A Novel Method for the Determination of Fibre Length Distributions from µCT-data

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Abstract

The determination of fibre length distributions (FLD) is especially important for modelling plastic deformation and the subsequent fracture of long fibre reinforced polymers (LFRP). Quantification of FLDs with non-destructive testing methods is currently an important challenge in material science. At present, reliable results can only be produced by optical measurements after incinerating the polymer matrix and the subsequent separation of each fibre. Fibre length distributions from µCT-data, especially of long fibre reinforced polymers, do not offer precise data as tracking algorithms can lose connected fibre paths leading to a bias in the FLD. To overcome such shortcomings, the algorithms implemented in this contribution incorporate the local orientation data of the image to improve the results of segmentation approaches and apply tensor-voting methods to distinguish noise or particles from fibres. For validation, artificial images were used as well as µCT-scans, which were validated manually.

First results show that erroneously connected or branched fibres could be corrected by the self-developed software to improve the precision of measured FLDs in the investigated samples. For the sake of completeness it has to be pointed out that large test samples have to be cut into smaller pieces to receive the necessary resolution of µCT-images and thereby many fibres are initially shortened. Nevertheless, the algorithm presented within this work provides reasonable data and has high potential for the characterization of long fibre reinforced polymers.

Keywords: Fibre Length Distribution, Microstructure Analysis, Fibre Reinforced polymers, X-Ray Computed Tomography, Image Processing

1. Introduction

The fibre length distribution (FLD) is a crucial material parameter for the mechanical modelling of long fibre reinforced polymers. While the fibre length has almost no effect on the elastic properties at higher aspect ratios [1], it influences the fracture behaviour significantly. Whereas ashing and subsequent optical measure is a commercially available way to obtain the FLD, there exist no non-destructive methods to compute the FLD alongside the FOD from the same scan. Teßmann, Mohr et al. [2] were calculating FLDs by a hessian-based procedure. Furthermore, Salaberger, Kannappan et al. [3] tested their algorithms on short fibre reinforced polymers. Nevertheless, for short fibre reinforced polymers it is self-evident that the required representative volume element (RVE) for the determination of a realistic FLD is smaller than for LFRP. In the investigation of short fibre reinforced polymers, it is easier to track fibres due to the possibility to acquire images with very high resolutions and a low amount of image blur in respect to the specimen size. Of course, high scan qualities lead to better results and reliable processing. In this context, X-ray computed tomography techniques for materials investigation were improved continuously within the last years to achieve resolutions below 1 µm voxel size. Currently, the challenge is to find a compromise between a sufficient image size in order to cover a representative amount of fibres and to reduce the bias in FLD that stems from cutting fibres at specimen boundaries and a good resolution with little image blur sufficient to resolve the gap between fibres that are almost touching in order to provide a good basis for the subsequently image processing.

The aim of the work presented in the following is to develop a procedure that is able to determine FLDs of long fibre reinforced polymers, even at moderate image quality. For that purpose, the CircularVoting is used as pre-filter to gain the medial axis of the fibres. It was developed by Benjamin Bertram at the Institute for Applied Materials and is open source software available on the Composight page on SourceForge [4]. The filter is integrated in the segmentation toolkit (cpsSegmentGUI) offering a graphical user interface. The pre-processing with CircularVoting avoids the connection of almost touching fibres, which should generally appear as skew lines in µCT-scans, but are connected due to the image blur. This effect will be called “cross-over link” (cf. bottom centre in Figure 5) in the following. Subsequently, the fibres are reduced to the medial axis by means of skeletonization [5]. The fibre tracking is executed by modified versions of Ignacio Arganda-Carreras’s ImageJ plugins Skeletonize (2D/3D) and AnalyzeSkeleton [6,7]. Because it is not possible to avoid all connections in cross-section areas of the fibres in pre-processing steps, the algorithm of the skeleton analysis was extended to remove all cross-over links in the resulting graph and connect branches that belong to the same fibre.

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2. Material and Methods

2.1 Specimen and Image Acquisition

All specimen images were acquired with an Yxlon-CT precision computed tomography system containing an open micro-focus X-ray transmission tube with tungsten target and a 2048 x 2048 pixel flat panel detector from Perkin Elmer. The scanned specimen for the testing of the following algorithms are made of long-fibre reinforced thermoplastic (LFT) with glass-fibres and a polypropylene matrix. The investigated materials had a fibre content of 10 % and 20 % by mass. In consideration of the densities of polypropylene ($\rho_p = 0.9 \frac{g}{m^3}$) and e-glass ($\rho_g = 2.6 \frac{g}{m^3}$), the fibre volume fractions can be calculated and result in values of 3.7 % and 8 % in the tomogram. The scanned section of the LFT10 specimen (low resolution sample LR) had a size of 9.2 x 7.36 mm and a thickness of 2.66 mm at a resolution of $5 \frac{\mu m}{voxel}$. The LFT20 sample (high resolution sample HR) was cut to a cylinder of $\phi 4$ mm at a thickness of 4 mm and has a resolution of $3 \frac{\mu m}{voxel}$. Due to the manufacturing process, the fibre orientation distribution has a very small component in the thickness direction of the plate. Additionally, artificial images were generated by a tool that is freely available on Composight [4] and produces a certain number of fibres with each desired distance, diameter and length in a cubic image of variable sizes [8].

![Figure 1: Slice of LFT10 in low resolution (left) and LFT20 in high resolution (right)](image_url)

2.2 Validation of the Methods

In a first step, tests with artificial images were performed to illustrate the effect of the CircularVoting image filter. Therein, images with synthetic fibres were generated with a diameter of 5 px and a distance of 5 px, contacting each other (left column in Figure 5). This scene was tested with parallel fibres and angles of 20 ° and 45 ° at a length of 60 px.

For the comparison of the FLD accuracy at different image qualities and sizes of the investigated image sections, the sample images were cropped according to Table 1 and compared with each other. This procedure was intended to provide further information about the correlation between the fibre orientation and the size of the extracted specimen.

<table>
<thead>
<tr>
<th>Diameter</th>
<th>2 mm (D2)</th>
<th>4 mm (D4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.6 mm (H0.6)</td>
<td>-</td>
<td>HR</td>
</tr>
<tr>
<td>1.5 mm (H1.5)</td>
<td>HR / LR</td>
<td>HR</td>
</tr>
</tbody>
</table>

Table 1: Test plan

For the validation of the results, two approaches were used. In the first one (V1), a fixed cubic image detail with an edge length of 0.5 mm was investigated once for each image resolution. Consequently, the image region of the 5 $\mu m$ resolution image had an edge length of 100 px while the 3 $\mu m$ picture yields to 166 px. In these sub-regions, each fibre was tested for its correct tracking. However, due to the small image region of the first validation method, a second test (V2) was performed on the entire images with 2 mm diameter. Therefore, 50 fibres were randomly chosen and manually evaluated to get a better impression of how the error affects the global FLD.
2.3 Image Pre-Processing
As a first step, it is advisable to segment the fibres in the image as well as possible. For this purpose, the CircularVoting filter [4] is used. This combines the coherence measure $T$

$$T(S) = \frac{\lambda_2}{\lambda_3}$$

that is derived from the Eigenvalues ($\lambda_1 \geq \lambda_2 \geq \lambda_3$) of the structure tensor $S$ [9] with a surface normal overlap measure $M$ as is motivated in [10]. The normal overlap scheme makes use of the fixed fibre radius $R$. In simple terms, $M$ is calculated from the neighbourhood mask that is shifted over each image position. A counter is increased for each of the neighbours that supports the hypothesis of a fibre being centred at the current window position. The main characteristics of such a neighbour are that it is $R$ voxels away from the centre and that its gradient points toward the centre. There are, however, free parameters that involve a trade-off between robustness to noise and blur of the accumulated filter response $\tilde{M}$. Figure 2 depicts a cross-section of a fibre with a radius of four voxels that is aligned to the z-direction of the image where the mask is currently perfectly centred at the fibre. The black and grey arrows represent the normalized image gradients resulting from the transition between the polymer matrix material and the glass fibre. The green spot illustrates the filter response, which takes on its maximum value in the centre of the fibre.

To amplify the fibre axis, finally, both image features, $M$ and $T$, are combined to generate the CircularVoting filter response $C$, using the weighted geometric mean

$$C_l = T_l^w \cdot M_l^{1-w}$$

where the weight $w$ can be adjusted for each material and image acquisition parameter set. One of the main advantages of this method is that spherical inclusions in the material can be suppressed by increasing $w$ due to the low coherence measure $T$, since $\lambda_2 \approx \lambda_3$ and consequently $T \approx 1$. This feature is very beneficial for polymers that contain mineral fillers, e.g. sheet moulding compounds (SMC), to distinguish filler particles from fibres. On the other hand, the surface normal overlap allows the clean separation of fibres where cross-over links would occur if the input was segmented by mere thresholding.

2.4 Fibre Tracking and Determination of FLDs
The determination of FLDs is based on the open source ImageJ plugins published by Ignacio Arganda-Carreras [7]. In a first step, the skeletonization is executed without any change from the original plugin. This reduces the diameter of the fibres to their medial axes by applying a morphological operator. The resulting skeleton has a thickness of only one voxel and each voxel of a straight fibre has only two neighbouring points (respectively one at end-points). In a first step, the AnalyzeSkeleton tool classifies each bright pixel to one of the following types [11]:

- End-point-voxels – less than two neighbours
- Slab-voxels – two neighbours
- Junction-voxels – more than two neighbours

Figure 2: Visualization of the surface normal overlap filter
Based on this data, the plugin builds a graph of the skeleton (cf. Figure 3) using the three different types of voxels mentioned above. While the original plugin returns the branch lengths of this state from each junction to junction or from a junction to an edge, it was extended to an advanced version for the fibre analysis, which connects the branches at junctions as described below, because straight fibres should not show any vertices.

### Figure 3: Example of a graph from the initial plugin by Ignacio Arganda-Carreras

Java is an object-oriented programming language and thus, the graph is built as a network of objects. A branch consists of a slab voxel and connects junctions or end-point voxels to each other. Due to this structure, it is easy to observe the entire graph structure by visiting the objects step by step, because of the interconnection of neighbouring objects.

The newly implemented part of the tool investigates each junction in the graph to resolve it and leave only straight fibres without vertices. In doing so, the algorithm analyses every junction and finds the best match of adjacent branches by comparing the branch alignments. Figure 4 depicts an example case for the fibre-labelling algorithm in 2D. The previous skeleton analysis sorted the red junctions already in a way that it is suitable for the plugin-extension while the black branches have to be labelled for the final fibre analysis. The algorithm starts at the first junction where four branches must be labelled. For this purpose, the orientation vector of each branch is calculated by observing the \( n \)th slab voxel from the current junction, where \( n \) is an adjustable parameter. If the branch has a length below \( n \), the last slab voxel is used to derive the direction. All vectors are normalised, stored temporary in an array for each junction and compared with each other by building the scalar...
product. At this point, it is possible to connect the best corresponding branches— that pair of which the scalar product is closest to minus one—by giving them the same labels. In the example, “1” is connected first, because it had a better correspondence due to the straight line. Subsequently, the two remaining curved branches are connected and labelled as “2”. At the second junction, the orientations are calculated as mentioned before, but when the branches are connected, the left branch already has a label. In this case, the corresponding branch is labelled with the same number as the one that has already received its designation. In the case of an odd number of branches at a junction (junction three), the remaining branch is assumed to be independent and gets its own label. If two corresponding branches are already labelled, like shown in junction three of the example, one of the branches including all its associated parts is relabelled. After finishing this procedure for all nodes, all branch lengths of the same label are summed up to the fibre length and saved to the FDL table. Furthermore, a 16-bit output image is created, which represents the fibres with the corresponding fibre labels as grey values. Because it is hard to distinguish fibres with almost the same grey value, a lookup table was created to apply a random colour to each fibre.

3. Results and Discussion

For the evaluation of the tests on artificial images, which are shown on the left hand side in Figure 5, the parameters of the segmentation tool were chosen to a radius of $R = 3$, a mask size of five voxels and $\sigma_R = \sigma_\alpha = 1$, which are radial and angular blurring parameters to realize the trade-off between robustness to noise and blur of the filter response $M$, mentioned in section 2.3. The middle column depicts the segmented images after simple thresholding, which all have connections between the fibres. The right hand side represents the results after applying the CircularVoting with subsequent thresholding.

As it can be seen in Figure 5, the CircularVoting clearly determines and improves the separation of the fibres, even if they are parallel and continuously touching each other. For that reason, we use the CircularVoting as a pre-filter for the subsequent skeletonization and fibre tracking. Even though the extension to the fibre-tracking algorithm is implemented to resolve connections at junctions that arise from the segmentation, it is impossible to extract a FLD from a graph, as it would result from the simple threshold segmentation of parallel and touching fibres as shown in Figure 5. Previous tests showed that for an effective use of the CircularVoting, a minimum fibre diameter of around three voxels is needed.

For the processing of the HR images, a single fibre has a diameter of five voxels and consequently, the parameters of the CircularVoting filter were set to $R = 3$ and $\sigma_R = \sigma_\alpha = 1$ at a mask size of four voxels. As can be seen from an image detail of 1.8 x 1.8 x 0.6 mm in Figure 6, the fibre-tracking algorithm works very well on this input data at high resolutions, even for curved and long fibres. As mentioned before, every fibre received a random colour for a better distinction of surrounding fibres. Figure 8 illustrates the same specimen over the entire cross-section of $04$ mm. The LR image was processed in the same way except the parameters of the CircularVoting, which were set to a radius of 1.5 pixels and $\sigma_R = \sigma_\alpha = 1$ and a mask size of three. Because of the low resolution of only 5 µm/voxel, the fibres have a diameter of only 3 voxels and the effect of the CircularVoting filter is less pronounced as it does at high quality scans. Figure 10 shows an image detail of the processed LR
image. Due to the changing colour along a single fibre, it is noticeable that several fibres were not tracked correctly over their full length. Figure 7 represents the FLDs in counts over fibre length while Figure 9 is depicted in percent on a logarithmic scale for all investigated images. Both HR D4 images have nearly the same distribution in percent with a maximum fibre length of over 7 mm while the HR test with a diameter of 2 mm in the x-y-plane differs significantly and the longest tracked fibre has a length below 3 mm.

As can be seen in the images, the fibre orientation has its preferred direction in the x-y-plane. It is obvious, that the FLD of the small diameter D2 is shifted to lower fibre lengths compared with D4, because most of the fibres are aligned to this plane and thus, they are cut on the edges. Due to the same reason, the size reduction in z-direction affects the length distribution less than cutting the x-y-plane, because fewer fibres are cut off. While the FLD of the D4 H1.5 mm image is shifted upwards compared with the one with a height of 0.6 mm (D4 H0.6 mm) in Figure 7, it is almost similar if we consider the histogram in percent. For clarification, Figure 9 shows the distributions in percent on a logarithmic scale. As expected, the length distribution in counts of the LR image is below the other curves due to the lower fibre fraction. Nevertheless, longer fibres than in the HR specimen were recognized. This effect could stem from two different reasons: On the first hand, the LR image could include longer fibres due to lower radii of curvature. On the other hand, the higher values in length could arise from wrongly connected fibres. Nevertheless, the logarithm scaled FLD shows a nearly constant slope up to the diameter of the specimens in Figure 9 with a subsequent drop of the curve. Up from this point, the measure can definitely not represent the real specimen FLD due to the chosen sample size.

![Figure 6](image)

Figure 6: Tracked fibers of the 20% LFT specimen coded by color (LFT20)

![Figure 7](image)

Figure 7: Fibre length distribution of the high-resolution (HR) and low-resolution (LR) image at different image details of diameter D and height H in counts N over fibre length
In the first validation on a fixed image detail of an edge length of 0.5 mm, the HR image included 81.5 % correctly tracked fibres while in the LR image only 58 % of the fibres were detected without errors (Figure 11). By means of the second validation on random fibres, 77 % in the high-resolution image and only 47 % in the low-resolution image were detected correctly.
4. Conclusion

In summary, it can be stated that the presented algorithms work well on high-resolution images while the number of errors increases with declining image quality. Of course, the FLD is cut off if specimens of small sizes are prepared, but for the current technological status, it is hardly possible to track fibres in large scans. With the available equipment at the Institute of Applied Materials and the current early state of the software, it is possible to determine FLDs of LFT-GF20 with a diameter up to 5 mm, with less than 20 % of the fibres tracked incorrectly due to the fibre-tracking algorithm. It is also possible to get even better accuracies with higher resolutions or less blurred images. One should keep in mind that this contribution deals mainly with FLDs of long fibres reinforced polymers, which are significantly falsified by the specimen preparation. According to the current state of the art, a high resolution image is still necessary for a correctness of nearly 100 percent. Nonetheless some solutions that can be applied to improve the results as possible: If the orientation of the fibres is known, the best way is to cut the specimen to a bar with the same orientation, because as few as possible of the fibres are cut off and if its longitudinal axis is aligned to the rotation axis of the CT, you can scan with high magnifications. Nevertheless, images can be stacked in this direction without any problems. Another viable solution for the competing parameters image size and spatial resolution is the use of statistical tools to determine precise FLDs, even if the specimen size is below the average fibre length.

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