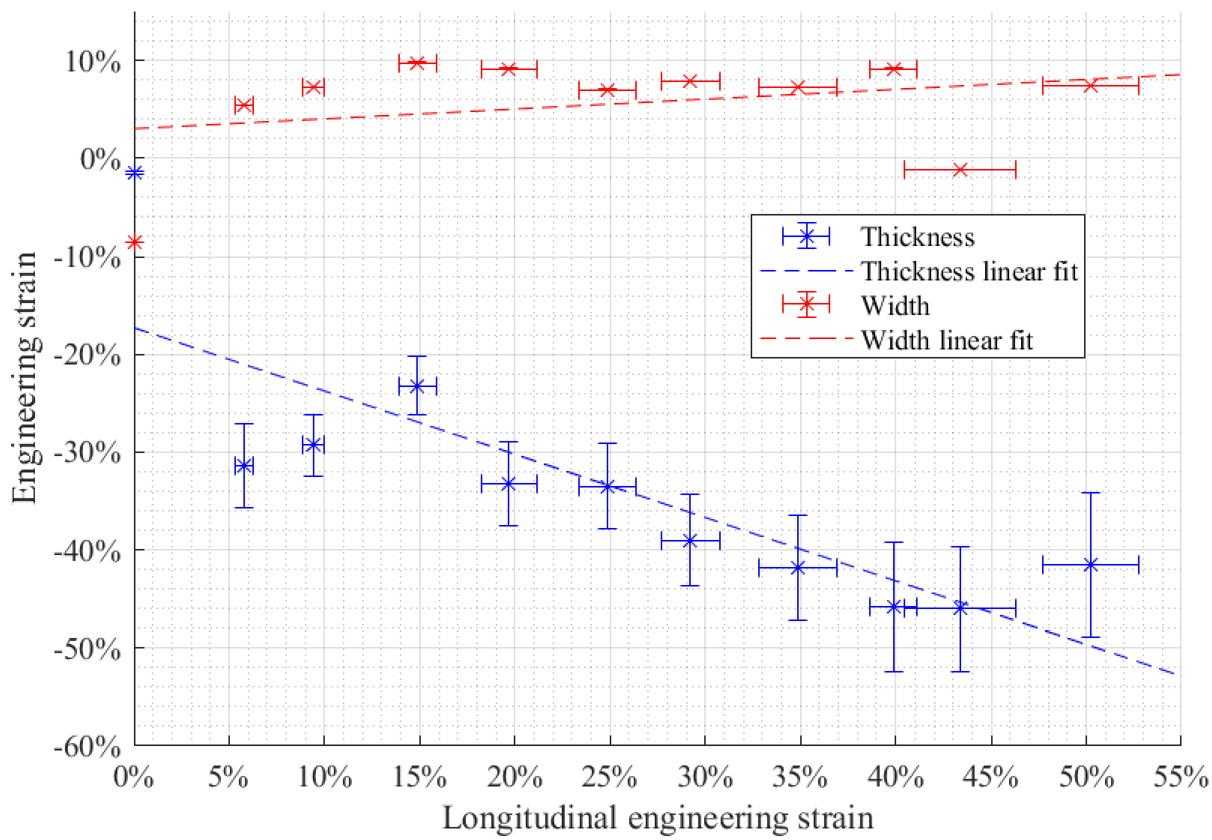

Figure 6: Thickness and Width strains based on the micrographs TuFF/PEKK

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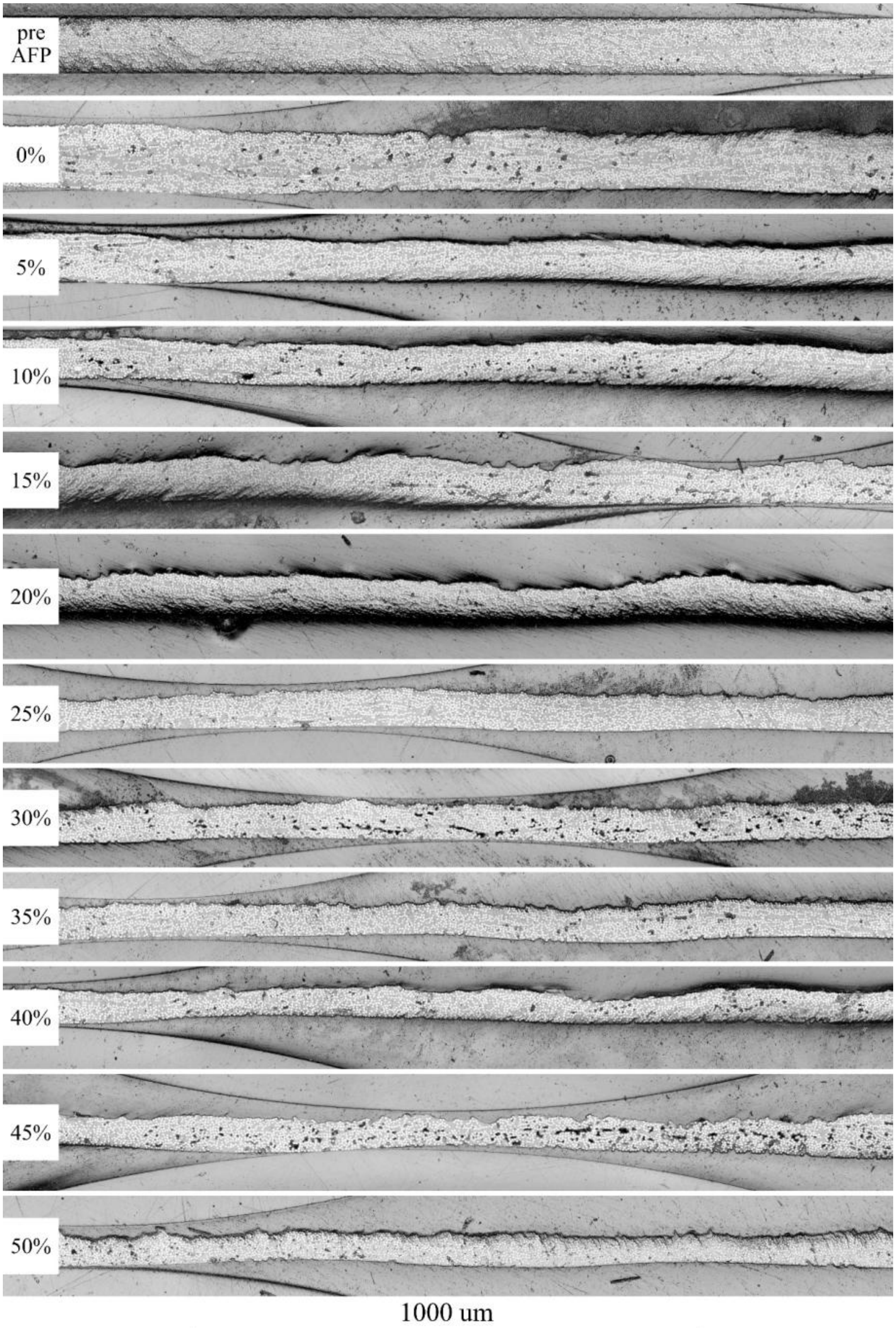

Figure 7: Microscopy samples of strained PEKK/TuFF material

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4. CURVILINEAR STRETCH STEERING EXPERIMENTS

4.1 Steering limit estimation

The minimal offset strain as a function of steering radius and tape width can be estimated with Eq.1. Using this formula and imposing a constant strain yields the formulas in Eq.3. (strains at the inner edge ϵ_i, the center of the tape ϵ_c and the outside edge ϵ_o). A conservative approach is to offset the inside edge strain to $\epsilon_i \geq 0$.

$$\epsilon_i = \epsilon_{offset} - \frac{w}{2r_c}$$
$$\epsilon_c = \epsilon_{offset} \qquad \text{Eq. 3}$$
$$\epsilon_o = \epsilon_{offset} + \frac{w}{2r_c}$$

Given those estimates, the maximum strain based on the tape width can be calculated and is shown in Table 1 for different steering radii. The strains are color based on the observations in the previous section. The estimations with the theoretical results from [6,7] for the MSR in regards to the width of the tape are compared in Figure 8. Stretch steering TuFF with a maximal strain of 20 % on the outside edge would yield a reduction in steering radius by around 1 order of magnitude (10x).

Table 1: Maximum strain during steering based on $\epsilon_i = 0$ for TuFF/PEKK

		Maximum strain based of an inside strain of $\epsilon_i = 0$					
Tape width (w)	in	0.125	0.25	0.5	1	1.5	2
	mm	3.175	6.35	12.7	25.4	38.1	50.8
Steering radii (r) [mm]	800	0.40%	0.79%	1.59%	3.18%	4.76%	6.35%
	750	0.42%	0.85%	1.69%	3.39%	5.08%	6.77%
	700	0.45%	0.91%	1.81%	3.63%	5.44%	7.26%
	650	0.49%	0.98%	1.95%	3.91%	5.86%	7.82%
	600	0.53%	1.06%	2.12%	4.23%	6.35%	8.47%
	550	0.58%	1.15%	2.31%	4.62%	6.93%	9.24%
	500	0.64%	1.27%	2.54%	5.08%	7.62%	10.16%
	450	0.71%	1.41%	2.82%	5.64%	8.47%	11.29%
	400	0.79%	1.59%	3.18%	6.35%	9.53%	12.70%
	350	0.91%	1.81%	3.63%	7.26%	10.89%	14.51%
	300	1.06%	2.12%	4.23%	8.47%	12.70%	16.93%
	250	1.27%	2.54%	5.08%	10.16%	15.24%	20.32%
	200	1.59%	3.18%	6.35%	12.70%	19.05%	25.40%
	150	2.12%	**4.23%**	8.47%	16.93%	25.40%	33.87%
	100	3.18%	**6.35%**	12.70%	25.40%	38.10%	50.80%
	50	6.35%	**12.70%**	25.40%	50.80%	76.20%	
	25	12.70%	**25.40%**	50.80%			
	10	31.75%	63.50%				

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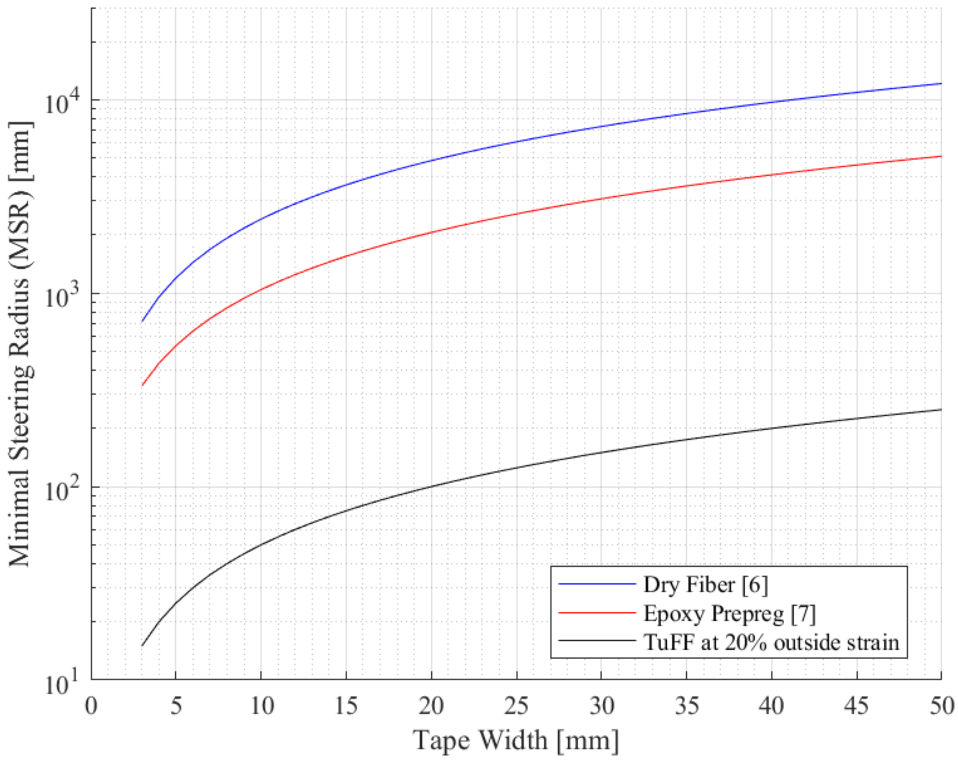

Figure 8: Analytical MSR over tape width for continuous fiber tape from [6,7] and TuFF/PEKK (outside edge strain of 20 %). TuFF tapes yield a 10x reduction in steering radius.

4.2 Curvilinear steering using TuFF

In order to demonstrate steerability of TuFF tape without wrinkling/buckling, an arc with radius of 100 mm was steered around a 120 degree turn using the Mikrosam equipment. The calculations suggest an offset strain of around 3.2 %. Considering a strain application accuracy of around 2 % (Figure 6), an imposed strain of 5 % was chosen for the experiments. Figure 9 shows a reference tow with no strain applied and the 5 % strain tow side-by-side. As expected, the tow in the reference image shows excessive folding at a steering radius of 100 mm. In contrast, the 5 % strained material does not show any folding or buckling.

To ensure that our predictions are realistic, the strain of the inner and outer length over 8 segments of 10 mm is measured. The outside edge has a total length of 87.4 mm. which equates to a total outside strain of 9.3 %. The inside length is stretched to 82.7 mm which is a strain of 3.4 %. Those strain numbers deviate from the expected values by around 1 % strain. Furthermore, it should be noted that a tape could shift while being placed and that a deviation of +1 mm on a steering radius of 100 mm could lead to a 1 % increase in strain.

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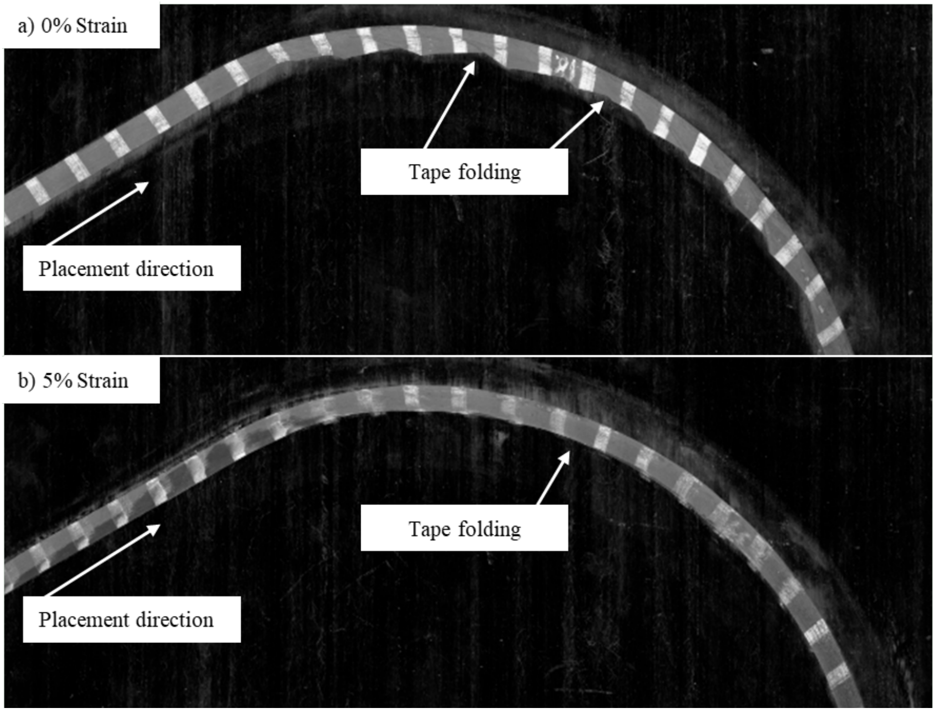

Figure 9: TuFF/PEKK - Comparison strain offset a) 0 % and b) 5 %

To further test the capability of stretch steering, a set of concentric 90 degree arcs are placed on a thermoplastic substrate with decreasing steering radius. This set of experiments is shown in Figure 10. The first tow placed is a continuous fiber tow steered on 250 mm radius. As expected, the continuous fiber tow at a steering radius of 250 mm shows excessive folding with seven folds on a center arc length of around 19 cm. Tows 2-6 are TuFF/PEI steered on radii of 200, 150, 100, 50, and 25 mm, respectively. Table 2 summarizes the strain results as well as observed defects based on the visual inspection. In the stretch steered TuFF, little to no defects are evident for steering radii above 100 mm. The defects at the end of the 200 mm and 150 mm radius are due to the tape losing tension at the feed roller and not being stretched appropriately. This is avoidable with enough straight run out at the end of the course. As the steering radius decreases to 50 mm and 25 mm, fraying on the out-side edge is visible. The fraying of the 25 mm radius is expected as its outside strain is above the levels specified in the previous section.

The slight fraying of the 100 mm radius cannot be explained by the observed strains and could be caused by tow movement during the placement process. One hypothesis is that the tow shifts slightly outside the heated zone of the laser, causing the laser to not sufficiently melt the outer edge of the tape. This could be addressed by using a wider laser optic. Alternatively, the fraying could simply be the separation of the 3 mm fibers at the outer radius and is an artifact of the tape splitting procedure used. Another observation is that the path alignment suffers while steering a radius that small. A technical challenge is to precisely quantify the drift from the programmed path for small radii, which is very critical since small deviations from the programmed path can lead to larger strain deviations. Overall, none of the samples showed the typical buckling defect from curvilinear steering.

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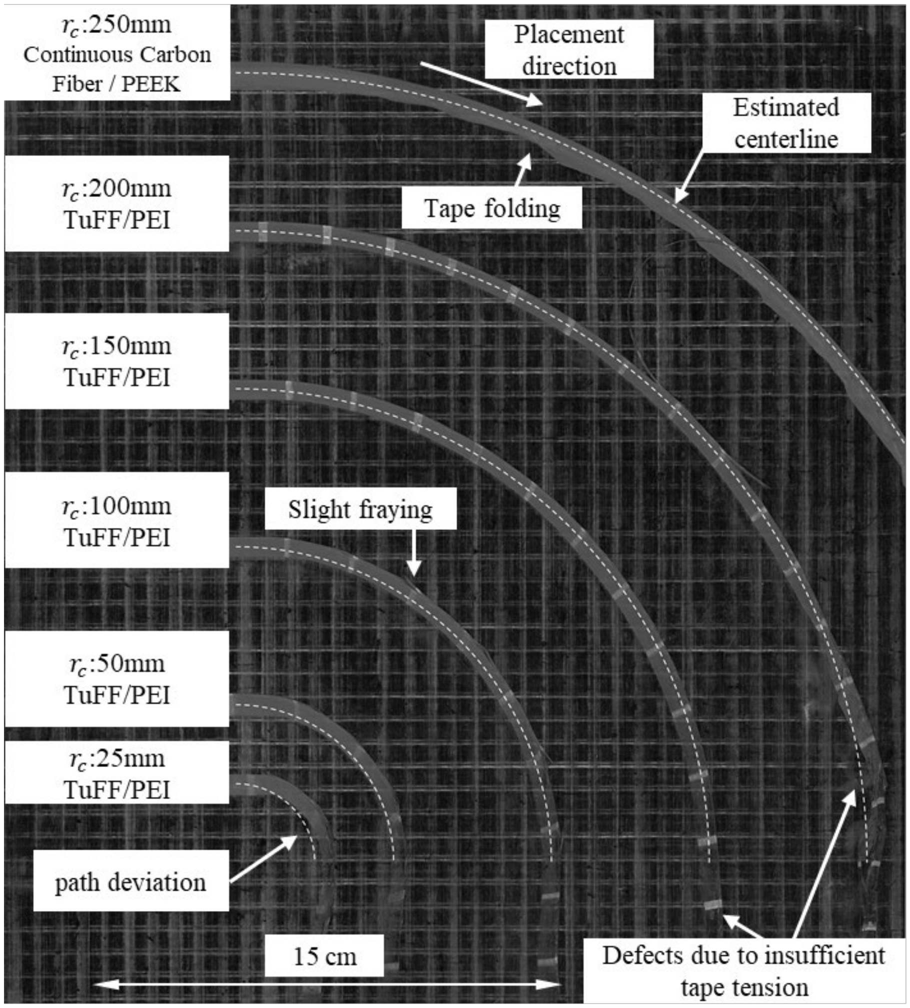

Figure 10: Steering trials TuFF/PEI

Table 2: Strain prediction and visual inspection of steering trials

Radii	Tape location	Predicted strain	Measured Strain	Visual defects
200	out	6.07 %	5.51 %	Minimal fraying on the outside edge
	center	4.57 %	4.47 %	
	in	3.07 %	3.43 %	
150	out	7.23 %	7.14 %	No defects observed
	center	5.23 %	5.58 %	
	in	3.23 %	4.02 %	
100	out	9.32 %	9.53 %	Slight fraying on the outside edge
	center	6.33 %	7.54 %	
	in	3.32 %	5.56 %	
50	out	14.56 %	20.44 %	Slight deviation off programmed path Slight fraying on the outside edge
	center	8.56 %	16.03 %	
	in	2.56 %	11.62 %	
25	out	43.10 %	40.64 %	Deviation from path by 3 mm
	center	31.10 %	33.55 %	Slight fraying on the outside edge
	in	19.10 %	26.46 %	Slight tape pull-up on the outside

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5. CONCLUSIONS

Current manufacturing approaches of highly tailored continuous fiber composites using variable angle tow laminates are limited to steering radii above 650 mm with 6 mm wide tape. The stretchable, highly aligned, short fiber TuFF material can offset the compressive strains during steering by in-situ stretching of the material and greatly reduce the MSR for this class of structures. This paper demonstrates the concept using 6.2 mm-wide TuFF tape made from 3 mm IM7 short carbon fibers and PEKK / PEI polymer. Straight paths were in-situ stretched on the laser assisted AFP system by Mikrosam. The measured tape stretch matched the requested strain closely and the material looked visually unchanged up to a longitudinal strain of 30 %. Micrographs of the strained tapes confirmed this strain limit. Steering trials were done placing tows from 25 – 200 mm showing no buckling or folding overall and no other defects up to a MSR of 100 mm. Local defects arise for smaller radii like path misalignment and slight fraying on the outer edges. Process optimizations were proposed to mitigate these defects. The approach provides a unique, automated pathway to fabricate highly tailored structures for weight critical applications.

6. ACKNOWLEDGEMENT

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