Using micro-CT to quantitatively validate the textile compaction simulation

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Abstract. The results of any dry textile compaction simulation have to be validated. Micro-CT is a perfect tool to facilitate such a task. By performing an equivalent dry textile compaction experiment inside a micro-CT, the actual deformation and placement of fibrous tows can be captured within a sample as it deforms. The resulting micro-CT images can readily be used to qualitatively validate a compaction model. This work presents a set of methodologies to facilitate a straightforward quantitative comparison between a micro-CT sample and an equivalent compaction model. The images from the micro-CT and the compaction models are subjected to various image processing techniques that are implemented in MATLAB. The program is designed to allow a user to process the images in a consistent and semi-automated manner while minimising the manual labour time. Various cross-sectional parameters of the tows at each image slice are computed automatically using an algorithm that can handle any arbitrarily shaped cross section. By presenting the computed data as a series of Excel files and 3D plots, this work concludes that micro-CT can be used to conveniently quantitatively validate the result of compaction models.

1. Introduction
The permeability of textile reinforcements is a critical model parameter for any mould filling simulation software. A complete simulation chain to predict the textile permeability can be broadly broken down into three logical steps: textile modelling, textile compaction simulation, and flow simulation. Due to the dominant influence of textile flow channel geometry on the predicted permeability, a textile compaction model that can capture realistic tow deformation behaviour is of utmost importance. Such a model needs to be validated both qualitatively and quantitatively. Over recent years, micro-CT has emerged as a reliable tool to perform qualitative validations because of its ability to capture the actual geometry of textile stacks at various compaction levels [1-3]. Its potential for quantitative validation has been hindered by the insufficient image contrast for automatic image segmentation. Bale et al. [4] coated carbon fibre preforms with SiC by chemical vapour infiltration technique before scanning the samples under micro-CT to have better observations of the tow boundaries. Template contours were drawn manually along the tow boundaries before fitting ideal ellipses that allowed various measurements of tow parameters. Pazmino et al. [5] analysed a single layer of E-glass non-crimp 3D orthogonal woven reinforcement under micro-CT. The cross-sectional shape of the tows was outlined by six points that allowed various geometric parameters of the tows to be measured using a convex envelope algorithm. Barburski et al. [6] studied the micro-CT images of twill-weave carbon fabric. The tow boundaries were outlined by a free-hand drawing operation followed by fitting ideal ellipses to these outlines. All of these
works, however, did not show how explicit quantitative comparison between the micro-CT images and the compaction models can be made. Furthermore, most works relied on having nearly elliptical tow cross sections so that ideal ellipses can be fitted to extract width and thickness information. This work addresses these issues and also means of minimising manual labour time.

In this work, a series of image processing techniques are executed in MATLAB to analyse the images of both micro-CT and compaction model. A convenient free-hand drawing technique is used to outline the tow boundaries from the micro-CT images. The tow boundaries from the compaction model are outlined automatically using MATLAB’s inbuilt edge detection function. An in-house algorithm allows both the width and thickness information to be extracted from any arbitrarily shaped tow cross-section. Finally, all of the outlined cross sections and the associated geometric parameters are summarized in a series of Excel files and 3D plots for aid of comparison.

2. Material and micro-CT scanner
The material used in this study was an 800 GSM E-glass plain weave. Several 40 mm diameter preform samples were prepared and scanned with a GE® Phoenix Nanotom device available in the Khalifa University of Science and Technology [7]. The device has a 40 mm diameter compaction fixture with a load cell capacity of 5 kN. The circular samples were compacted in this fixture at a crosshead speed of 5 mm/min to a certain compaction level and then paused to relax. For each sample, after sufficient stress relaxation was achieved, scanning was done at 25 µm voxel size. This installation allows the same compacted sample to be further compacted, relaxed and scanned, thus enabling the deformed shape of the same sample to be observed at various compaction levels.

3. Processing micro-CT images
The raw micro-CT images were subjected to various image processing techniques, automatically executed within MATLAB. At the beginning of the program execution, a graphical user interface (GUI) allowed the user to enter basic inputs which include the initial image, the final image, the total number of images, and the total number of fibrous tows to be analysed. As will be explained later, the user has the flexibility to choose which tows in the images to be processed. The general processing methodology is presented below. The program was designed to process a series of images along one tow direction (weft or warp) at one time instant (the geometry at different times can be analysed in the same way).

3.1. Image enhancement
The raw grey-scale micro-CT images needed to be enhanced to allow accurate identification of the tow boundaries. Based on the initial input from the user, the program automatically chose the set of images to be processed and ordered them based on their names. Each image was complemented such that the dark regions become lighter and the light regions become darker. Following this, the image contrast was enhanced by saturating the bottom 1% and the top 1% of all pixel values. This percentage was determined by trial and error and can be adjusted as wished. An example of raw and processed images is presented in figure 1(a) and 1(b), respectively. Notice how the tow boundaries in the raw image are very difficult to discern and how the image enhancement process improved their visibility and sharpness significantly.

![Figure 1](image_url)

**Figure 1.** Comparison of the (a) raw and (b) processed micro-CT image.
3.2. Identification of tow boundaries
Following the image enhancement process, the tow boundaries were ready to be located. An interactive GUI was created to allow the user to perform free hand drawing to outline the tow boundaries at every chosen image. The order in which the user outlines the tows defines the tow IDs (numbered sequentially) and this is established when processing the very first image. Therefore, when outlining the tow boundaries of subsequent images, the user must be consistent with this established order. The GUI allows zoom and undo operations, allowing for a robust and accurate outlining process. Following this outlining process, both the centroid location and the area of each tow cross section of each image were determined and recorded automatically. Figure 2 shows an example of the result of these procedures, showing the drawn tow outlines and the identified centroid locations.

![Figure 2](image-url)

**Figure 2.** Drawn tow outlines and the identified centroids.

3.3. Geometric measurements
From the boundary location process described previously, the locations of the pixels that made up the tow boundaries were recorded which allowed various cross-sectional parameters (width, thickness, and angle of rotation) to be computed automatically. The algorithms to compute these geometric parameters must be able to handle any arbitrary cross-sectional shape in a consistent manner. The geometric data were then stored for later 3D visualization and written to a series of Excel file. In the following, the methodologies to compute these geometric parameters are outlined.

#### 3.3.1. Width and angle
To compute the width of a particular tow cross section, the coordinates of the most left and right pixels were identified. It was found in some cases that there was more than one pixel along the same vertical line at these extreme positions. To address this issue, the y-coordinates of these pixels were averaged to give a unique pixel coordinate at each extreme position. The width was then computed as the magnitude of the line connecting the (y-averaged) coordinates at the left and right-most position of the tow boundary, by Pythagoras’ theorem. An example of such a connecting line is shown in figure 3. Following this, the angle between the connecting line and the global horizontal axis gave the measure of cross sectional rotation.

![Figure 3](image-url)

**Figure 3.** The width and thickness lines

#### 3.3.2. Thickness
To compute the thickness of a particular tow cross section, the midpoint of the connecting line described previously was computed. From this midpoint, a perpendicular line (refer to figure 3) was drawn out in both directions until it hit the identified tow boundary. The distance between the two points of intersection gave the measure of tow thickness.

![Figure 4](image-url)

**Figure 4.** Raw cross sectional image captured by HyperView
4. Processing images from the compaction model
The dry textile compaction simulation was done in ABAQUS. To allow both quantitative and qualitative comparisons with the micro-CT images, it is desirable to extract the same geometric parameters from the deformed textile model as for the micro-CT images presented in section 3. The general processing methodology is presented below.

4.1. Image extraction
The ABAQUS output (.odb) file contained the information of the textile deformed geometry. This file was imported into HyperView™. HyperView™ allows the current view at its viewport to be exported as an image file. This way the cross-sectional pictures at various locations within the deformed textile model were extracted. The user has the flexibility to control the number of cross-sectional pictures along the direction of interest (weft or warp) by using the in-built options within HyperView™. Once this direction of interest is chosen, the deformed tows running in the other direction (warp or weft) were removed manually by the user for easier analysis in the subsequent steps. Figure 4 illustrates an example of a cross sectional image captured by HyperView™ from a compacted 4-layer non-nested plain weave stack. The images extracted from HyperView™ were then inputted to MATLAB to be processed.

4.2. Image preparation
Since the extracted images came from a simulation, the colours of the tows and the background could easily be made distinct. This allowed for automatic image segmentation to isolate individual tow cross section as can be seen in figure 5(a). Minor modification to the binarised images were made to remove the incomplete tow cross section connected to the image boundaries. An algorithm was employed to detect for any object connected to the image boundaries and to delete them. The final cleaned image can be seen in figure 5(b).

4.3. Identification of tow boundaries
Referring to figure 5, the identification of tow boundaries was simpler than for the micro-CT analysis. Instead of applying the free hand drawing algorithm as done for micro-CT images, Canny’s edge detection algorithm [8] was employed to identify the tow boundaries. Following the edge detection procedure, information such as the tow centroids, the tow areas, and the minimum rectangles enclosing individual tow cross section were readily computed and recorded. Using a GUI, the user assigns IDs to each tow by clicking on the tow cross sections in the very first image, from the preferred first to last cross section in an orderly manner. For the subsequent images, the program can keep track of the tow IDs automatically. For example, consider a tow cross section with a tow ID=1 in the ith image. For the (i+1)th image, the program computes the distance between the centroid of image i, ID=1 and the centroids of all tow cross sections in the (i+1)th image; the cross section which results in the minimum distance is considered to be image i+1, ID=1. Figure 6 shows an example of the identified tow boundaries from the edge detection algorithm, super imposed on the original grey-scale image. The tow edges and centroids were accurately identified. The numbers located near the centroids corresponds to the user-assigned tow IDs.

![Figure 5. The binarised images from the compaction model (a) before and (b) after boundary cleaning.](image-url)
4.4. Geometric measurements
Following the previous steps, the location of the pixels that made up the tow boundaries at each image are available which allowed the measurements of various cross-sectional parameters (width, thickness, and angle of rotation). To understand the methodologies to compute these parameters, the reader is referred back to section 3.3. The whole computation process was completely automated.

5. Results
In the previous sections, slightly different approaches were adopted to process the images from the micro-CT and the compaction model. At the end, both approaches resulted in the same data type that could be processed and presented in an identical manner. This way, direct comparisons between a real sample and a compaction model can be carried out rationally. The results are gathered and can be presented as a series of 3D plots and excel files. Figure 7 shows an example of such a 3D plot from processing the micro-CT images. The plot shows the 3D centreline path of a particular tow from the micro-CT sample. The discrete user free-hand drawn tow boundaries distributed along the tow centreline are also shown. The centroid coordinates are also presented for completeness sake. For convenience and ease of visualisation, the variation of the geometric parameters (width, thickness, and angle of rotation) can be displayed using colour transition along the tow centreline, which can be interpreted from a colour bar/legend besides the plot. In this example, the colour transition refers to the variation of tow width. Figure 8 shows the equivalent 3D plot of a tow from the compaction model. In this case, the discrete tow boundaries along the tow centreline correspond to the boundary pixels determined by the edge detection algorithm. Both figures can be opened in MATLAB simultaneously and rotated for better visualization. In addition to these plots, a series of similar 3D plots that contain all of the tows are readily produced.

Figure 6. Drawn tow outlines and the identified centroids from compaction simulation.

The boundary pixels identified from the edge detection algorithm did not distinguish which tow cross section the tow-slices belongs to. Hence, an extra assignment step was necessary. The minimum bounding rectangles obtained from the edge detection algorithm were used to isolate/crop each tow cross section from the cleaned binary image (figure 5(b)). Each of the cropped binary images contained the information of a complete tow cross section (from which the minimum bounding rectangle was calculated) and (possibly) some incomplete tow cross sections from the adjacent tows in its close proximity. These unwanted cropped parts were cleaned using the same algorithm that transformed the figure 5(a) to figure 5(b). By performing this extra step, the boundary pixels that corresponded to a particular tow cross section could be assigned to that cross section.
6. Conclusions

This work has presented a set of methodologies to extract the geometric parameters of fibrous tows from micro-CT images and textile compaction models. These methodologies are coded and implemented in MATLAB to create a consistent and semi-automated image processing program that minimises the manual labour time. Due to the insufficient contrast available in micro-CT images, the boundaries of tow cross sections are difficult to discern automatically, and so are captured using a free hand drawing algorithm that allows zoom and undo operations. The tow colours from the compaction model can be freely adjusted which allows image segmentation and edge detection algorithms to be executed automatically. The program allows important tow cross sectional parameters (width, thickness, and
angle of rotation) to be computed for any arbitrarily shaped cross sections, in a consistent fashion. The geometric data of each tow cross section at each image are then stored. A series of 3D plots are readily produced using MATLAB. These plots show the 3D tow paths along with the identified tow cross sections. The variation of the geometric parameters can be added by having a colour transition along the tow paths. The same computed geometric parameters are also stored in a series of Excel files should the user wish to perform further analysis and of the data. Using these approaches, it has been demonstrated that it is possible to make a qualitative and a quantitative comparison between a micro-CT sample and a textile compaction model.

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