X-RAY ANALYSIS OF SHEARED TEXTILE COMPOSITE REINFORCEMENT

Marcin Barburski[a,b*], Xinwei Zhang[a], Ilya Straumit[a], Stepan V. Lomov[a]

[a] *Department MTM, KU Leuven, Kasteelpark Arenberg 44 B-3001 Leuven, Belgium*
[b] *Institute of Architecture of Textile, Technical University of Lodz, 116 Zeromskiego Street, 90-924 Lodz, Poland*
**marcin.barburski@mtm.kuleuven.be*

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Abstract
The micro-CT(X-ray micro computed tomography) technique is used to show the mesoscopic internal structure of the woven fabric in this paper. Simple shear is an interesting deformation mechanism for woven fabric for example during covering the mould. The internal structure change of the fabric after shear deformation is chosen as a subject of this paper. The cross section shape, area, and middle line coordinate are the main parameters that can be obtained from micro-CT scanning and image processing procedures. Change of yarns parameters during shear of a carbon fibre twill fabric is quantified. Details of the image data processing for sheared fabric cross sections are discussed.

1. Introduction

In the manufacturing process of the composite component, the forming behaviour of textile reinforcements, or fabrics, highly influences the composite quality. The forming ability of the fabric into different shapes is largely related to the fabric architecture, which would affect the mechanical properties of the composite consequently [1,2]. Simple shear and shear slip are considered as two major deformation mechanisms for fabrics. For woven fabric, simple shear is more dominant than shear slip [3-5]. Besides the influence on the forming ability of fabrics, shear deformation also influences the permeability of fabrics[6]. The forming of fabrics will induce shear deformation to the fabrics, which will change the fibre volume fraction and geometrical structure of the reinforcements. These changes will have an effect on the permeability of the fabrics and will finally influence the impregnation process. So fabric under shear deformation is chosen as a subject of the present paper. The complexity and variability of the internal architecture make micro-CT an optimum technique for the internal architecture analysis of fabrics. All in all, the measurements of yarn internal geometry of fabrics before and after shear deformation would provide useful basis for further analysis of fabric mechanical property and is of great importance for composite manufacture optimization in the future.

2. Materials and methods

The material used in this study is carbon fabric with 2*2 twill pattern provided by Hexcel Fabrics. The areal density of the fabric is 285 g/m^2.The fibre tows in both warp and weft directions are 6K, and the fibre tows are equally spaced in both directions. The parameters of the fabric are given in Table 1[6].

Manufacturer	Hexcel Fabrics
Fabric	G0986 D1200 Carbon fabric
Architecture	2*2 twill
Fabric areal density [g/m²]	285
Sett [yarns/cm]	Warp : 3.5
	Weft : 3.5
Yarns	Carbon HT
Yarns linear density [tex]	400
Type	HTA 5131 6K
Filament diameter [µm]	7
Fibre density [kg/m³]	1.78

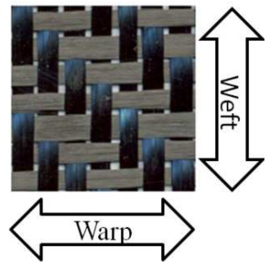
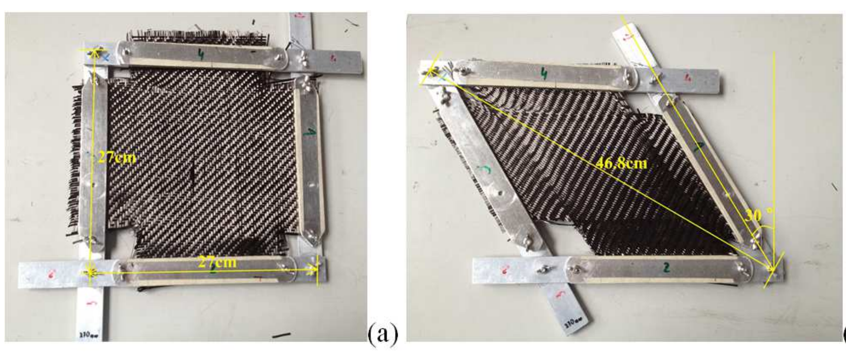


Table 1. Parameters of the carbon woven fabric [6]

To impose shear deformation on the fabric, it is cut into cross shape and fixed in a hinged rig fixture which resembles a picture frame. The frame with the size of 27*27 cm^2 consists of four fixtures in each corner. The initial configuration of frame is square, and then the configuration transformed into a rhomboid [7]. The nominal shear angle is achieved when the diagonal line length reached the pre-calculated value, for 30 degree the diagonal length is 46.8 cm. Figure 1 (a) and (b) show fabric before and after shear with shear angle of 30 degree respectively. Once the diagonal length reached the pre-calculated value, the two flexible fixtures are also fixed. And transparent tape is stick to surface of the fabric on both sides. Then the fabric is removed from the frame and cut into small sample for micro-CT. Each small sample has at least six yarns in warp direction; two sides of the sample are parallel to the weft direction. The sample set consists of a sample without shear, and samples with shear angles of 30, 45 and 50 degree.



(a) (b)

Figure 1. Fabric fixed in frame before (a) and after shear (b) with shear angle of 30 degree

The small cut-offs from the samples are used for micro-CT scanning. Skyscan 1172, located in KU Leuven, in Department of Metallurgy and Materials Engineering (MTM), is used in the work reported here. The X-ray source voltage is set to 60 kV and current to 173 µA to acquire high quality images. Besides fabric with shear angle of 45 degree, of which pixel size is 6 µm, other fabric samples all have the same pixel size of 7.6 µm. No filter was used during scanning process. The duration of the scanning depends on both sample size and parameters used; for these samples it was about 2 hours per sample. The sample rotates in the sample chamber with rotation step of 0.7 degree and a series of radiographs are taken during rotation. Skyscan reconstruction software NRecon is then used to obtain a set of equally spaced 2D slice images. Transaxial and sagittal are two orthogonal slice planes that are of interest in this paper. Figure 2 shows the optical microscopy image of fabric; transaxial and sagittal plane positions are marked in the image. For each sample, thousands of slices parallel to each plane are obtained, and then plane positions of interest must be chosen for further measurements. In figure 2, the structure of unsheared fabric (a) is more simple than of the fabric with shear deformation (b). The positions for both transaxial and sagittal planes of unsheared fabric are chosen in the same way, that is first close to the middle line of the fabric, and then the next line close to the middle line of spacing between two adjacent yarns. However, for the fabric with shear deformation, the cross-sections of yarns in each slice is hard to distinguish from each other. As in figure 2(b) the slices plane may not be equally spaced, but the slices with clearer cross section of yarns are preferred. This is also applied to fabric with other shear angles. For each sample, nine slice plane positions are chosen for both transaxial and sagittal planes.

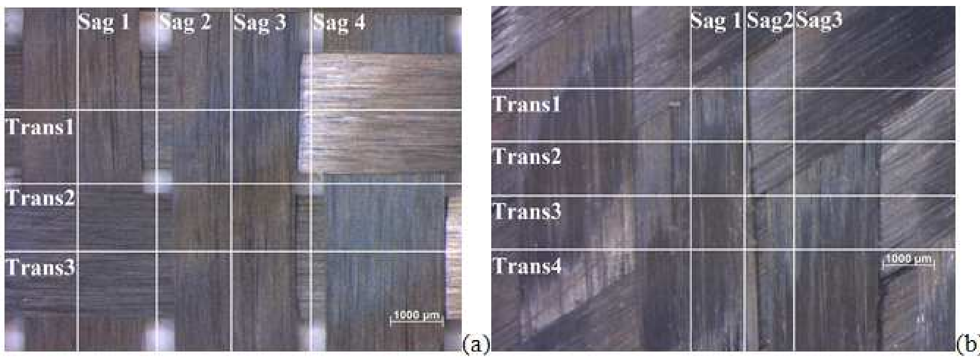


Figure 2. Optical microscopy image of fabric with cross section positions labelled in the image, (a) fabric without shear, (b) fabric with shear angle of 30 degree, Trans = transaxial and sag = sagittal

After slice planes are chosen, the image analysis procedure for the cross section of yarns is carried out the ImageJ software. The yarn shape, geometric centre of yarn and area of yarn are parameters of interest. The measuring procedure has two basic steps. First is outlining cross section shape by freehand drawing option and measure the centre coordinates, area and aspect ratio automatically after setting the parameters to be measured. Second is using "fit ellipse" operation to fit cross section of the yarn to an ellipse, and then measure the major and minor length, aspect ratio and area of the ellipse shape. The shape of the cross section of yarn is close to ellipse and the fitting step is based on the same area of the initial shape, then in further measurements "fitting ellipse" operation is used. Figure 3 shows the initial outline of a yarn drawn by hand (a) and the fitted result (b).

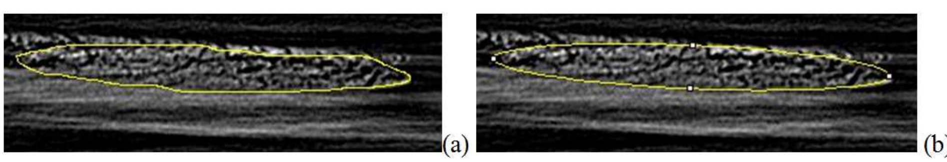


Figure 3. Cross section of the same yarn in a transaxial slice plane, (a) drawn by hand, (b) fitted result

Similarly, the cross sections in sagittal slices can also be measured. For each slice, at least 4 yarns can be distinguished from each other. While the cross sections in slices may not be real cross sections of the yarns, 2 major corrections should be made. The first is the cross sections of warp yarns in sagittal slices. Figure 4 shows the fabric under shear deformation is scanned by micro-CT. The sagittal plane is not vertical to the warp yarn direction, and then the cross section measured in sagittal plane should be corrected. It is assumed that the minor length of the ellipse does not change, but the major length of the ellipse is changed with different shear angle θ. The major length is proportional to cos(θ) due to the geometrical relationship as shown in equation (1). Then aspect ratio, which is defined by major length divided by minor length is also proportional to cos(θ), shown in equation (2). And area, which is defined by pi multiplied by product of major length and minor length， is also proportional to cos(θ), shown in equation (3). All sagittal slices should be corrected with cos(θ) for major length, aspect ratio and area with corresponding shear angle.

$$a_2 = a_1 \times \cos\theta \tag{1}$$

$$\frac{a_2}{b_2} = \frac{a_1}{b_1} \times \cos\theta \tag{2}$$

$$S_2 = \pi \times a_2 \times b_2 = \pi \times a_1 \times b_1 \times \cos\theta = S_1 \times \cos\theta \tag{3}$$

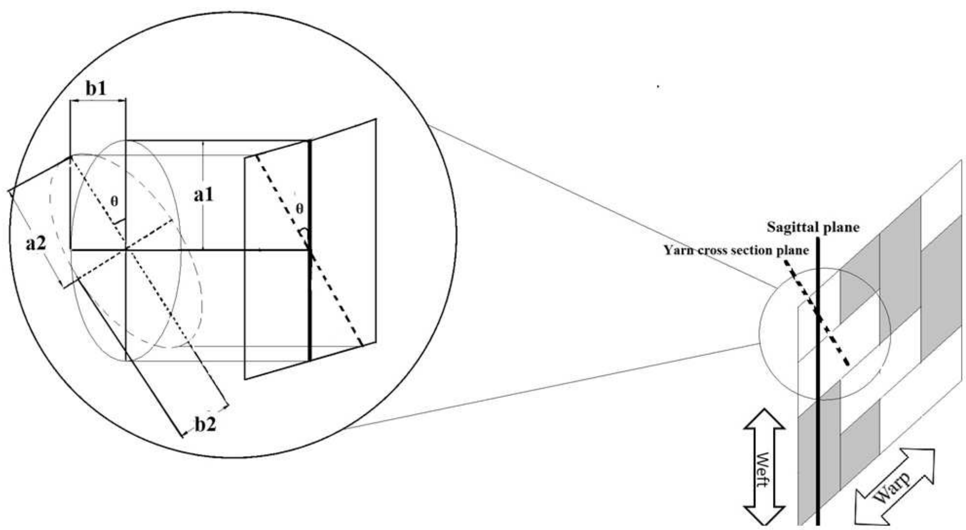


Figure 4. Schematic presentation of correction for warp yarn cross section, right is a macroscopic image and left magnifies a part of the right one, white and gray represent warp yarn and weft yarn respectively

A similar correction procedure is needed for both transaxial and sagittal slices obtained from micro-CT. As shown in figure 5(a), take the warp yarn as an example, due to the existence of two weft yarns, the warp yarn turns to crimp, and the angle is measured as α. The crimp angle is measured by ImageJ as shown in Figure 5(b). This angle is much smaller than shear angle. The maximum crimp angle is around 8°, cos(8°)≈0.990, which means that the correction is quite small. The crimp angle for each sample is measured separately, but the cos(α) is all around 0.99, then the measured results for crimp angle will not be covered in this paper. Equations for correction are also in the same form as shown before.

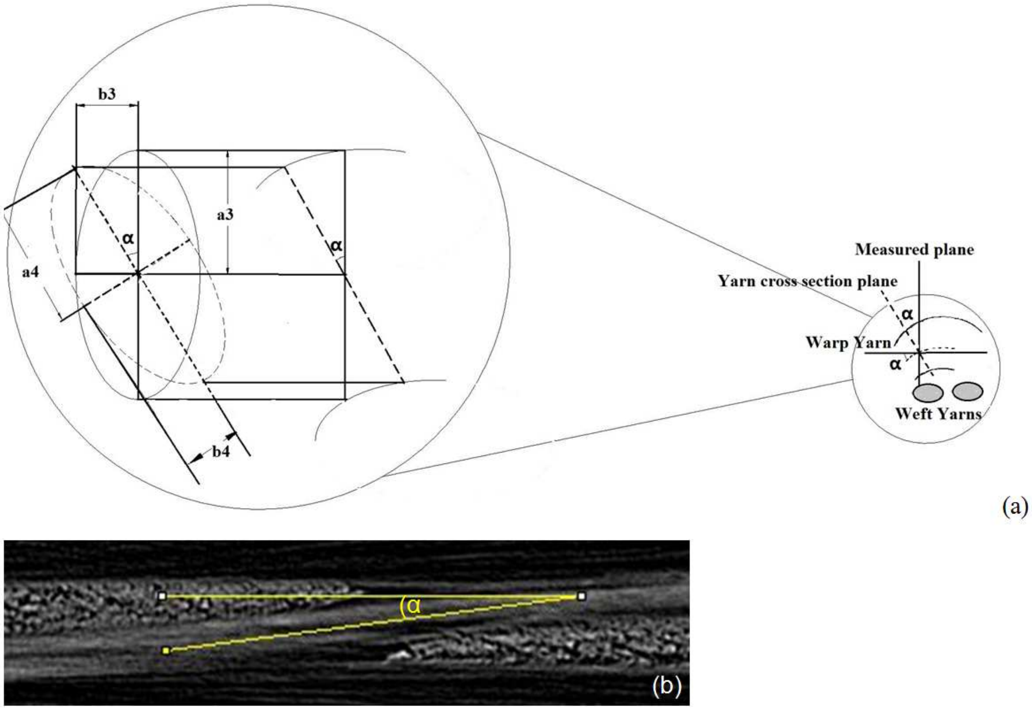


Figure 5. (a) is schematic presentation of correction for crimp, (b) shows crimp angle measured by imageJ

$$a_4 = a_3 \times \cos\propto \quad (4)$$

$$\frac{a_4}{b_4} = \frac{a_3}{b_3} \times \cos\propto \quad (5)$$

$$S_4 = \pi \times a_4 \times b_4 = \pi \times a_3 \times b_3 \times \cos\propto = S_3 \times \cos\propto \quad (6)$$

3. Results

Apart from the micro-CT scanning, the fabric was also inspected by means of optical microscopy and scanned with digital desktop scanner. Figure 6 shows how fabric structure changes with increase of shear angle. The initial fabric has some spacing between the weft and warp yarns (a), but weft and warp yarns come into contact with each other beyond shear angle of 30º. The structure becomes more condensed and it can be easily seen from figure 6 that the number of yarns inside the 2 cm interval is increasing. Due to the existence of lock-up angle, fabrics with the shear angle of 45º and 50º have some wrinkling in some places of the fabric. These also can be seen from figure 6, which shows unequally placed yarns inside the same fabric. This may cause the shear angle to become not uniform and may also bring in other deformation mechanisms rather than simple shear. All in all, shear deformation not only influences the yarn structure in warp or weft direction, but also may bring in contact between yarns in two directions and may also bring in complex deformation pattern when the shear angle is larger than lock-up angle.

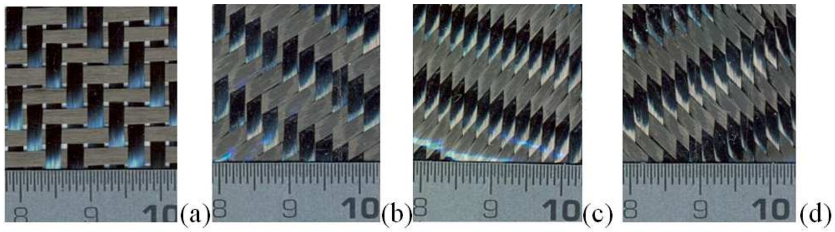


Figure 6. Fabric with shear angle of 0º(a), 30º(b), 45º(c) , 50º(d) scanned by a table scanner

The micro-CT also gives the similar results for fabric under shear deformation. Figure 7 shows several sagittal slices of fabric under different shear angles. It is clear that fabric without shear weft yarns (with ellipse shape) can be easily distinguished from warp yarns (with wavy line shape). But yarns in two directions become more close to each other and for larger shear angle, it is hard to distinguish yarns in one direction from yarns in the other direction. This will bring in extra difficulty in recognizing the yarns and measuring the yarns' cross-section parameters. The manual measuring procedure is time-consuming and difficult, so automatic recognition of yarn structure may be worthwhile studying for future work [8,9]. And the yarn shape has also changed from ellipse to more random shape, which may be caused by the contact between the adjacent yarns.

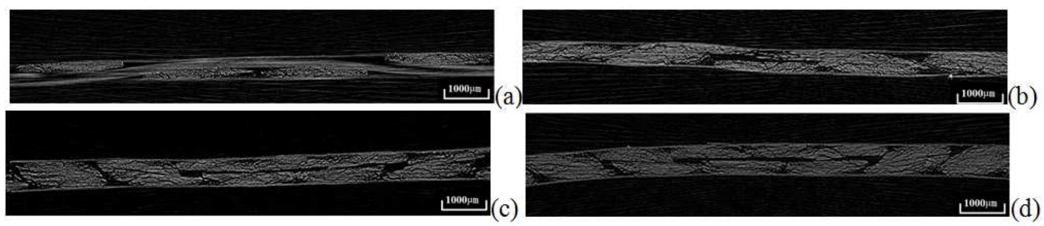


Figure 7. Fabric with shear angle of 0º(a), 30º(b), 45º(c) , 50º(d) scanned by micro-CT in transaxial plane

The measurements done by scanner, optical microscopy and micro-CT are compared in the following way. The weft yarn width of fabric becomes smaller due to the interaction between the adjacent yarns. The width can be directly measured in the images obtained with scanner and optical microscopy, while the yarn width is considered to be the major length of the ellipse in the micro-CT image for weft yarn. The width is represented in figure 8, which takes fabric without shear deformation as an example.

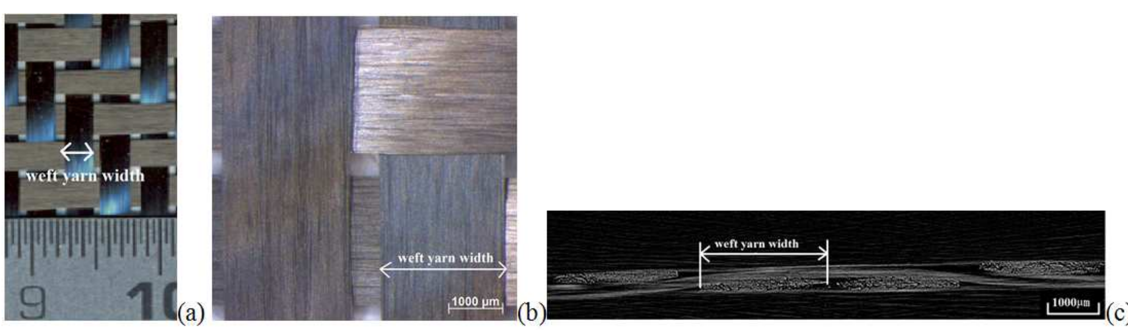


Figure 8. Weft yarn width represented in images obtained with scanner (a), optical microscopy (b) and micro-CT in transaxial plane (c)

The weft yarn width is measured in these three kinds of scanning technique and the results are quite close to each other according to figure 9. The width is calculated by averaging width of all the measureable positions inside one fabric.

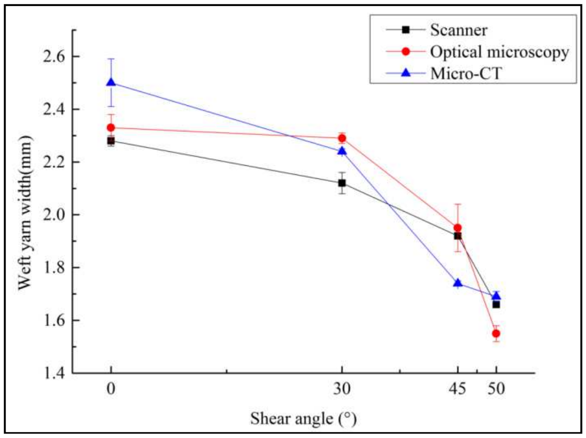


Figure 9. Weft width length measurements done by scanner, optical microscopy and micro-CT

Besides the weft yarn width decrease, due to the shape change and more condensed pattern of the fibres inside the yarn, the area of weft yarn also decrease according to the area measurements from the micro-CT image. The area mentioned in figure 10 is also the average value of the weft yarns inside one fabric.

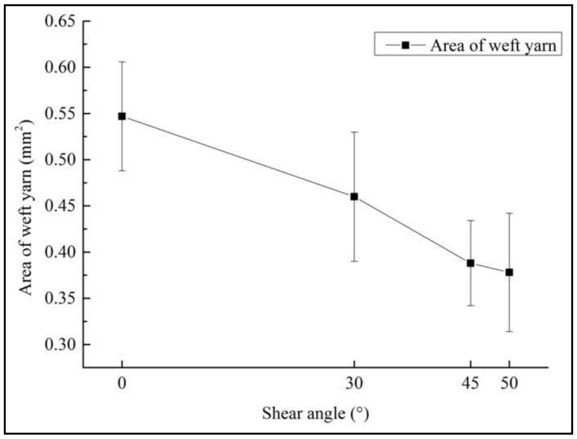


Figure 10. Area of weft yarn measurements done by micro-CT

As for the minor length of yarn, which can only be measured from micro-CT, the results show that it does not change that much as major length. The difference of minor length for different shear angles is less than 0.1 mm and has the same order of magnitude for its standard deviation.This may be due to the fact that the initial structure is more loose in major length direction, while the fires in minor length direction are more condensed, then shear changed little in the minor length.

The warp and weft yarns should be the same due to the balanced structure, but the measurements showed some difference between the two directions. This may be due to the manufacturing process and may also be caused by the flexible structure of the fabric.

4. Conclusion

The micro-CT as a non-destructive technique is widely used in analysing the internal structure of fabric. The 3D images obtained with micro-CT make it easier to observe the complex structure of inspected object than standard microscopy techniques, which only gives 2D image slices. In this paper, carbon woven twill fabric was analysed. The geometrical parameters of yarns in each image were measured with ImageJ. After shear deformation, the cross-sections of yarns not only changed their shapes but also changed their geometrical parameters as well. The weft yarn width and the area of yarn decrease due to a more condensed pattern of the fibres inside the yarn. The data on centre coordinates of yarns together with area could be further used to build the 3D textile structure with other software. The measurable geometrical parameters under shear deformation could be further used in estimating the permeability and other mechanical behaviours of the reinforcements.

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