LOCAL COMPRESSIBILITY OF DRAPED WOVEN FABRICS

D.S. Ivanov[1], C. Van Gestel[2], S.V. Lomov[2], I.Verpoest[2]

[1]*University of Bristol, Advanced Centre for Innovation and Science (ACCIS), Queens Building, University Walk, Bristol, BS8 1TR, UK*
[2]*Katholieke Universiteit Leuven, Department Metallurgy and Materials Engineering (MTM) Kasteelpark Arenberg 44, 3001, Leuven, Belgium*
[*]*Dmitry.Ivanov@bristol.ac.uk*

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Abstract
Thickness of infused components obtained under flexible moulding conditions is hard to control. Prior to impregnation the textile preform is constrained by a film, which pressurises the fabric when vacuum is applied. Hence, one of the important factors affecting the resultant thickness of the preform is its compressibility. Draping deformations affect the fabric properties and result in non-uniform thickness. This situation is particularly pronounced for thick components of complex shapes. This paper presents experimental measurements of yarn compaction and fabric compressibility at different draping angles, highlighting important topology features.

1. Introduction

One of the essential control issues of resin infusion is the out-of plane behaviour of draped preforms. In contrast with the RTM process where a rigid upper mould is typically used, a flexible film constraints the impregnated material when vacuum pressure is applied. Pressure imposed by the film is sometimes complemented by added weight. Drape affects the yarn architecture and the fibre volume fraction, leading to an increased stiffness of the preform. These changes may cause non-homogeneity in component thickness.
Another important aspect of fabric deformability is the resultant fibre volume fraction of the infused composite. For example in order to compete with the autoclave process, the resin infusion has to provide a sufficiently high fibre volume fraction (>60%). It is therefore important to understand what is the minimum pressure required to achieve this goal.
The current paper follows the investigations of the thickness evolution while shearing of [1] where it had been found that an increase of the fabric thickness is quite substantial – up to 100% and higher prior to wrinkling. In order to simulate the preform behaviour under mould pressure, the thickness of draped fabrics is measured using an experimental set-up similar to the one used in [2].
To have a better understanding of yarn behaviour within the compressed fabric, a yarn compression test has been conducted and has been accompanied by the in-situ measurement of

yarn widening. The results of the yarn and the fabric compaction lead to an important insight of fabric topology.

2. Fabric compaction

1.1 Experimental set-up

Four carbon fabrics have been tested: a biaxial non-crimp fabric (NCF) with chain stitching, a twill weave, and an unbalanced quasi-unidirectional (qUD) NCF and qUD weave – Table 1. All the materials are employed in aerospace applications and are manufactured by resin infusion.

Fabric	**Biaxial NCF**	**Twill fabric**	**qUD-NCF**	**qUD-weave**
Areal density, g/m^2	548	370	274	290
Stitching pattern	Chain	2×2	Tricot	Plain
Carbon tow yarns, K	12	12	12	12
Stitching/binding yarns	PES 5 Tex	n/a	PES 5 Tex	Glass, 4%

Table 1. Properties of tested carbon fabrics

Cruciform samples of the fabrics were manually sheared in a square metal frame to a predefined angle. The frame dimensions were 127 mm², which ensures that the fabric area was representative. The cross-shaped preform (the sample width measures 160 mm and the arms are 84 mm wide) was clamped to the frame by four flat aluminum bars. Each bar was tightened to the frame by two steel screws. There was one screw at each side of the sample edge so that it did not pierce the fabric. The clamping force was just sufficient to prevent fibre slippage at the maximum shear angle of 30°. Once sheared, the frame was locked by tightening the corner screws to ensure that the shear angle remains the same during the subsequent compaction testing.

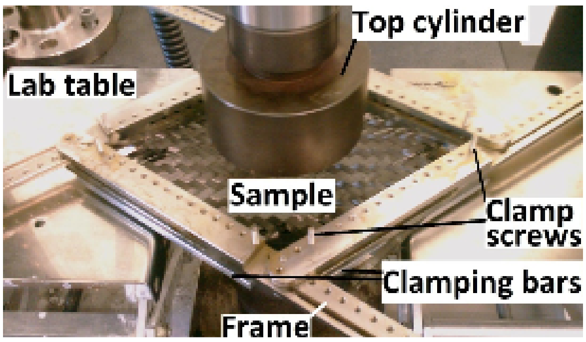


Figure 1. Compaction of the fabric sheared in the metal frame.

The sheared frame is set onto a support with an adjustable height and mounted into an Instron 5567 tensile machine with a 5 kN load cell (~0.2 N precision). A rotating platform is brought in contact with the preform so that it touches but does not rest on it. A 7 cm diameter cylinder delivers pressure into the fabric, leading to a maximum pressure of about 1.2 MPa, which exceeds the maximum pressures generally employed in the infusion process. The machine stiffness is measured prior to the test and the machine displacement is then filtered out in the post-processing of the results. The test is conducted at constant rate of 1 mm/min. Load and displacement data are recorded 10 times per second.

Each sample was cycled three times in loading/unloading to replicate the debulking process. It has been found that after the second cycle the material behaviour does not evolve substantially.

Compression curves are recorded for 0°, 10°, 20° and 30° fabric shearing. Both the single fabric layers and the double layer stack are tested. For the double layer fabric stacks, a 0°/0° lay-up is used for the biaxial NCF and a 0°/90° lay-up for the rest of the fabrics. Three samples for every material configuration have been used to verify test repeatability. A moderate scatter of the compaction curves has been observed.

1.2 Results of compaction testing

Figure 2 summarises the output of the testing. Similar trends are observed for all the studied fabrics.

(1) The curves tend to converge to a certain compressibility limit – above 5 bar further thickness reduction is nearly negligible. The rate of convergence is decelerated for the sheared fabrics. The fabrics are compacted to 30-50% of their initial thicknesses.

(2) Shearing increases the resistance of the materials. The thickness compressibility limit increases along with the shear angle. For all the considered architectures, the fabric thickness is higher for the sheared preforms compared to the non-sheared ones.

(3) As expected, nesting deteriorates the average ply thickness for any given pressure. The nested plies exhibit about 5-10 % higher compaction than the single-ply preforms. The nesting of woven fabrics is pronouncedly higher than the nesting of the NCF fabrics. The nesting of the NCF fabrics can be explained by local buckling of stitching yarns resulted from the draping.

(4) The nesting effect is more pronounced for the sheared fabrics as the topography is rougher, exhibiting higher hills and deeper valleys. The only exception is the qUD-NCF, where shearing occurs primarily due to the relative tow slippage without substantial lateral yarn interaction.

(5) Basic resin infusion operates at one bar (~0.1 MPa). At this pressure the thickness difference between a non-sheared fabric and a fabric that has been sheared to above 20° can be significant. For instance, shearing increases the thickness limit of the biaxial fabrics up to 15%. However for the qUD fabrics the difference does not exceed 5%.

(6) The initial thickness of the sheared fabric does not influence the compressibility limits. For instance, it has been found that the relative thickness reduction of the biaxial woven is higher at 20° shear than at 30°.

It is important to understand whether the difference in the compaction limit results in the correspondent evolution of the fibre volume fraction. The volume fraction is governed by two competing factors, namely the increase in areal density (proportional to the cosines of the shear angle) and the decrease in compressibility due to draping deformations. In Figure 3 the fabric fibre volume fractions are given for the nested double layer stacks.

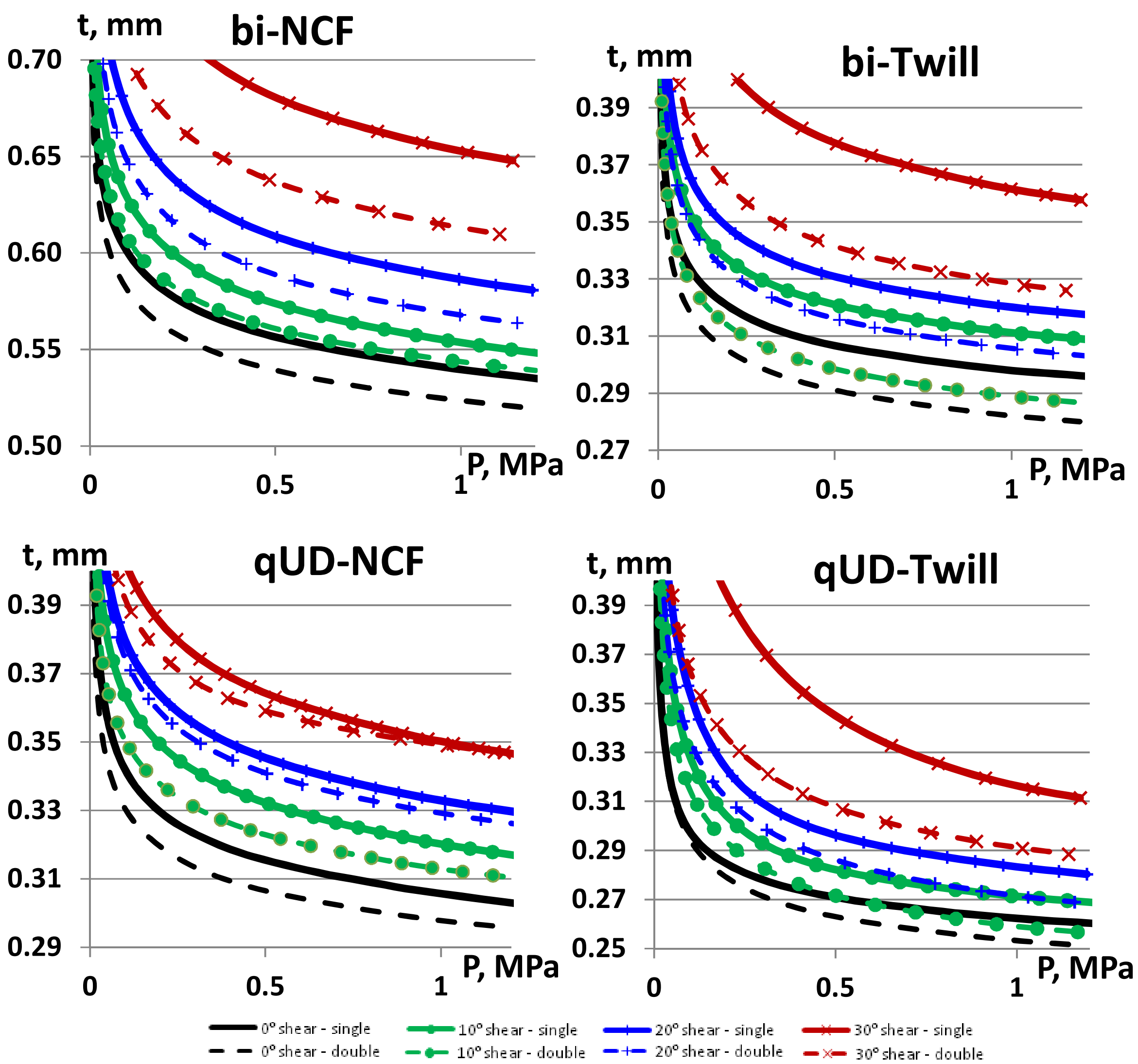


Figure 2 Average fabric layer thickness for single layers and double layer sheared stacks of biaxial NCF (bi-NCF), balanced twill (bi-Twill), quasi-UD NCF(qUD-NCF) and quasi-UD twill (qUD-Twill) .

At one bar, the fibre volume fractions of all the fabrics are close to 50%. When approaching the compaction limit, it converges to 55-60% depending on the preform. The fabric packing for 0° and 30° shear is slightly higher than at the intermediate angles. The results suggest that draping of a complex component is likely to lead to non-uniform thickness distribution rather than fibre volume fraction variation across the component length.

Micro-structural investigation of the fabrics has not detected any visible flattening of the yarns, subtle intra-yarn gap occurrence was more prevalent. It appears that a minor twist of the yarns is sufficient to prevent fibre spreading. To confirm that and to measure the inter-tow fibre volume fraction at the compaction limit, compression testing of a UD tow extracted from the biaxial twill is conducted with in-situ spread monitoring. The test routines and the results are presented in the next paragraph.

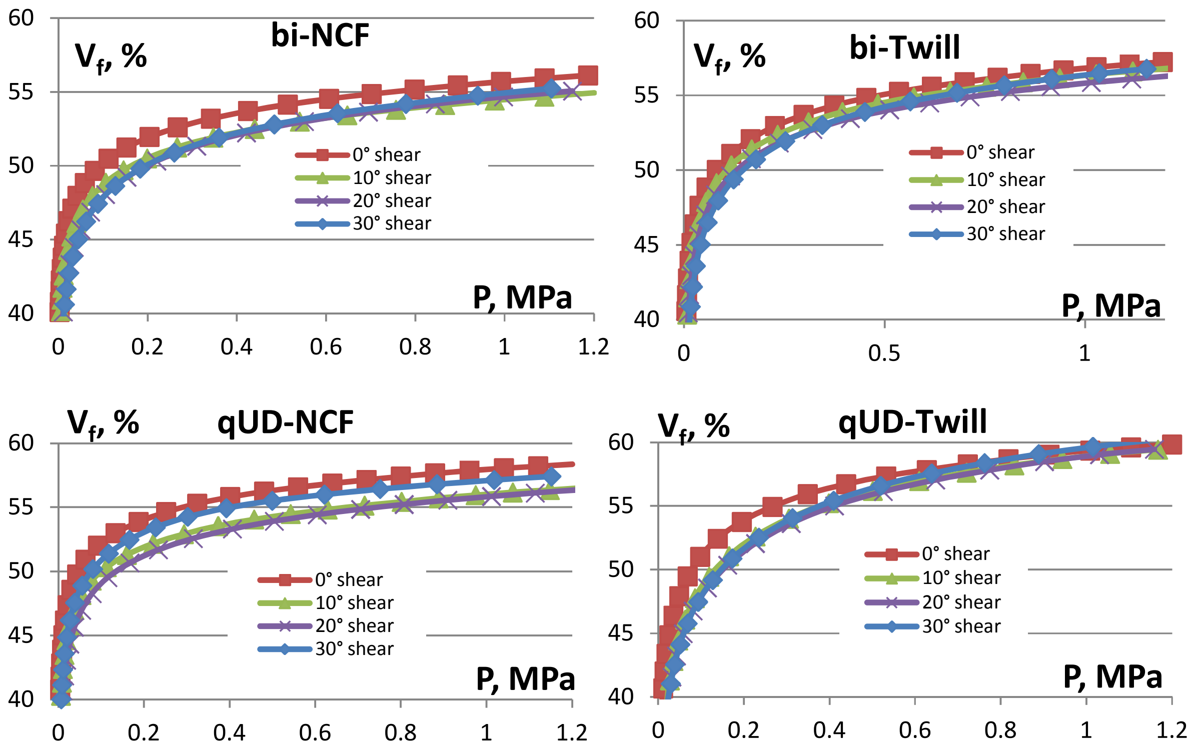


Figure 3. Fibre volume fraction of (non-)sheared double stack preforms as function of applied pressure.

3. Yarn compaction measurements

The twill could easily be disintegrated and the yarns were extracted without fibre loss, reorientation, or any other damage. The extracted 12K yarns had the width of 5 mm and the initial thickness varies in the range of 0.16-0.22 mm. The uncertainty of the initial thickness is due to crimp of the yarn, as it comes from the woven fabric. The yarns were compacted on a glass platform with an optical camera registering fibre spreading through the glass. A 1 kN load cell was mounted above a 50 mm diameter metal punch, which allowed 1 MPa pressure to be exceeded. Parallelity of the punch and the supporting glass was verified by a satisfactory level of homogeneity in the test with the use of a pressure sensor. Machine compliance was measured and eliminated in the result post-processing. Yarn widening was studied by digital image correlation (DIC), which follows the evolution of a grey-scale speckle pattern naturally created by the epoxy binder – Figure 4. The strain averaged over the width of the yarn is taken as the measure of the expansion.

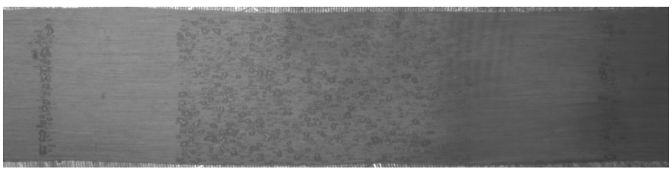


Figure 4. Yarn image as seen by the optical camera. Speckles on the surface are the binder particles. Full 5 mm yarn width is shown.

In similarity to the fabrics, the UD yarns exhibit significant compressibility evolution after debulking – Figure 5. Debulking increases the through-thickness deformation to ~5 % from the first to the second load cycle, and ~2 % from the second to the third cycle. Yarn compressibility limit of 0.13 mm is approached at ~0.3 MPa.

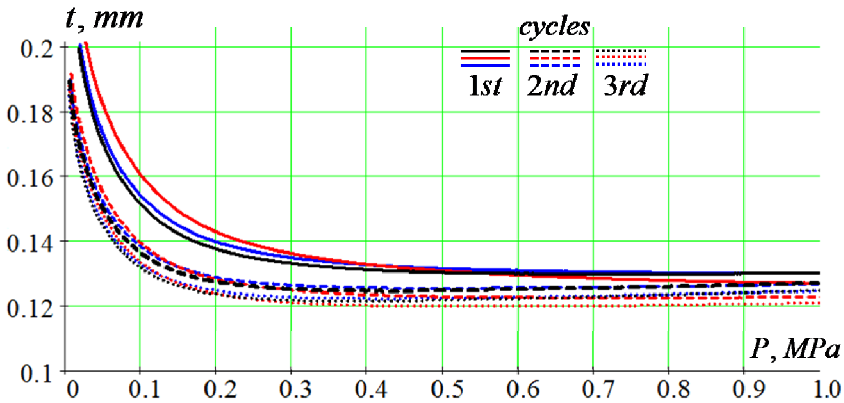


Figure 5. Yarn thickness against applied pressure

In comparison with through-thickness strain, the transverse strain develops rather slowly – Figure **6**. It is found that these yarns experience 0.8-1.0 % of the transverse expansion at 18 % applied strain. The lack of spreading may well be owed to the fact that the yarns are slightly twisted to prevent scattering of the fibre bundle. The rough surface of carbon yarns, sizing, and epoxy binder adds to the stability of the system, which becomes quite resistant to the transverse expansion.

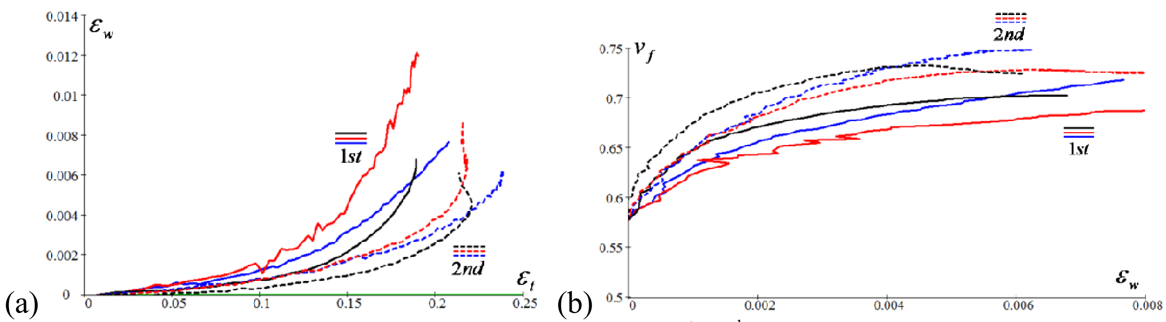


Figure 6. (a) Transverse strain versus trough-thickness strain (1st, 2nd are cycles of loading), (b) Fibre volume fraction as function of the transverse strain (1st, 2nd are cycles of loading)

The ability of the yarn to expand degrades after the first cycle, but the deformation level at which pressure locking occurs is achieved at much higher deformations.

The same observations can be expressed in terms of fibre volume fraction within the yarn. The initial fibre volume fraction is ~57 %. During the first cycle of deformation, the fibre volume fraction can reach 65-70% but does not evolve any further. After the second cycle an extra 5 % can be gained.

To study the effect of the shear frame clamping on the transverse compaction and expansion of an individual yarn, pretension has been applied. A 2kg weight was hung at the yarn end and at the location where the yarn bent over the set-up edge a silicon sheet was put underneath it to reduce friction within the set-up. A difference in compaction with the unloaded yarns was observed neither for yarn compressibility, nor for the yarn transverse expansion under compression.

4. Discussion and conclusions

Comparing the compressibility limits of the single ply twill fabric and the extracted yarns leads to an important insight to fabric topology. Conventional geometrical models of fabrics imply that yarn width is smaller than the inter-yarn distance. For balanced fabrics, the inter-yarn gap guarantees that the yarn constitutes half of the fabric thickness. However, the current experimental results show that half of the fabric limit thickness is higher than the limit thickness of an individual yarn - 0.15 mm at 0° shear and 0.18 mm at 30°. This can only be the case if the yarn width exceeds the inter-yarn distance and overlaps with neighbouring yarns of the same direction – Figure 7. In other words, the weft yarns are squeezed between two parallel warp yarns and vice versa.

In making an estimation of the final fabric thickness accounting for the yarn overlap, simple assumptions can be employed:

(1) The yarn thickness in the sheared fabric at the limit fabric thickness reaches the limit thickness of the yarn: $t_y = 0.13$ mm

(2) The inter-yarn fibre volume fraction at the compressibility limit of the fabric is equal to the fibre volume fraction of the yarn at the limit yarn thickness: $v_f =$ 0.70%.

(3) The yarn cross-sections can be roughly approximated by ellipses. Correspondingly, the yarn width must be $w = 6.26$ mm to provide the fibre volume fraction limit. It can be assumed that this width remains the same for all shear angles.

(4) The inter-yarn spacing of the fabric in its original configuration was measured for non-sheared configuration: $d = 4.23$ mm. The inter-yarn distance for the sheared configuration is estimated to be $d\cos(\alpha)$.

(5) The thickness in the centre of the overlap v is the thickness of the fabric as it represents the thickest possible location over the unit cell, which cannot be compacted any further.

As a result thickness estimation can be presented as:

$$t = t_y + 2t_y\sqrt{1-\left(\frac{d\cos(\alpha)}{w}\right)^2} \tag{1}$$

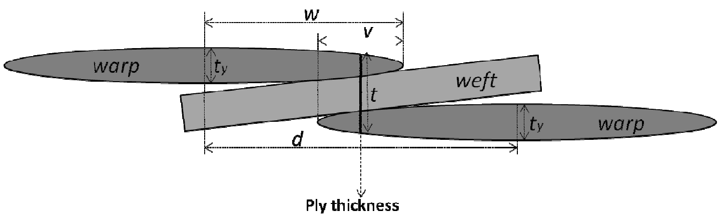


Figure 7. The scheme illustrating yarn overlap.

These elementary assumptions provide some meaningful results. They show not only the trend but also predict fabric thickness values with satisfactory accuracy – Table 2. It should be emphasized though, that this model does not aim for a precise prediction of fabric compressibility, but does illustrate the importance of modelling the right fabric topology. This is particularly important when setting up finite element models of fabrics.

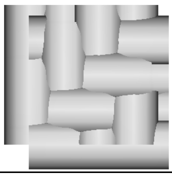
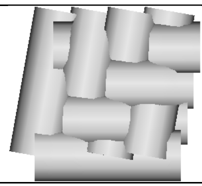
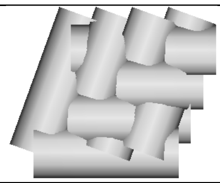
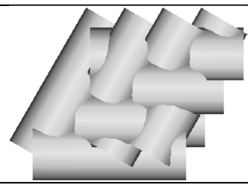
Shear angle,°	**0**	**10**	**20**	**30**
Thickness: Experimental measurements, mm	0.30	0.31	0.32	0.36
Thickness: Analytical estimation (1), mm	0.32	0.32	0.33	0.34
Illustration: WiseTex model of the sheared fabric with overlaps [3]				

Table 2. Limit thickness of single ply twill fabric at 1.2 MPa

5. Acknowledgements

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6. References

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