Title: *Feature-Based Design for Manufacturing Guidelines for Dry Fibre AFP*

Authors (names are for example only): Mattia Di Francesco
Laura Veldenz
Simon Astwood
Peter Giddings
Giuseppe Dell'Anno
Kevin Potter

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ABSTRACT

This work provides a validated method to define feature-based Design for Manufacturing guidelines for the layup of bindered dry fibre tapes by laser-assisted Automated Fibre Placement, based on the layup of unidirectional strips. Unidirectional strips and Quasi Isotropic preforms were laid over 90° corner inner mould tools, using a range of process parameters. The effect of the tool geometry (5 to 25 mm radius) and of the process parameters (compaction force and roller material) on the preform thickness were measured using a non-contact laser line scanner. The method was used to determine the minimum tool corner radius which yields satisfactory quality preforms. This was found to be 25 mm.

INTRODUCTION

Dry fibre tapes laid up by Automated Fibre Placement (AFP) have the potential to reduce the manufacturing cost compared to prepreg materials [1]. The technology is in its early stages of development, and the capabilities of the process with respect to the layup of complex geometries are yet to be defined fully [2].

When a thick preform is impregnated, consolidated and cured over an inner mould tool, the consolidation of the preform is essential to manufacture defect free parts geometrically in tolerance. Excessive bulk would cause the formation of out-of-plane wrinkles [3], while corner over-compaction would cause uneven laminate thickness and/or prevent full impregnation.

The aim of this work is to identify the technology envelope with respect to the layup of inner moulded 90° convex corners with respect to the requirements imposed by the post-process: atmospheric pressure consolidation, impregnation and cure.

M. Di Francesco, L. Veldenz, S. Astwood, P. Giddings, G. Dell'Anno, The National Composites Centre, Feynman Way Central, Bristol, BS16 7FS, UK

K. Potter, Department of Aerospace Engineering, University of Bristol, Queen's Building, University Walk, Bristol, BS8 1TR, UK

EXPERIMENTAL SETUP

Machine Details

A state-of-the-art, industrial, laser-assisted AFP machine by Coriolis Composites SAS, France (Figure 1-a) was used to layup simultaneously up to 8, nominally 6.35 mm wide, bindered dry fibre tapes supplied by Hexcel Corporation, US (HiTape® UD210 IMA/V800E/ZD4/6.35MM).

The heat source for the process is a Laserline GmbH LDF 6000-100 6 kW fibre-coupled diode laser, which was de-powered to 3 kW (two diode stacks at $\lambda = 1025 \pm 10$ nm). The laser is installed remotely from the fibre placement head and the beam is guided through a fibre optic cable to a homogeniser optic, delivering a nominally homogeneous (~ 7 % power variation across the course width), 57 mm wide and 8 mm high rectangular laser beam at the focal point (Figure 1-b).

A 40 Shore hardness silicone roller (8F14-S40SH-BL, Laser L Density White), recommended for the layup of materials which require a laser heater, “Silicone”, and an intermediate stiffness foam roller (8F14-M510, IR Low Density Foam Red), recommended for the layup of materials which require an infra-red heater, “Foam”, were used for this work.

The laser power was specified in the Human Machine Interface (HMI) as a function of the layup speed to achieve a nominally constant surface temperature at the “visible nip point” (Figure 1-b). The roller cooling device (Figure 1-a) was not used.

The nominal compaction force was also specified in the HMI. The compaction force was 446 ± 37.9 N and 1206 ± 49.1 N (double standard deviation, 2σ) for the 200 N and 1000 N cases respectively.

Dimensions and Setup Design

A set of 5, unidirectional (UD), 10 plies thick, approximately 400 mm long test strips was laid up for a number of combinations of the tool corner radius (5, 10 and 25 mm), the layup orientation (0°, ± 45° and 90°), the compaction force (200 N and 1000 N nominal), and the roller material (Foam and Silicone).

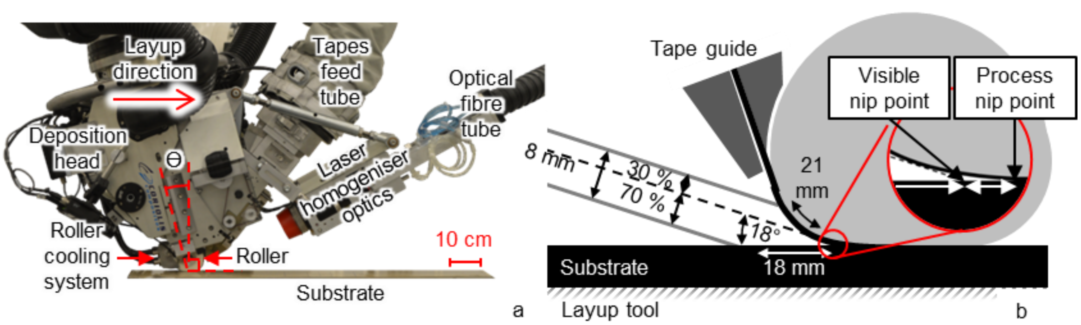

Figure 1. Laser-assisted Coriolis Composites AFP machine head showing the installation of the laser homogeniser optics (a) and laser beam target, power split and temperature measurement location (b).

The material was laid up over a Nylon film (Airtech, Wrightlon® 7400) vacuumed to the surface of a an interchangeable radius 90° corner aluminium tool with a coated nylon peel ply 60BR, 60g/m^2 in between. The UD strips were one course wide (8 tapes, 50.8 mm), with the exception of the 0° strips over the apex of the 10 and 25 mm radius corner, which were 2 tapes (12.7 mm) and 4 tapes (25.4 mm) wide, respectively. Only one tape (6.35 mm wide strip) could be laid over the 5 mm radius, but 10 plies could not be stacked because the strip was unstable and could not withstand the manufacturing induced stresses. The layup speed was set at 400 mm/s, however, the actual speed is affected and typically reduced by the complex machine kinematics when laying up the ± 45° and 90° plies over the corner. The layup speed was measured to be as low as ~ 10 mm/s at the corner apex.

Similarly, a 600 x 400 mm, 26 plies thick, Quasi-Isotropic (QI) [(-45, 45, 0, 90)s, 0, (-45, 45, 0, 90)]s preform was laid up over a range of corner radii (5, 10, 25 mm), and five additional equivalent preforms were laid up for the 10 mm radius case. The machine was setup to feed and cut the material at 200 mm/s and to accelerate/decelerate at 1000 mm/s^2 to the maximum layup speed of 1000 mm/s, apart from the first ply which was programmed to layup at a constant speed of 200 mm/s to improve first ply adhesion to the vacuum bag. As for the strips, the actual layup speed over the complex geometry (± 45° and 90° plies) is lower than the set-up value.

Thickness Measurement

The thickness of the preforms (UD and QI) was measured using a contactless articulated arm with an integrated laser line scanner (76 μm nominal accuracy, 2 σ). The thickness of the UD ± 45° and 90° strips, and of the QI preforms was measured at three critical regions: corner apex and the two sides, as detailed in Figure 2. The thickness of the UD 0° strips was measured at the corner apex only.

The thickness was measured with respect to a surface which was best fit to the tool scan data with a deviation no greater than ± 100 μm (2 σ).

The preform fibre volume fraction (UD and QI) was calculated from the measured thickness based on the number of plies (10 or 26), the nominal areal weight of the material (210 g/m^2) and density of carbon fibre (1.79 g/cm^3).

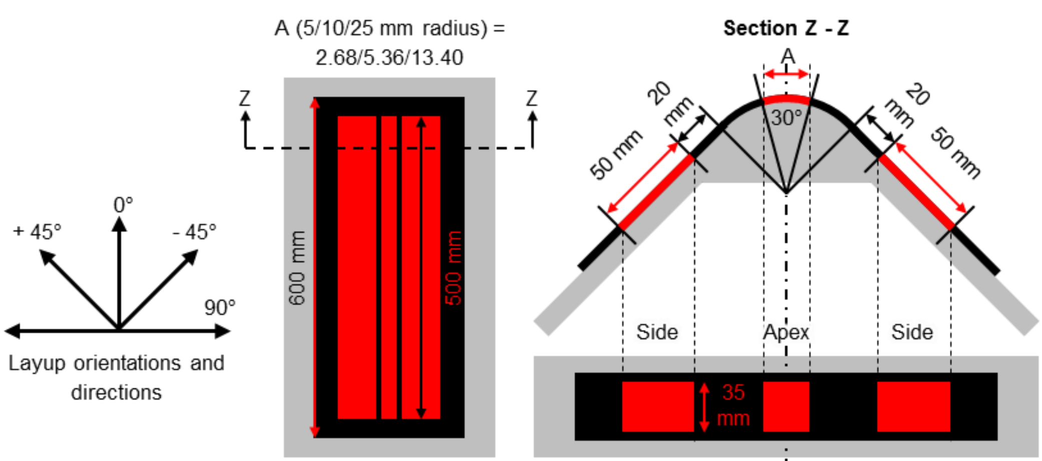

Figure 2. Experimental setup and measurement locations.

EXPERIMENTAL RESULTS

During the experimental work, a single factor (corner radius, roller material or compaction force) was varied at one time, and the results compared with the baseline configuration (10 mm corner radius, 200 N compaction force and Silicone roller) for each layup orientation (0°, ± 45°, 90° and QI), to determine its effect on the apex and sides preform fibre volume fraction (Table I).

The significance of the effect of each factor was determined by calculating its Standardised Effect (SE), defined as the ratio of the difference between the means ($\bar{x}_2 - \bar{x}_1$) and the standard error ($\sqrt{(\sigma_1)^2/n_1 + (\sigma_2)^2/n_2}$). This was compared with the *t* statistic for $\alpha = 0.05$ (95 % confidence) to determine its statistical significance. Similarly, the fibre volume fraction of the apex and the sides were compared for each of the ± 45° and 90° configurations to determine the difference and its significance.

The results for the 0° layup show that:

- Increasing the corner radius from 10 to 25 mm produces a preform with a higher fibre volume fraction
- Both using a more conformable foam roller and increasing the compaction force reduce the fibre volume fraction

The results for the 45° layup show that:

- Both the 5 and 25 mm corner produce a corner apex fibre volume fraction which is lower than the baseline 10 mm one
- Both using a more conformable foam roller and increasing the compaction force increases the corner apex fibre volume fraction with respect to the baseline
- The difference in preform fibre volume fraction between the corner apex and the sides is significant, and lowest for the 25 mm corner radius case

The results for the 90° layup show that:

- The larger the corner radius, the lower the preform fibre volume fraction at the corner apex
- Both using a more conformable foam roller and increasing the compaction force have a statistically insignificant impact on the corner apex fibre volume fraction with respect to the baseline
- The difference in preform fibre volume fraction between the corner apex and the sides is large, and lowest for the 25 mm corner radius case

The results for the QI layup show that:

- The larger the corner radius, the lower the preform fibre volume fraction at the corner apex
- The larger the corner radius, the lower the difference between the corner apex and the sides preform fibre volume fraction

TABLE I. EXPERIMENTAL RESULTS.

Orient.	**Config.**	**Apex**			**Sides**			**Apex vs. Sides**	
		$\bar{x} \pm 2\sigma$	$\bar{x}_2 - \bar{x}_1$ (95% CI)	**SE**	$\bar{x} \pm 2\sigma$	$\bar{x}_2 - \bar{x}_2$ (95% CI)	**SE**	$\bar{x}_2 - \bar{x}_2$ (95% CI)	**SE**
0°	**Basel.**	41.0% ± 0.3%	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**	**n/a**
	Radius 5 mm	un	un	un	n/a	n/a	n/a	n/a	n/a
	Radius 25 mm	46.5% ± 0.4%	5.5% ± 0.6%	23.06	n/a	n/a	n/a	n/a	n/a
	Roller Foam	36.3% ± 0.6%	-4.7% ± 0.7%	15.72	n/a	n/a	n/a	n/a	n/a
	Force 1000 N	23.9% ± 17.1%	-17.1% ± 2.3%	17.9	n/a	n/a	n/a	n/a	n/a
45°	**Basel.**	59.0% ± 0.2%	**n/a**	**n/a**	**45.7% ± 0.2%**	**n/a**	**n/a**	**13.3% ± 0.4%**	**84.88**
	Radius 5 mm	56.5% ± 0.9%	-2.4% ± 1%	5.6	43.7% ± 0.4%	-1.9% ± 0.5%	9.38	12.8% ± 1.1%	27.91
	Radius 25 mm	57.0% ± 0.4%	-1.9% ± 0.5 %	9.04	45.2% ± 0.5%	-0.5% ± 0.7%	(1.94)	11.9% ± 0.7%	39.45
	Roller Foam	59.5% ± 0.3%	0.6% ± 0.4%	3.19	45.3% ± 0.3%	-0.3% ± 0.4%	(2.17)	14.2% ± 0.4%	82.68
	Force 1000 N	62.1% ± 0.3%	3.1% ± 0.4%	18.61	44.9% ± 0.4%	-0.8% ± 0.5%	3.82	17.2% ± 0.5%	82.68
90°	**Basel.**	61.0% ± 0.4%	**n/a**	**n/a**	**47.2% ± 0.2%**	**n/a**	**n/a**	**13.7% ± 0.5%**	**61.36**
	Radius 5 mm	60.6% ± 0.4%	-0.3% ± 0.6%	1.27	43.8% ± 0.7%	-3.4% ± 0.7%	11.01	16.8% ± 0.8%	48.74
	Radius 25 mm	58.7% ± 0.7%	-2.3% ± 0.8%	6.35	47.4% ± 0.4%	0.2% ± 0.5%	(0.73)	11.3% ± 0.8%	31.22
	Roller Foam	60.5% ± 0.5%	-0.5% ± 0.7%	(1.51)	47.1% ± 0.3%	-0.1% ± 0.4%	(0.66)	13.4% ± 0.6%	49.52
	Force 1000 N	61.3% ± 2.3%	0.3% ± 2.5%	(0.27)	46.3% ± 0.6%	-0.9% ± 0.7%	3.31	15.0% ± 2.5%	13.82
QI	**Basel.**	58.5% ± 0.5%	**n/a**	**n/a**	**45.3% ± 0.7%**	**n/a**	**n/a**	**13.2% ± 0.7%**	**39.12**
	Radius 5 mm	58.8%	0.3%	un	43.8%	-1.5%	un	15%	un
	Radius 25 mm	54.5%	-3.9%	un	42.6%	-2.8%	un	12%	un

S.E. = Standardised Effect. The effect is not statistically insignificant if the S. is greater than the *t* statistic (t = 2.776 at α = 0.05 and 4 degrees of freedom)
n/a = Not Applicable
un = Unavailable

DISCUSSION

From Unidirectional to Quasi Isotropic Preforms: Validation

The measured fibre volume fraction at the corner apex of the 0°, ± 45° and 90° UD preforms, laid up over the 5, 10 and 25 mm corner radii tool using the silicone roller and a nominal compaction force of 200 N, was used to estimate the QI preforms fibre volume fraction at the corner apex. This was estimated as the weighted average of the UD preforms fibre volume fraction in each of the four orientations.

The estimated corner apex preform fibre volume fraction was found to be lower than what was measured for the 5 and 10 mm radius cases, and in agreement with the measurements for the 25 mm radius case (Figure 3-a).

This difference can be attributed to the fact that the 0° plies are further compacted by the layup of the subsequent ± 45° or 90° ply (Figure 3-b) when the radius is small. The corner apex preform fibre volume fraction was re-estimated by assigning to each 0° ply the fibre volume fraction of the subsequent ± 45° or 90° ply, and this yields good predictions for the 5 and 10 mm cases, but overestimates the 25 mm one (Figure 3-a).

Preforms' Suitability for Impregnation and Cure

Having determined that the results from the UD strips can be used to infer the fibre volume fraction of a QI layup, a set of criteria are required to evaluate the suitability of the AFP made preforms for consolidation and impregnation under atmospheric pressure.

At present, the experience with the impregnation of AFP deposited bindered dry fibre preforms is limited to flat geometries. Therefore, three preform criteria were tentatively defined based on previous experience with prepregs and non-crimp fabrics:

1. The preform fibre volume fraction shall not exceed that of a flat laminate which was infused and cured by the same method. This is 55.5 % ± 1.9 % for a HiTape®, flat, QI preform infused under atmospheric pressure
2. The preform bulk factor, defined as the relative difference in thickness between the preform and the cured laminate, shall be as low as possible, and ideally no greater than 10 % (i.e. the preform fibre volume fraction should not be lower than 50 % for a 55 % fibre volume fraction laminate)
3. The preform fibre volume fraction shall be consistent across the part (tolerances are currently undefined)

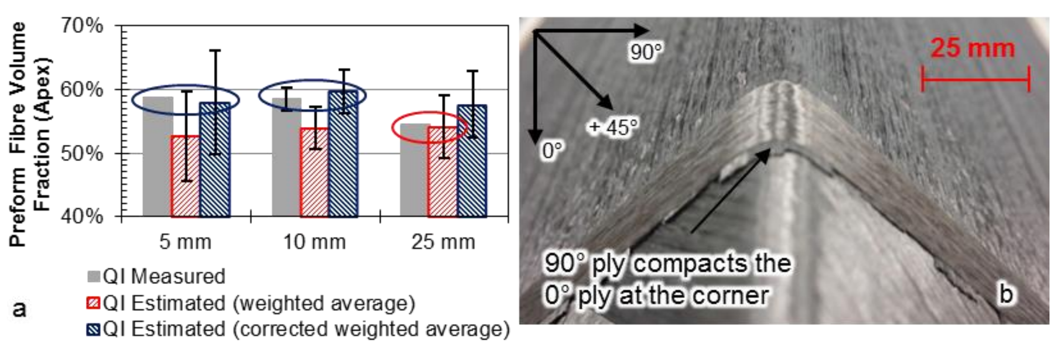

Figure 3. Validation.

The results show that an AFP machine can be used to layup over a convex 90° corner having a radius as small as 5 mm (Figure 4.). However, the smallest tested corner radius that meets the three preform criteria is 25 mm. The 25 mm corner radius UD preforms have a lower degree of over-compaction at the corner apex than their 5 and 10 mm radius counterparts for the ± 45° and the 90° cases. They also feature the highest preform fibre volume fraction for the 0° layup, while still being below the 55 % fibre volume fraction limit. The 25 mm radius preforms are also the ones having the greatest preform thickness uniformity, defined as the smallest difference between the preform fibre volume fraction at the apex and the sides. The 25 mm radius QI preform, is the only one having an overall fibre volume fraction at the corner apex lower than 55.5 % ± 1.9 %.

The effect of the other two parameters (roller and compaction force) is non-statistically insignificant, but in the direction opposite to the desired one according to the three criteria, for the ± 45° and 0° cases. The preform fibre volume fraction increases above the already over-compacted baseline layup in the ± 45° case, and decreases below the already under-compacted baseline layup in the 0° case. The effect of the roller and the compaction force is statistically insignificant for the 90° case.

It shall be noted that this only applies to the layup of plies following a geodesic path (i.e. no in plane fibre steering). Should the layup not follow a geodesic path, increasing the compaction force and/or using a more compliant roller may prove beneficial as it minimises the areas of non-contact between the roller and the tool [4-5].

Furthermore, [2] shows that there is currently no dominant design in the bindered dry fibre tapes market, and that different suppliers manufacture products having different features (e.g. binder type, binder application method, areal weight, etc.). Similarly, there is a relatively wide range of commercially available fibre placement machines capable of processing bindered dry fibre tapes, each having its own features (e.g. heating system, compaction device, etc.). The results are therefore only valid for the machine and material tested. Nevertheless, the procedure, which was validated in the previous section, which involves laying up unidirectional strips to determine feature based Design for Manufacturing guidelines, is transferable.

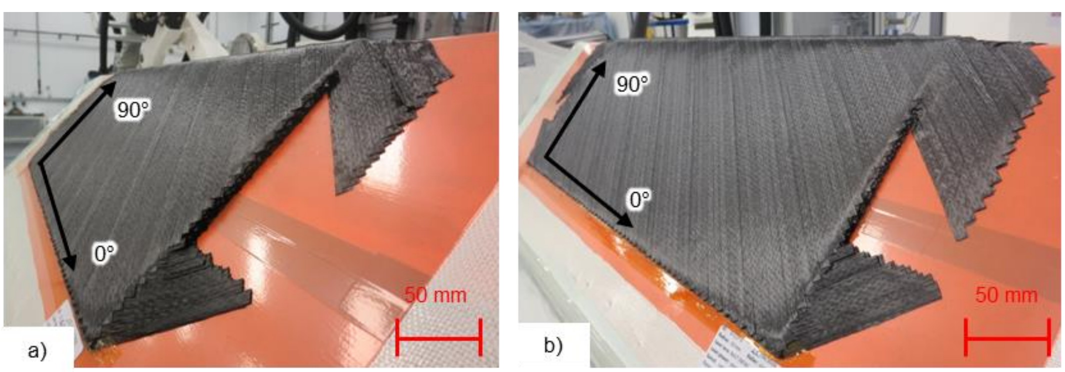

Figure 4. 26 plies, QI, preform over a 5 mm radius corner (a) and a 10 mm radius corner (b) showing good quality top ply (– 45°) in both cases.

CONCLUSIONS AND FURTHER WORK

This paper presents a validated, effective and efficient methodology based on testing the manufacturability of unidirectional strips to determine feature based Design for Manufacturing rules for the layup of bindered dry fibre tapes by laser-assisted Automated Fibre Placement.

Within the limits of the tested configurations, it can be concluded that inner moulded 90° convex corners should have an inner radius of no less than 25 mm, and are best laid up using a stiff roller (silicone) and a low compaction force (200 N nominal).

Moreover:

- Layup by AFP over a convex corner having a radii as small as 5 mm is technically feasible, but corner apex over-compaction to well above the 55 % finished laminate target occurs, which is likely to produce non-uniform thickness laminates. This is to be verified as part of further work
- Using a softer roller (foam), or increasing the compaction force, (1000 N nominal) did not deliver an improvement on the baseline configuration (silicone roller and 200 N nominal compaction force)

Finally, the results are only valid for the machine and material tested and cannot be generalised without testing a range of machines and dry fibre materials, which is also part of further work.

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