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Single Curvature Bending of Structural Stitched Textile Reinforcements Part I: Experimental Work

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Abstract—**Aerospace structural components made from polymer matrix composites (PMCs) offer numerous advantages. Their high stiffness and high strength combined with low densities enable lower fuel consumption coupled with higher payloads. As a result, PMCs provide an important economic advantage over typical metallic airframes. Textile reinforcements for PMCs are made by assembling reinforcement fibres, typically carbon. Then, the textile reinforcements are typically cut into smaller pieces, stacked, draped and assembled into a dry assembly called a preform, the shape of which generally approaches that of the PMC part to be made. This manufacturing process is labour intensive and expensive.**

Novel thick, net-shape, drapable, high fibre volume fraction (v_f) textile reinforcements used toward manufacturing aerospace PMCs are being developed at the University of Ottawa. The technology enables the manufacturing of flat, drapable multilayered near net-shape preforms. The bending and in-plane shear behaviours of such novel thick reinforcement textiles was investigated to understand and define the behaviour of such thick fabric reinforcements when formed into required shapes. A bending apparatus was developed for investigating the bending behaviour of these novel thick reinforcement fabrics.

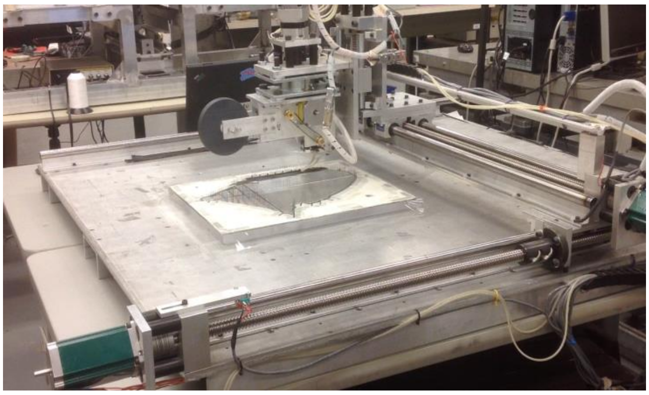
Index Terms: **3D reinforcement textiles, bending test, thick carbon fibres reinforcement, dry fabrics, Polymer matrix composites, Non-crimp fabrics.**

I. INTRODUCTION

Manufacturing processes for advanced textile reinforcements that feature novel characteristics such as yarns oriented along the thickness, higher thicknesses that correspond to those needed for producing PMC parts from a single piece or layer of reinforcement, as well as complex shapes and near net-shape contours that correspond more or less closely to those of the PMC parts to be produced, are evolving very rapidly. Different textile solutions are being devised depending on the structural performance needed of each final PMC part, on the composite manufacturing process used for making a given PMC part, and most fundamentally on the shape of the specific part to be produced. Textile manufacturing processes are reviewed in this thesis. 3D weaving and stitching appear to offer the greatest potential amongst the more established and available 3D textile manufacturing processes, although yarn interlacing in the thickness reduces in-plane structural properties of PMC parts made from the former whilst the latter may lead to weaker interlaminar performance in PMC parts [1]. On this aspect, as with many others such as flexibility offered by different textile processes over in-plane yarn orientations, often the best compromise must be found.

II. NOVEL CARBON FIBER PREFORMS

A novel, patented textile reinforcement manufacturing technology aiming at producing thick, net-shape, drapable, high v_f textile reinforcements used toward manufacturing aerospace PMCs is being developed at the University of Ottawa. The technology, referred to in this paper as University of Ottawa advanced preforming technology (uO-APT), enables the manufacturing of flat, drapable multilayered near net-shape preforms featuring steered yarns assembled by directional stitching, Figure. 1 [2], [3].



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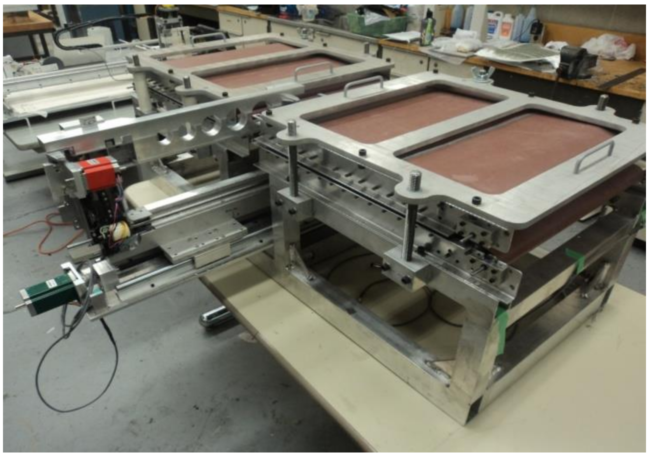

Figure 1. uO-APT prototype manufacturing equipment for laydown (top) and stitching (bottom) [3].

The evolution of the uO-APT process can be traced to Master's theses completed at the University of Ottawa by Nicholas Burnford [2], Andrew Stewart [4], Aymen Sakka [5], Scott Audette [6] and Thanos Drivas [3]. Important contributions were made by undergraduate students Alex Maclure, Helene Fortier, Khadijah Ahmad, Yue Heng 'Jack' Xu, Cedric Eveleigh and also by Master's student Lucas West and to the completed PhD thesis of Reza Samadi.

The uO-APT pre-production process enables the design and manufacturing of thick, net-shape, flat drapable reinforcements featuring variable spacings between adjacent yarns, allowing them to be steered in their initial manufacturing plane. Local alterations to yarn spacings enable local tailoring of the forming behaviour of the reinforcement, and eventually of its processing properties and of the structural properties of the resulting PMC part. By tailoring tow spacings in a targeted manner it is possible to produce a final-thickness reinforcement that is uniquely suited for forming on a precise geometry.

The bending behavior of thick structural textile reinforcement plays a central role in preforming operations involving such textiles, and so it is crucial to probe and document it towards understanding reinforcement forming and the eventual onset of buckling. In the present work the bending behavior of both 3D reinforcements produced at the University of Ottawa using the uO-APT process, and of stacks of industrial fabrics commonly used in manufacturing load-bearing aerospace PMC parts, was investigated using a bending rig designed for this purpose as part of the work. The novel 3D uO-APT reinforcements required testing towards defining and understanding their material properties and constitutive behaviour. The bending behaviour of such thick structural textiles was the subject of very limited investigation work with virtually no results available in the open literature.

The process of forming thick, dry textile reinforcements to complex shapes must be engineered robustly through predictive design. To this end the axial, shear and bending behaviour of reinforcement textiles must be investigated. The axial behaviour of a textile subjected to tension can be quantified using axial or biaxial tensile tests, and the shear behaviour can be quantified using bias extension or picture-frame tests. The bending behaviour can be quantified using the ASTM D1388 cantilever bending test or the Kawabata evaluation system for fabric bending (KES-FB), but both suffer from restrictions in using them on thick reinforcement textiles.

Boisse *et al*. [7] investigated the influence of tensile, in-plane shear and bending stiffnesses on the onset of wrinkling during textile forming. Wrinkling is a major defect that can occur upon forming textile reinforcements. The onset of wrinkles will happen readily in unfavourable forming scenarios as the bending and shear stiffnesses of fabrics are low.

Two main test configurations were used for measuring textile bending properties. First is the ASTM cantilever bending test initially developed by Peirce, as reported by de Bilbao *et al*. [8]. In this test the textile is cantilevered and the bending moment resulting from the overhanging textile mass is related to the curvature calculated from the geometry of the bent specimen. For stiff and thick reinforcement textiles, significant curvature calculated from the geometry of the bent specimen will not be realised hence quantifying it meaningfully will be fraught with difficulty.

The second test configuration is embodied in the Kawabata evaluation system for fabric bending (KES-FB). Kawabata's evaluation system includes multiple devices that were designed for measuring numerous basic mechanical properties of fabrics. The bending test quantifies properties in pure bending and enables the direct recording of the bending moment as a function of sample curvature. The fabric sample is held between a fixed clamp and a moving clamp. The setting of the sample within clamps ensures pure bending during the test as the moving clamp rotates around the fixed one resulting in curvature that is constant through the sample length at any given time [9]. While KES-FB does enable the measurement of bending properties it is not suitable for stiff, thick reinforcements. Sample dimensions are 1 cm length in the bending direction by 20 cm width. The apparatus was developed for low stiffness fabrics such as those aimed at garment applications. Testing stiff and thick reinforcements may be accommodated by a reduction in sample width; still, measurements may be impossible altogether as the system is designed for very low bending moments [8].

Yu *et al*. [10] studied the bending behaviour of fabrics and yarns using another device, the Kawabata bending evaluation system for fabrics and yarns (BES-FY). The authors investigated mainly the effect of BES-FY system parameters such as the distance between u-shaped pins, length of the sample mounted on the two jaws, and diameter and speed of upward motion of the u-shaped pins, on the bending stiffness measured. Their work showed that bending stiffness of fabrics and yarns is best calculated at curvatures within 1.5 to 2.5 cm^{-1} in the BES-FY apparatus, and that the relationship between bending moment or bending stiffness and curvature can be divided into distinct zones that may be represented using constant, linear and quadratic functions.

Bilbao *et al*. [9] introduced a cantilever beam fabric bending test coupled with optical curvature measurement. The optical module takes images of the bent sample, which are processed to extract the shape of the bent sample. A preliminary step of pixel calibration is required so that pixel measurements may be translated into accurate dimensions through scaling. The authors observed that the standard cantilever test is limited because of its reliance on the elastic linear model, and that the bending behaviour of fabrics cannot be predicted accurately only from its yarns properties.

Investigations conducted in the context of this thesis quickly revealed that the two main devices that have been used for measuring fabric bending properties, the KES-FB system [9] and the ASTM cantilever bending device [8] are unsuitable for testing stiff, thick fabrics where significant forces are applied and small curvature radii must be imposed. An additional important objective of the work undertaken here was to replicate the way in which such textile reinforcements are bent in actual PMC manufacturing operations, as closely and reproducibly as possible. Therefore, an apparatus was designed and manufactured for testing thick and stiff textile reinforcements; this apparatus is referred to as the bending rig (BR) henceforth.

III. EXPERIMENTAL

Two types of carbon fibre reinforcements were characterized in this work, using a purposely designed bending rig that aimed at reproducing industrial preforming operations as closely as possible whilst obtaining documented and reproducible data. An experimental plan was devised towards quantifying the effect of textile reinforcement thickness, yarn and stitch orientations as well as fibre volume fraction v_f on the bending behaviour. Results obtained with different textile constructions are compared. Figure. 2 shows a flow chart of the tests conducted to investigate the bending behaviour.

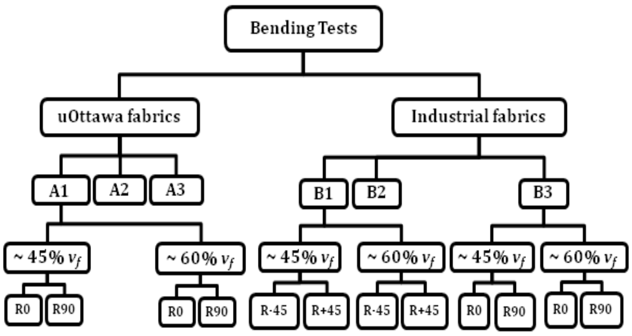

Figure 2. Bending tests flow chart.

Two types of carbon fibre reinforcements were tested in bending, labeled types A and B. Type A reinforcements consisted of a single, thick bidirectional textile layer made of superimposed arrays of parallel carbon fibre yarns assembled by stitching in a final operation using the uO-APT process, Fig. 3, left. Conversely, type B reinforcements consisted of stacks of thin individual bidirectional textile layers, each layer being individually assembled by stitching prior to stacking, Figure. 3, right. Type A reinforcements are thick, monolithic single layer textiles whilst type B reinforcements are stacks of thin textile layers that can be separated readily one from another.

Type A reinforcements were made from Tenax-J grade HTS40 E13 12K, 800 tex carbon fibre yarns. Nominal yarn centre-to-centre in-plane distance within each array of parallel yarns was set to 4.0 mm leading to a surface density of 200 g/m^2 per unidirectional array of parallel yarns. The reinforcements were stitched using Cansew PF 68/2 16 tex lock stitch lines with 20 mm centre-to-centre in-plane spacing. All type A reinforcements were bidirectional, symmetrical and featured even numbers of yarn arrays; numbers of arrays and their orientations in each reinforcement tested are specified in Section 3.3.3. Each type A reinforcement was stitched in one direction only; stitch lines ran parallel to one carbon yarn direction in some samples, and they ran between both carbon yarn directions in other samples as specified in Section 3.3.3. All type A reinforcements were manufactured at the University of Ottawa using dedicated equipment and a patented process.

Type B reinforcements consisted of stacked layers of Saertex 534 g/m^2 [+45°/-45°] bidirectional non-crimp stitched carbon textiles made from Tenax HTS40 12K yarns assembled using parallel lines of unspecified non-structural stitch. Stitch lines ran along the 0° direction with 5.0 mm centre-to-centre in-plane spacing. Numbers of textile layers within each type B reinforcement stack tested in bending are specified in Section 3.3.3.

Type A reinforcements were stitched along one direction only. Yarns in the outermost arrays on both external faces had to run in the same direction to ensure that these yarns and all those from arrays in between remain assembled in the integrity of the reinforcement, stitch line direction in type A reinforcements had to differ from the direction of yarns in the outermost arrays. Contrary to type A reinforcements, each reinforcement layer. Furthermore, and again to ensure the distinct layer within type B reinforcement stacks featured yarns in different orientations on each face. In this case, the need to ensure the integrity of the reinforcement dictates that

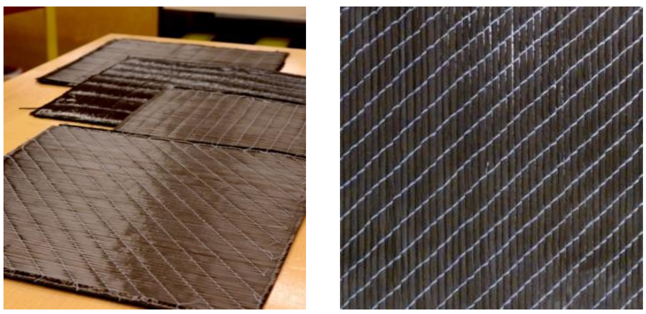

Figure 3. Carbon fibre reinforcements made using the uO-APT process (left); sourced from Saertex (right).

stitch lines in type B reinforcements cannot run parallel to either yarn direction, hence the construction and orientations specified above. As explained in the following sections, carbon yarn orientations relative to bending orientation in tests were similar for reinforcement types A and B with yarns running either parallel and perpendicular to the bending plane, or at +45° and -45° to the bending plane, in all cases. Considering tests performed on reinforcements where carbon yarns ran parallel and perpendicular to the bending plane, in the case of type A reinforcements stitch lines also ran parallel or perpendicular to the bending plane, whilst in the case of type B reinforcements stitch lines ran at +45° or -45° from the bending plane. However, considering tests performed on reinforcements where carbon yarns ran at +45° and -45° to the bending plane, it should be noted that stitch lines ran parallel or perpendicular from the bending plane for both types of reinforcements; all yarns and stitch lines orientations are stated explicitly in Section 3.3.3, for all reinforcements. Beyond stitching, all reinforcements and reinforcement stacks tested were directly comparable in terms of thickness, v_f, carbon yarn orientations and how they may be used in building composite structures.

IV. BENDING APPARATUS

The objective in designing the bending apparatus used in this work was to enable bending of reinforcements of varied thickness and v_f over a single curvature surface of constant radius, in a process similar to that induced by preforming ancillaries used in forming reinforcements in actual manufacturing of PMC parts and structures. Another central aim was to measure the evolution of the force required to do so whilst enabling direct observation of the reinforcements as they bent. The magnitude of the bending force is immaterial in most practical manufacturing situations; however, it is insightful in identifying and understanding the behaviour of the reinforcements as they are bent, in making comparisons between tests, and in enabling the detection of any instability occurring during bending tests say from fibre, yarn or textile buckling. The apparatus appears in Figure. 4. The apparatus was mounted on an Instron 4482 universal testing frame equipped with a 100N load cell. Forces and displacements measured by the testing frame were used directly; no correction to the latter was required given the small forces involved. The apparatus was designed for bending cantilevered samples over a constant radius surface to a 60° angle.

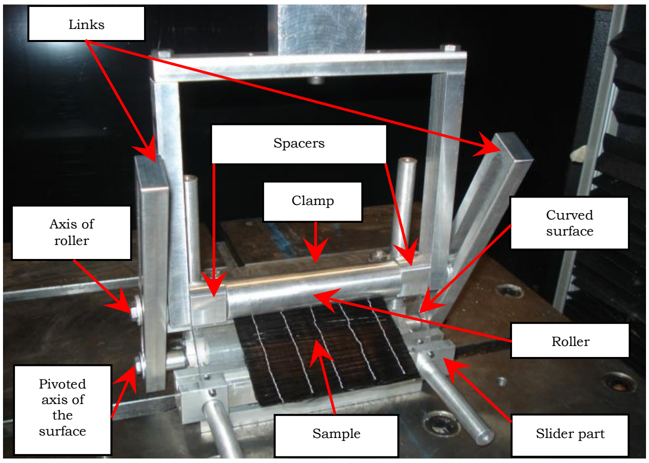

Figure 4. Bending apparatus.

In an approach similar to industrial practice reinforcement samples were bent by a low-friction roller rotated and pivoted over the sample. A thick, translucent curved surface was used enabling some visual observation of the inner side of the reinforcement during bending. Flat-sided circular spacers mounted on both sides of the roller ensured accurate fibre volume fractions in samples under the roller, during testing.

The spacers were used upon rig preparation and sample mounting, before testing; then they were rotated prior to actual testing to ensure that no friction with the curved surface occurred. The curved surface and base were attached to the lower platen of the Instron frame, whilst the roller axis was connected to the frame’s cross-head through a sturdy upper linkage. The rotation axis of the lower linkage and the axis of the curved surface were coincident. Fig. 5 identifies reference directions R0 and R90 for the apparatus, used for identifying bending orientations.

V. UOTTAWA FABRICS

Samples featuring different numbers of layers, v_f, yarn directions and stitch line orientations were tested for both reinforcements type A and type B. All sample and testing configurations are summarized in Table 1 through Table 3 for type A reinforcements, and Table 4 to Table 6 for type B reinforcements. All tests were conducted using a 50.8 mm curved surface radius. Tests conducted using type A reinforcements were classified into test groups A1, A2 and A3 where samples used in test groups A1, A2 and A3 featured 8, 12 and 8 superimposed arrays of parallel yarns respectively. Stitch lines ran at 0° and 90° from yarns in test groups A1 and A2, and at 45° from yarns in test group A3. Test groups A1, A2 and A3 were further classified into sub-groups based on v_f and thickness; 2 values of thickness and corresponding v_f under the roller were used. For groups A1 and A3, thicknesses of 2.0 mm and 1.5 mm were used leading to nominal v_f values of approximately 45% for sub-groups A1/45 and A3/45, and approximately 60% for sub-groups A1/60 and A3/60. For group A2 thicknesses of 3.0 mm and 2.0 mm were used leading to nominal v_f values of approximately 45% for sub-group A2/45 and approximately 66% for sub-group A2/66. It should be noted that nominal v_f is the same for sub-groups A1/45, A2/45 and A3/45 enabling a direct evaluation of the effect of the number of layers at constant v_f, whilst targeted thickness is the same for sub-groups A1/45, A2/66 and A3/45 enabling the direct comparison of the effect of v_f at constant thickness.

As stated above, type A tests were classified into sub-groups based on the way samples were mounted into the bending apparatus, using the orientation of stitch lines as reference. All samples were symmetrical balanced bidirectional with yarns running at 0° and 90° from stitch lines in groups A1 and A2, and at –45° and +45° from stitch lines in group A3. Tests were conducted with stitch lines running along apparatus reference directions R0 and R90 for groups A1, A2 and A3 leading to 12 type A reinforcement sub-groups A1/45/R0, A1/45/R90, A1/60/R0, A1/60/R90, A2/45/R0, A2/45/R90, A2/66/R0, A2/66/R90, A3/45/R0, A3/45/R90, A3/60/R0 and A3/60/R90. It is worth noting again that in type A reinforcements, stitch lines are not parallel to the outer yarns; in this work they can extend perpendicularly or at +/-45° from the outer yarn direction.

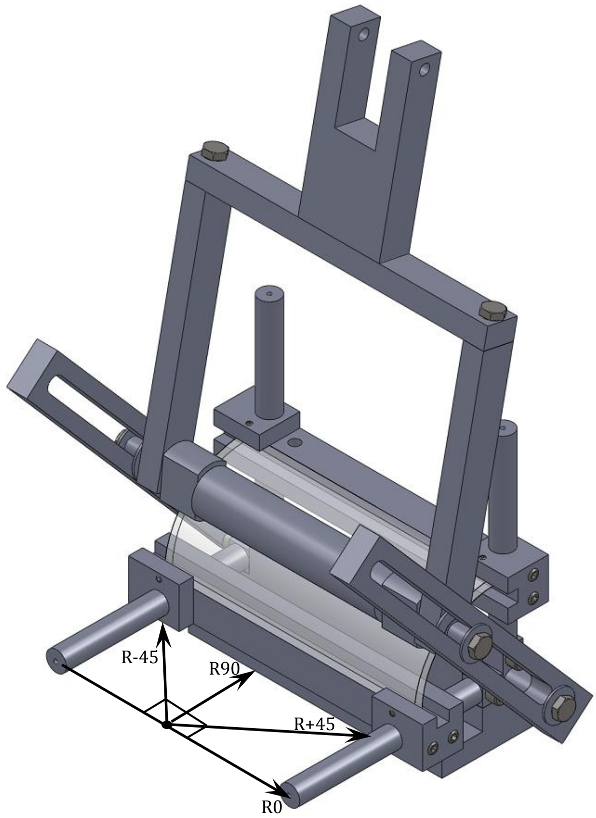

Figure 5. Orthogonal reference directions used for the apparatus.

Lastly for type A reinforcements, 3 different physical samples were used for every testing configuration and sub-group, with each sample bent for 3 consecutive cycles leading to 108 bending tests performed for these reinforcements. Sample and cycle are identified by appending to the above sub-group numbers, labels such as S1-C2 for sample 1 and cycle 2 for example. Sample data appear in Tables 1, 2 and 3 including number of superimposed arrays of parallel yarns; yarn stacking sequence expressed relatively to a 0° orientation local to the reinforcement only; stitching orientation expressed relatively to a 0° orientation local to the orientation only; set-up of the sample into the apparatus expressed using the direction of the stitch lines and apparatus reference orientations R0 and R90; reinforcement thickness imposed under the roller through spacers (*SPR*); measured sample mass; measured in-plane sample dimensions; and calculated reinforcement fibre volume fraction under the roller (v_f).

Different spacer sizes (*SPR*) were used for enforcing nominal v_f values of 45%, 60% and 66% under the roller in samples being bent. The v_f calculations for sample A1/45/R90/S1 are detailed here as an example. Sample dimensions were 102 mm by 105 mm with a measured mass (*MM*) of the sample of 17.22 g. For a spacer size of 2 mm, sample thickness of 0.2 cm leads to a v_f nearing 0.45 as shown. Assuming an even thickness throughout the sample for calculations only, the

Table 1. Characteristics of group A1 samples made from uO-APT reinforcements.

Type	Group	Arrays	Stitching	Sub-group	Sample setup in apparatus			Sample specifications			
					Stitch direction	*RR* (mm)	*SPR* (mm)	Sample No.	Measured Mass (MM) (grams)	Dimensions (mm)	v_f
uO-APT	A1	8 parallel yarn arrays - $[90/0/90/0]_S$	Along 0° in reinforcement	A1/45	R0	50.8	2.0	S1	16.36	105 x 100	0.44
								S2	15.79	100 x 100	0.45
								S3	15.27	100 x 100	0.43
				A1/60			1.5	S1	16.02	100 x 102	0.60
								S2	17.08	101 x 102	0.63
								S3	16.05	100 x 102	0.60
				A1/45	R90	50.8	2.0	S1	17.22	102 x 105	0.46
								S2	17.19	102 x 108	0.44
								S3	16.63	100 x 110	0.43
				A1/60			1.5	S1	16.33	100 x 103	0.60
								S2	16.05	100 x 100	0.61
								S3	16.93	100 x 101	0.64

volume of the sample *V* expressed in mm^3 is:

$$V = 102 \cdot 105 \cdot 2 = 21\,420 \quad (1)$$

Knowing the density of HTS40 carbon fibres as 1.76 g/cm^3 [202] the mass *m* expressed in g that the volume would have if it was occupied entirely from carbon (100% v_f) is:

$$m = V \cdot \rho = 21.42 \cdot 1.76 = 37.70 \text{ g} \quad (2)$$

The value of v_f is the ratio of measured mass *MM* to theoretical mass m at v_f = 100%:

$$v_f = \frac{MM}{m} = \frac{17.22}{37.70} = 0.4568 \quad (3)$$

Table 2. Characteristics of group A2 samples made from uO-APT reinforcements.

Type	Group	Arrays	Stitching	Sub-group	Sample setup in apparatus			Sample specifications			
					Stitch direction	*RR* (mm)	*SPR* (mm)	Sample No.	Measured Mass (MM) (grams)	Dimensions (mm)	v_f
uO-APT	A2	12 parallel yarn arrays – [90/0/90/0/90/0]	Along 0° in reinforcement	A2/45	R0	50.8	3.0	S1	24.68	100 x 103	0.45
								S2	24.07	100 x 101	0.45
								S3	23.66	100 x 99	0.45
				A2/66			2.0	S1	23.83	100 x 100	0.66
								S2	23.21	101 x 101	0.65
								S3	24.12	100 x 102	0.67
				A2/45	R90	50.8	3.0	S1	24.66	100 x 103	0.45
								S2	23.78	100 x 98	0.46
								S3	23.29	102 x 98	0.44

				A2/66			2.0	S1	24.40	100 x 102	0.68
								S2	24.31	100 x 102	0.68
								S3	24.01	100 x 102	0.67

Table 3. Characteristics of group A3 samples made from uO-APT reinforcements.

Type	Group	Arrays	Stitching	Sub-group	Sample setup in apparatus			Sample specifications			
					Stitch direction	*RR* (mm)	*SPR* (mm)	Sample No.	Measured Mass (MM) (grams)	Dimensions (mm)	v_f
uO-APT	A3	8 parallel yarn arrays - $[90/0/90/0]_S$	Along 45° in reinforcement	A3/45	R0	50.8	2.0	S1	13.55	90 x 95	0.45
								S2	15.74	100 x 95	0.47
								S3	15.58	100 x 95	0.47
				A3/60			1.5	S1	16.20	101 x 101	0.60
								S2	15.92	100 x 103	0.59
								S3	15.95	100 x 102	0.59
				A3/45	R90	50.8	2.0	S1	16.35	104 x 97	0.46
								S2	16.48	104 x 100	0.45
								S3	15.55	102 x 96	0.45
				A3/60			1.5	S1	15.97	99 x 104	0.59
								S2	16.20	99 x 105	0.59
								S3	16.47	100 x 104	0.60

A spacer *SPR* and corresponding sample thickness of 1.5 mm lead to a v_f nearing 0.60 as shown below. In this case, sample volume *V* expressed in mm^3 is:

$$V = 102 \cdot 105 \cdot 1.5 = 16\,070 \tag{4}$$

Theoretical sample mass *m* expressed in g assuming a theoretical 100% v_f becomes:

$$m = V \cdot \rho = 16.07 \cdot 1.76 = 28.27 \tag{5}$$

The fibre volume fraction of the sample is:

$$v_f = \frac{MM}{m} = \frac{17.22}{28.27} = 0.6090 \tag{6}$$

VI. INDUSTRIAL FABRICS

Tests conducted on type B reinforcements were designed for being directly comparable with the above tests conducted on type A reinforcements. They are classified into groups B1, B2 and B3. Samples used in test groups B1 and B3 featured 3 layers of 534 g/m^2 Saertex HTS40 12K fabric for a total surface density of 1602 g/m^2. Yarns aligned at [90°/0°], bonded together by pillar stitching at 45°, very closely matching the 8 arrays of parallel yarns in groups A1 and A3 reinforcements at 200g/m^2 per array and 1600 g/m^2 in total. Samples used in group B2 featured 4 layers of Saertex HTS40 12K fabric for a total surface density of 2136 g/m^2, compared with the 12 arrays of yarns in group A2 reinforcements at 2400 g/m^2 in total.

Type B tests were classified into sub-groups based on v_f and thickness, similarly to type A tests described above. For groups B1 and B3, thicknesses of 2.0 mm and 1.5 mm lead to nominal v_f values of approximately 45% for sub-groups B1/45 and B3/45, and approximately 58% for sub-groups B1/58 and B3/58. For group B2, different thicknesses of 2.7 mm and 1.8 mm lead to nominal v_f values of approximately 45% for sub-group B2/45 and approximately 63% for sub-group B2/63, enabling the same comparisons as above. Detailed information appears in Tables 4 to 6.

Table 4. Characteristics of group B1 samples made from industrial reinforcements.

Type	Group	Arrays	Stitching	Sub-group	Sample setup in apparatus			Sample specifications			
					Stitch direction	*RR* (mm)	*SPR* (mm)	Sample No.	Measured Mass (MM) (grams)	Dimensions (mm)	v_f
Saertex industrial reinforcement	**B1**	**3 layers - $[(0/90)]_3$**	**Along 45° in reinforcement**	**B1/45**	**R-45**	**50.8**	**2.0**	**S1**	**15.99**	**100 x 103**	**0.44**
								S2	**15.94**	**102 x 102**	**0.44**
								S3	**15.98**	**102 x 102**	**0.44**
				B1/58			**1.5**	**S1**	**16.36**	**101 x 103**	**0.60**
								S2	**16.40**	**102 x 103**	**0.59**
								S3	**15.17**	**100 x103**	**0.56**
				B1/45	**R+45**	**50.8**	**2.0**	**S1**	**16.17**	**102 x 104**	**0.43**
								S2	**15.68**	**101 x 103**	**0.43**
								S3	**15.67**	**101 x 102**	**0.43**
				B1/58			**1.5**	**S1**	**16.26**	**103 x 103**	**0.58**
								S2	**15.37**	**100 x 102**	**0.57**
								S3	**15.98**	**102 x 104**	**0.57**

Type B tests were further classified into sub-groups based on stitch line orientations. All samples were balanced bidirectional with yarns running at –45° and +45° from stitch lines in all groups to guarantee reinforcement integrity as per Saertex construction. Tests were conducted with stitch lines running along apparatus reference directions R–45 and R+45 for groups B1 and B2 as shown in Fig. 6, and along apparatus reference directions R0 and R90 for group B3 leading to 12 type B reinforcement sub-groups B1/45/R–45, B1/45/R+45, B1/58/R–45, B1/58/R+45, B2/45/R–45, B2/45/R+45, B2/63/R–45, B2/63/R+45, B3/45/R0, B3/45/R90, B3/58/R0 and B3/58/R90. Type B reinforcement stacks were balanced but not symmetrical, as a result of textile construction.

Three different physical samples were used for every type B testing configuration with each sample bent 3 in consecutive cycles leading to an additional 108 bending tests for type B reinforcements, bringing the total to 216 tests.

Using sample B1/45/R+45/S1/T3 as an example, the following information can be read from the tables. The sample is made from Saertex fabric and is from group B1,

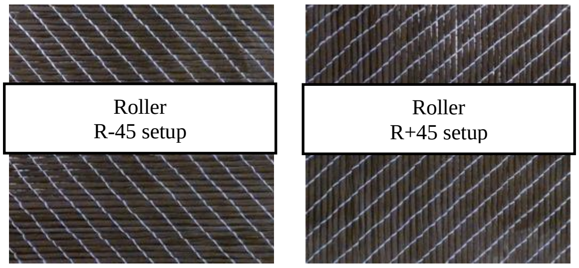

Figure 6. Stitching direction setup with respect to roller.

Table 5. Characteristics of group B2 samples made from industrial reinforcements.

Type	Group	Arrays	Stitching	Sub-group	Sample setup in apparatus			Sample specifications			
					Stitch direction	*RR* (mm)	*SPR* (mm)	Sample No.	Measured Mass (MM) (grams)	Dimensions (mm)	v_f
Saertex industrial reinforcement	B2	4 layers - $[(0/90)]_4$	Along 45° in reinforcement	B2/45	R-45	50.8	2.7	S1	21.33	103 x 105	0.42
								S2	21.36	104 x 104	0.42
								S3	21.50	104 x 105	0.42
				B2/63			1.8	S1	21.11	103 x 105	0.62
								S2	21.33	103 x 104	0.63
								S3	21.29	103 x 105	0.63
				B2/45	R+45	50.8	2.7	S1	20.66	100 x 103	0.43
								S2	21.55	103 x 104	0.43
								S3	21.55	103 x 105	0.42
				B2/63			1.8	S1	20.73	103 x 105	0.61
								S2	21.56	105 x 105	0.62
								S3	20.97	103 x 105	0.62

featuring 3 layers. The test was conducted as R+45, where stitch lines are at +45° to the roller. A nominal fibre volume fraction of 45% was enforced by the use of 2 mm spacers. S1 means that this sample was the first to be tested in its sub-group and C3 indicates that this was the third cycle in testing the same sample. Sample groups constituted from stacks of Saertex reinforcements were labelled B1, B2, and B3 to indicate that they are directly comparable with samples from groups A1, A2 and A3 made from the uO-APT process, respectively. It should be noted that the numbers of layers in samples made from stacked industrial reinforcements differed from the number of arrays of parallel yarns in uO-APT samples, due to the difference in density per array or layer between the two reinforcements.

Table 6. Characteristics of group B3 samples made from industrial reinforcements.

Type	Group	Arrays	Stitching	Sub-group	Sample setup in apparatus			Sample specifications			
					Stitch direction	*RR* (mm)	*SPR* (mm)	Sample No.	Measured Mass (MM) (grams)	Dimensions (mm)	v_f
Saertex industrial reinforcement	B3	3 layers - $[(0/90)]_3$	Along 45° in reinforcement	B1/45	R0	50.8	2.0	S1	15.71	100 x 105	0.43
								S2	15.88	104 x 104	0.42
								S3	16.03	100 x 105	0.43
				B1/58			1.5	S1	15.87	100 x 100	0.60
								S2	16.50	102 x 105	0.58
								S3	14.90	100 x 100	0.56
				B1/45	R90	50.8	2.0	S1	15.83	100 x 105	0.43
								S2	16.13	100 x 105	0.44
								S3	15.76	100 x 105	0.43
				B1/58			1.5	S1	15.53	100 x 100	0.59
								S2	16.38	104 x 104	0.57
								S3	16.30	104 x 104	0.57

As an example, samples from group A1 featured 8 arrays of parallel yarns, which compares closely to samples from group B1 in terms of total surface density. The equivalent number of layers for group B1 which gives the same fibre volume fraction at the same thickness can be calculated as follows.

Considering for example reinforcements from group B1 with a spacer thickness *SPR* of 2.0 mm, and knowing that the density of carbon fibres is 1.76 g/cm^3 [202] and that the surface density of the industrial fabric is 534 g/m^2, assuming in-plane sample dimensions of 100 mm by 100 mm or 100 cm^2 and a measured mass (*MM*) of the sample as follows:

$$MM = 534 \cdot 0.1 \,.\, 0.1 = 5.34 \text{ g} \quad (7)$$

The volume *V* of the sample expressed in cm^3 is:

$$V = 100 \cdot 0.2 = 20 \, cm^3 \quad (8)$$

The theoretical sample mass *m* expressed in g assuming a theoretical 100% v_f is:

$$m = V \cdot \rho = 20 \cdot 1.76 = 35.2 \text{ g} \quad (9)$$

Targeting a fibre volume fraction of 0.45 in the sample under the roller, the number of layers *NL* of Saertex reinforcement required for testing samples from group B1 is:

$$NL = \frac{0.45 \cdot 35.2}{5.34} = 2.966 \cong 3 \quad (10)$$

The same number of layers is required for reaching a target fibre volume fraction of 0.45 for samples from group B3. Considering reinforcements from group B2 with a spacer thickness *SPR* of 2.7 mm with other quantities unchanged, assuming again in-plane sample dimensions of

100 mm by 100 mm and a measured mass (MM) of the sample as follows:

$$MM = 534 \cdot 0.1\ 0.1 = 5.34\ \text{g} \quad (11)$$

The volume V of the sample expressed in cm^3 is:

$$V = 100 \cdot 0.27 = 27\ cm^3 \quad (12)$$

The theoretical sample mass m expressed in g assuming a theoretical 100% v_f is:

$$m = V \cdot \rho = 27 \cdot 1.76 = 47.52\ \text{g} \quad (13)$$

Again targeting a fibre volume fraction of 0.45 in the sample under the roller, the number of layers NL of Saertex reinforcement required for testing samples from group B2 is:

$$NL = \frac{0.45 \cdot 47.52}{5.34} = 4.004 \cong 4 \quad (14)$$

Similar calculations conducted for samples from groups B1 and B3 made from 3 layers of Saertex reinforcement bent with a spacer thickness SPR of 1.5 mm can be conducted, leading to a fibre volume fraction v_f of 0.58 under the roller for these samples. Further calculations conducted for samples from group B2 made from 4 layers of Saertex reinforcement bent with a spacer thickness SPR of 1.8 mm lead to a fibre volume fraction v_f of 0.63 under the roller for these samples.

VII. BENDING TESTS PROCEDURES

The bending apparatus was designed for testing samples fixed as a cantilever beam and bent over a single curvature surface of specified radius, made of translucent polyacrylonitrile (PAN). Ends of the curved surface were mounted into two slider parts which may be adjusted to fit curved surfaces of different radii in future work. Reinforcement samples were bent using a roller pivoted over the sample, above the curved surface with a predefined spacing. Spacers assembled on both sides of the roller ensured a specific fibre volume fraction in samples under the roller during testing. All apparatus parts were assembled on a base that was attached to the lower platen of an Instron 4482 universal testing frame. The cross-head of the testing frame was connected to the roller via two rigid links. As the cross-head moves downward, it pushes down on the roller, which rotates on its axis but also around the central pivot of the apparatus, coincident with the axis of the curved surface, enforcing the sample into bending over the surface and replicating an industrial preforming operation.

The actual test procedure is described step by step in the following pages using sample A1/45/R0/S1/C3 as an example. From the sample name, the following information can be gathered:

- Sample is from group A1 hence made from uO-APT reinforcement with 8 superimposed arrays of parallel yarns;
- Fibre volume fraction of 45% is enforced through the use of 2.0 mm spacers;
- Test is conducted using setup R0 hence stitch lines are parallel to roller;
- S1 indicates that sample is the first tested within its sub-group;
- C3 indicates the third cycle in testing the same sample.

The first step towards testing was to cut samples from larger reinforcement layers with specific dimensions compatible with the bending apparatus. A photograph of uO-APT reinforcement layers ready for cutting into smaller samples appears on the left side of Fig. 3.

The bending has an opening of 125 mm widthwise. Along their length, samples were cut so that they may cover a 90° angle on the curved surface once bent; curved surface radius RR on the apparatus was 50.8 mm for all tests. Typical sample dimensions were 100 mm by 100 mm. Fig. 7 shows a sample from group A1 after being cut and prepared for testing. Cutting uO-APT reinforcements was done manually using a sharp blade. The operation was somewhat difficult to conduct whilst maintaining relatively accurate dimensions for all samples; this caused some scattering in fibre volume fraction values of the samples as reported in the above tables.

The second step consisted in installing spacers that induced the required fibre volume fraction v_f under the roller during bending. In this case and for group A1, an SPR value of 2.0 mm translates to a nominal v_f of 45%.

The third step consisted in attaching the apparatus to the Instron 4482 universal testing frame.

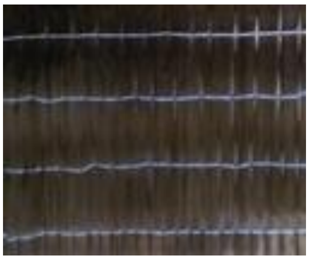

Figure 7. A bending test sample from group A after being cut.

The fourth step was to set the sample in the upper clamp of the bending apparatus so that the stitch direction would be parallel (R0) or perpendicular (R90) to roller as shown in Fig. 8.

The fifth step was to move the cross-head to its starting position, link it to the apparatus, and calibrate the load cell.

The sixth step was to start the bending test and record both the force and displacement with the help of data acquisition software Bluehill 2.0 from Instron that controls the testing frame, until the end position was reached, Fig. 9.

The seventh and final step was to return the cross-head to its starting position and repeat the procedure for the same sample, without removing the sample.

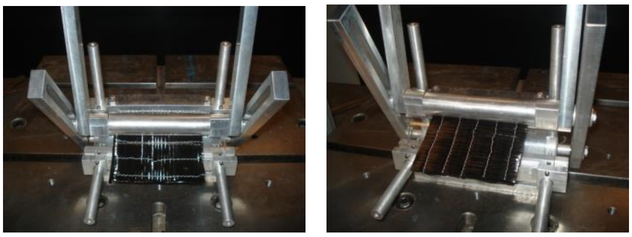

Figure 8. Bending tests samples mounted in apparatus; R0 test set-up (left) and R90 test set-up (right).

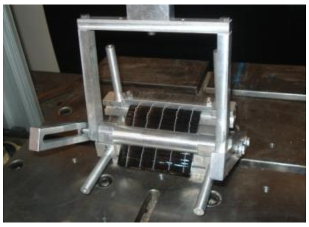

Figure 9. End position of the roller.

VIII. REPRESENTATIVE RESULTS

Curves of the bending moment as a function of the bending angle are presented here. Selected curves appear in Figure. 10 to Figure. 13. The magnitude of M_B varies up to 500 N.mm for bending angles θ ranging from 23° to approximately 60° for all samples. The angle 23° represents the value of the bending angle θ of the apparatus in its starting position. Figure. 10 shows a set of curves representative of many results obtained in this work. The bending moment increases quickly from zero to values that generally fluctuate smoothly around an average value from a bending angle of about 25° towards final bending values of about 55°. Figure. 10 shows 3 curves corresponding to 3 successive loading cycles applies successively on the same sample. Values of the bending moment decrease through the cycles, as they do for the vast majority of the results obtained.

Some curves featured specific elements of behaviour. Curves on Figure. 11 feature large pikes; these pikes can be associated directly to the passage of the roller over stitch lines in some cases where uO-APT preforms were bent in a configuration where these stitch lines were parallel to the roller axis; such pikes are not present in cases where stitch lines were perpendicular to the roller.

Curves on Figure. 12 featured smaller pikes and troughs that could not readily be associated with precise features of the textile reinforcements, although the distance may correspond more or less closely to the nominal distance between yarns or between stitch lines in industrial Saertex reinforcements; such behaviour was observed only in a limited number of cases. In many cases such as this one, a 4th bending cycle was performed on the sample aiming at confirming observed behaviour.

Curves on Figure. 13 features small-amplitude noise, or roughness; a number of curves showed such behaviour. Again in the case presented in Fig. 12, 4 bending cycles were performed.

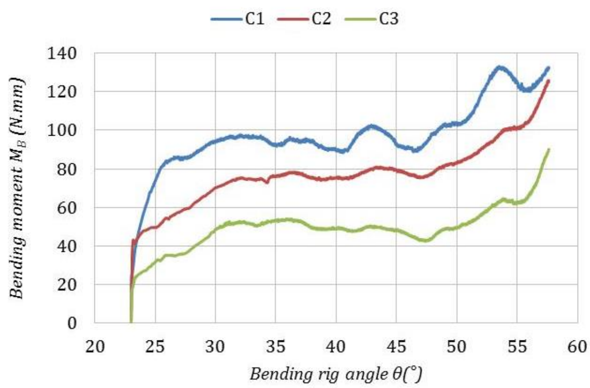

Figure 10. Curves of the bending moment as a function of the bending angle for sample A3/45/R90/S3, cycles C1, C2 and C3, representative of the results of many bending tests.

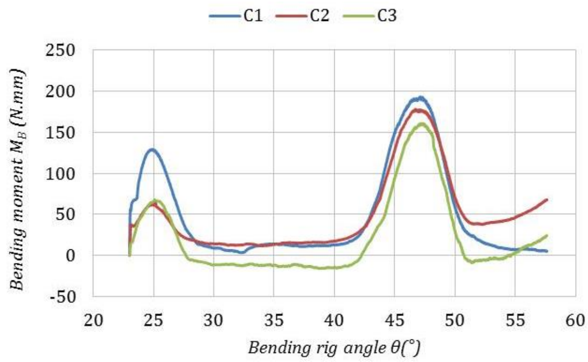

Figure 11. Curves of the bending moment as a function of the bending angle for sample A3/45/R0/S2, cycles C1, C2 and C3, featuring large pikes that can be related to stitch lines.

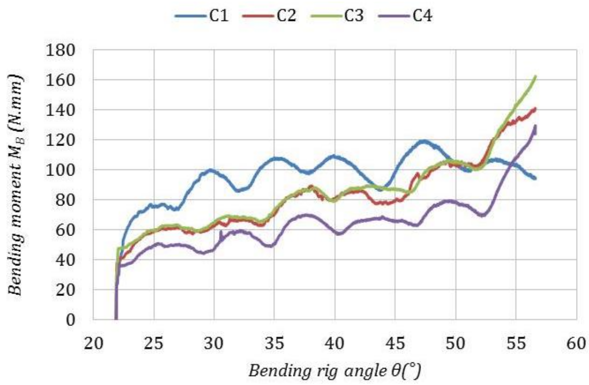

Figure 12. Curves of the bending moment as a function of the bending angle for sample A2/45/R0/S3, cycles C1, C2 and C3, featuring smaller pikes that cannot be related directly to precise features.

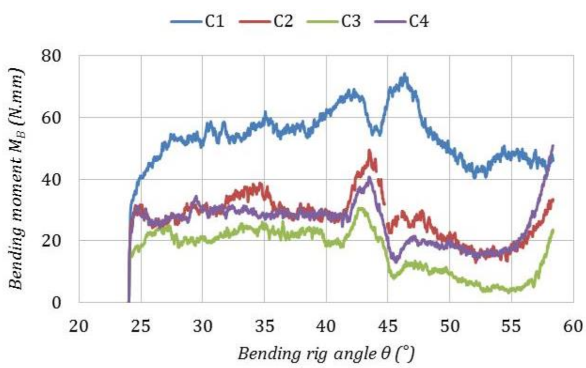

Figure 13. Curves of the bending moment as a function of the bending angle for sample A3/60/R0/S1, cycles C1, C2 and C3, featuring roughness.

IX. CONCLUSION

To define the behaviour of new preforms during forming, one of the major aspects of the response of such thick preforms that needs to be investigated is the bending behaviour. In contrast to the ASTM cantilever bending test and the KES-FB test which are not suitable for testing thick fabrics, the bending apparatus used in this work was devised to investigate the bending behaviour of thick fabrics. The newly introduced apparatus proved to be a good method that can be used to investigate bending behaviour of reinforcement of varied thickness and v_f on a single curvature. Also, the adjustable design of the bending radius enables extending the investigation to different radii.

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BIOGRAPHIES

Hafeth Bu Jldain, Dr. Bu Jldain received his Bachelor's degree in Mechanical Engineering from Garyounis University in Bengahzi, Libya in 1993. In 2005 he completed his Master's degree at Luebeck University in the field of biomechanics, Luebeck-Germany. There he created a finite element model using ANSYS software to the simulate the loading of a macerated human femur and conducted different experimental tests using tensile testing machine to measure the real material properties of the macerated human femur and compare it with the finite element model simulation results. In 2006 he accepted a post-doctoral position in the Mechanical Engineering Department at Omar Al-Mukhtar University, Al-Beida, Libya. In 2015 he finished his PhD in Mechanical Engineering at University of Ottawa, Ottawa, Canada. Dr. Bu Jldain rejoined the Department of Mechanical Engineering at Omar Al-Mukhtar University in 2016. His research interests center on using the finite elements analysis method in the fields of composites, solid mechanics and biomechanics.