Computed tomography for analysis of fiber distribution in carbon fiber preforms

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Abstract

This paper presents a method for computation of the fiber content of carbon fiber preforms from 3D computed tomography (CT) data. Quantitative estimations of the fiber content are deduced under the assumption of the presence of regions with maximum possible fiber packing. This method is used to compare the influence of different sewing techniques onto the global or the local fiber content of small preform samples. The principle functioning of the method has been verified on a 19 piece test sample. Further tests were performed to examine the influence of a reduced acquisition angle as well as of an appropiate material calibration.
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1. Introduction

One main goal in the construction of modern aircrafts is a significant weight reduction. For that, materials like carbon fiber reinforced composites are used, which can satisfy the requirements lightness and stability. A standard method to construct such parts is the Resin Transfer Moulding technique (RTM), where so called preforms are formed to the resulting shape, which are then infiltrated with resin. The project „Flexnaht-Strukturen" examines the sewing process used in manufacturing of complex 3D-preform structures consisting of carbon fibers. A principal object is the determination, how the fiber distribution is influenced by the sewing process. Another goal is the validation of X-ray techniques for the monitoring of the production process. This technique should be able to detect defective parts in early production steps. Axial and planar computed tomography as well as radioscopy and scanning methods which record two- resp. three-dimensional data sets will be considered.
This contribution presents a short survey of the project "Flexnaht-Strukturen". The main part focuses on the possibilities of 3D computed tomography (CT) for fiber content determination in small perform samples.

2. ‚Flexnaht-Strukturen' - project

General intention of the ‚Flexnaht-Strukturen' - project is the cost-effective operation of the RTM technique, whereby the carbon fiber preforms are sewed together in one of the preparatory steps. Preferred application of that technology is the production of airplane doors. Supporting organisation of that project is the Bavarian Research Foundation (BFS). The project started in 2005 and will end in 2008.

2.1 Project partners

Leading partner of the Flexnaht project is Eurocopter Germany. They are further on responsible for the definition of the materials, fabrication of the preforms as well as the sewing technology. The other partners are grouped into small and medium enterprises and research facilities. The company Aerostruktur performs construction studies as well as the construction of the defined components, frames, bearers and skin, itself. The company Fischer + Entwicklungen deals with the construction and fabrication of production tools as well as the documentation of the production.
As one of the three research partners, the institute for polymer engineering of the university of Bayreuth is working on physical-chemical and dynamic material characterisation. The institute of polymer technology of the University of Erlangen is dealing with the determination of the bearing strength of the CFRP samples. Finally, the development center for X-ray technology (EZRT) is responsible for non-destructive testing of the carbon fiber preform samples. Some more information can be found in [1,2].

2.2 Materials and buildup of preforms

Preforms are semifinished parts of varying geometry, consisting of carbon fibers. A set of for example 12.000 individual fibers are bundled to so called rovings. Many of these rovings are sewed together, constituting two-layered MAG fabrics (“Mulitaxialgelege”), where each layer may have individual fiber orientation. The cross section of the rovings within MAG is approximately elliptical with dimensions of about 4 mm times 0.1 mm.
Typical orientations of the fibers have angles of 0°, 90° or ± 45° or 60°. Several stacked and again sewed layers of MAG form a so called sewing panel. These panels may have dimensions of more than one square meter.

2.3 Preform production

The goal is the production of complex 3D shaped samples consisting of carbon fibers, which may simply be transferred to the conclave for injection of the plastic resin. The sewing technology serves here as alternative for the binder technology and is responsible for the fixation of the different MAG layers.
The first step is the deposition of the MAG layers, which are sewed together in a two dimensional manner, resulting in sewing panels. From these sewing panels, the individual parts are cut out. These layer parts are then subsequently sewed together to form two- or three dimensional structures, until the final preform is reached.
That type of production contains a large number of manual machining steps and is therefore correspondingly expensive. In order to sort out defective samples at an early stage, quality control systems would be desirable after each processing level.

2.4 Defect types in preforms

In preform production, a variety of different defects may occur, whereas a part of them is optically accessible, for example wrong seam position, stitching width or seam discontinuity. For the most part, these defect types may be detected by optical inspection methods. However, there are defect types concerning the inner layers, which are optically not accessible. The most important among them are misaligned fibers, typically wrong orientation or wrong stacking of the MAG layers. This means, the orientation of the whole layer or some individual rovings is imperfect, for example due to distortions during fiber deposition. Furthermore, voids or foreign material inclusions may occur. One goal of the Flexnaht project is the determination, which of these defect categories may reliably be detected by means of X-ray testing.

3. X-ray testing on carbon fiber preforms

In principle, X-ray technology offers the possibility to visualize the interior of a specimen. Concerning carbon fiber preforms, there are however some complicating constraints. Particularly, there is the consistency and the size of the preforms, which hinder their manipulation. The X-ray absorption of carbon declines significantly at energies of 20 keV. The low X-ray contrast is not really a problem in preform inspection, since the fibers have to be contrasted only against air. Difficulties arise, if carbon fiber has to be separated from sewing yarn or the polymer matrix. The possibilities of X-ray testing have to be investigated in two directions:

- A concept for inline testing should be found out, and
- The influence of different sewing parameters to the fiber volume content should be determined.

3.1 X-ray methods

The different applicable X-ray techniques differ mainly in the number of projections and the geometry of views, which are made from the sample. Radioscopy is a simple projection technique, which does not reveal any depth information of the sample structure without further assumptions. These methods are well suited for the detection of defect types which differ strongly in absorption compared to their neighbourhood, for example foreign materials. Within certain limits, preform contours or missing layers may be also detected. As there is only one projection to acquire, radioscopy is suited for inline measurements. Tomosynthesis is a method for the reconstruction of cross sectional layers from large planar objects. Commonly, that technique is used for offline- or inline inspection of printed electronic circuit boards. The application of these two techniques to carbon fiber preform testing is presented in [3]. Further potential X-ray methods are X-ray topography or X-ray refraction technique, which are based on monochromatic radiation [4].

3.2 Computed tomography for analysis of fiber content in preforms

Computed tomography requires a whole rotation of the sample within the course of the beam, therefore it is mainly suited for the examination of small parts. The main advantage of that technique is the possibility to produce quantitative estimations of the fiber volume content. Two main goals of the analysis using CT-data are:

- Visualisation of the three-dimensional fiber distribution in preforms.
- Detection of possible influence of sewing parameters on the local fiber content.

The output of that approach will be shown on a 19 piece set of preform samples. In addition, the influence of beam hardening and linearization as well as the influence of limited angle acquisitions will be shown on another test piece.

3.2.1 Method for quantitative determination of fiber content

As mentioned above, the principal goal of the presented CT investigations is to determine the influence of the sewing process to the local fiber content of the sample. This information will be used later to visualize suspicious regions in an appropriate way. For the fiber content, there are three measures to be distinguished:

- The global fiber content is defined as the mean fiber content within the sample volume.
- The local fiber content is the value at a particular voxel position.
- The filtered local fiber content is the mean fiber content within a certain definable neighbourhood.

In order to set up and test the presented approach, a sample containing 19 test pieces was used. The pieces have a size of 40 * 40 mm² (fig. 1). These pieces were fabricated using 4 different sewing parameter settings:

- 2 types of yarn
- 2 perpendicular seam orientations

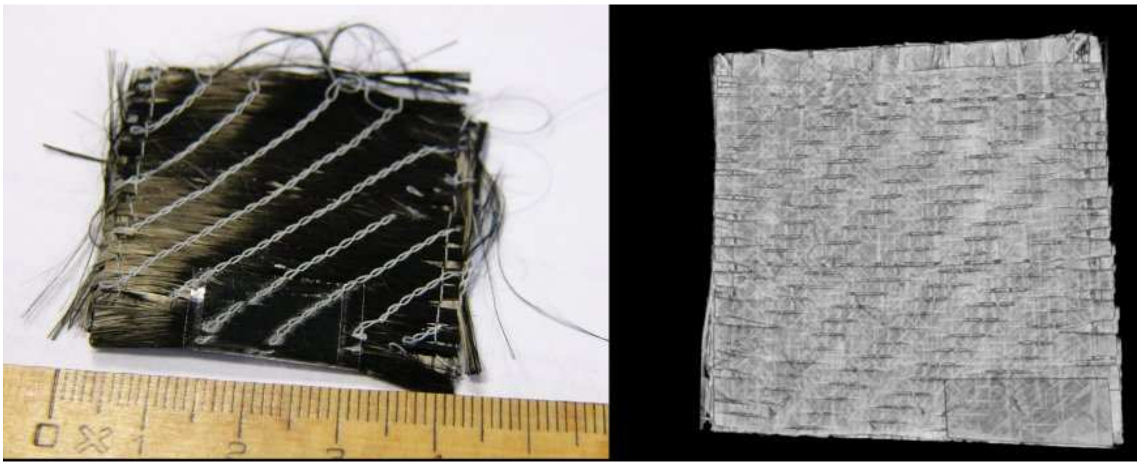


Figure 1: Photo of one test piece (left) and a three-dimensionally rendered visualization (right).

3.2.2 Assumptions

For the determination of the fiber volume content, a basic assumption is made. In order to get a quantitative estimation of the fiber content, it is required that inside the sampled voxel volume should exist a region of maximum fiber density for data normalisation purposes. As mentioned above, the roving cross section becomes elliptic during fabrication of MAG layers. Their dimensions are approximatively 1 to 4 mm by 0.1 to 0.2 mm. An outline is given in fig. 2 showing rovings of 2 mm by 0.15 mm. Due to the sewing force, it is very likely, that there are regions of highest fiber density inside the roving. In order to be able to map these regions, the grid size of the voxel volume should be at least less than the smallest roving dimension. For the CT acquisitions, a voxel size of 63 µm was chosen. The right image in Figure 1 shows a 3D rendering of such a preform voxel volume.

The maximum possible fiber density within carbon rovings corresponds geometrically to the most dense cylinder packing. That type of computation is required in bottle- or fuel rod packaging technology. The densest packing is reached with a hexagonal packing (compare fig. 2; for simplicity reasons, only rectangular packing is outlined). The maximum achievable fill factor is of course independent of the fiber diameter and amounts approximately to 90.7%. That means for the data normalisation that the maximum grey values within the voxel volume represent a local fiber content of 90.7 %.

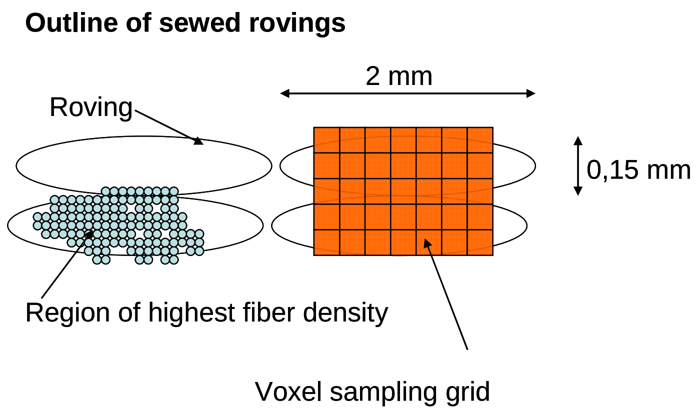


Figure 2: Outline of the voxel sampling of the fiber rovings.

3.2.3 Volume data processing

In order to determine fiber volume content from CT voxel volumes, the following image processing steps are carried out:

1. Determination of the maximum grey value within the rovings. This is currently done manually by evaluation of the grey value histogram.
2. Appropriate conversion of the voxel volume into a volume, where each voxel represents the percental local fiber content.
3. Segmentation of the sample domain using morphological operators.
4. Computation of the fiber content:
   - The global fiber content is given by the mean value within the whole sample region
   - In contrast, the local fiber content is given by averaging the fiber content within a certain neighbourhood region.
5. Optional three-dimensional visualization of the local fiber content. Here, a color coding for inadmissible values can be useful for further examinations.

3.3 Demonstration of the method on a test sample

The measurements for the method validation were done on a micro-CT system. The applied high tension was 100 kV, in order to limit the influence of beam hardening. The magnification amounted to approx. 6.5, which resulted in an effective voxel size of 63 µm. The number of projections was 800 per scan. The samples were scanned pairwise, separated by polystyrene.

3.3.1 Local and filtered local fiber content

The local fiber content of the first group of the four sewing parameter settings is shown in Figure 3. The graph shows the histogram of the fiber content within the sample region. The curves with two peaks represent the local fiber content data. The first peak is due to sampling effects at the sample border. At the other end, the rise at 91 % is due to some voxels within a label bonded at the samples. In the filtered fiber content data, the first peak disappeared. The individual distributions show relatively good accordance. The second peak, representing the most frequent fiber content is located in the range between 50 and 55 %.

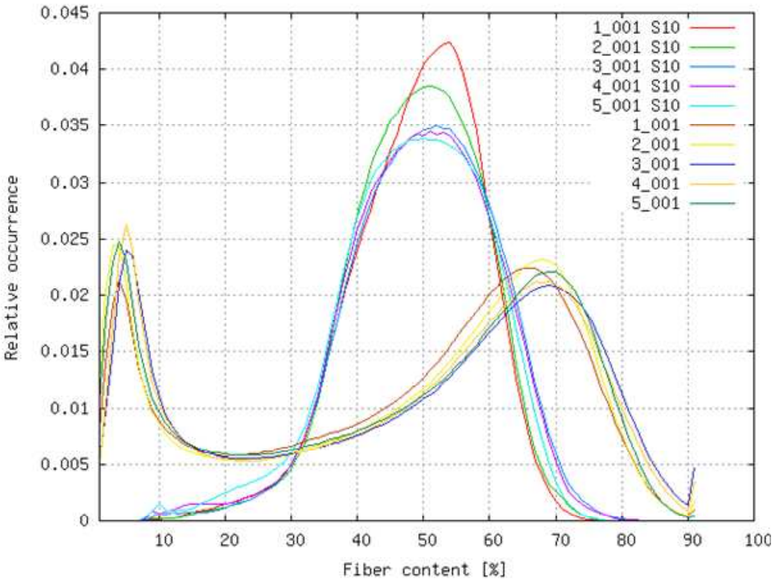


Figure 3: Relative occurrences of the fiber content percent values

Figure 4 shows a cut through the local fiber content volume. On the left, the local fiber content slice is shown, whereas the filtered local fiber content slice is shown at the right. The filtering was done with a ball-shaped filtering element of 1.2 mm diameter. The stitching holes at the sample border become clearly visible after filtering, which is a result of the three-dimensional filtering. The profile at the left shows the fiber content along the vertical red line in the filtered image. At the stitching holes, the fiber content drops at least 20 %-points compared to their neighbourhood. That value may be used to sort out inadmissible samples.

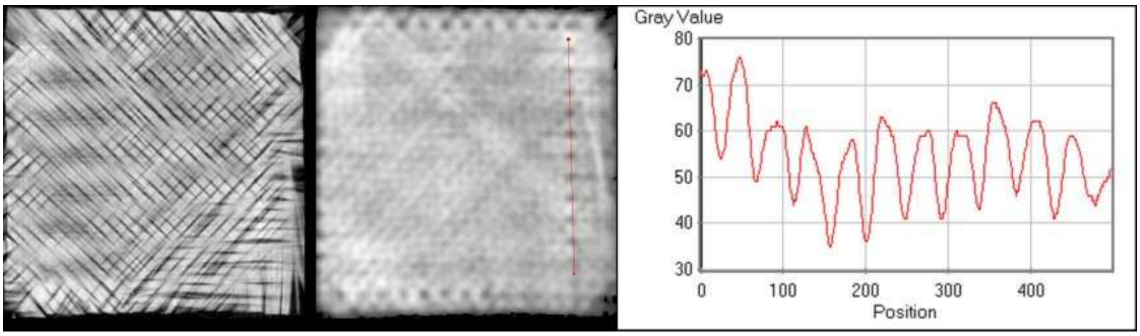


Figure 4: Slice of a preform (left), the filtered slice (center) and the gray value profile of the line in the filtered slice (right)

3.3.2 Classification of sewing setup

Figure 5 shows a diagram where the global fiber content of the four sewing parameter groups are compared to each other. As can be seen in the diagram, the mean global fiber content and the most frequent fiber content are no useful criteria to distinguish different sewing parameters, as the different colours cannot be separated from each other.

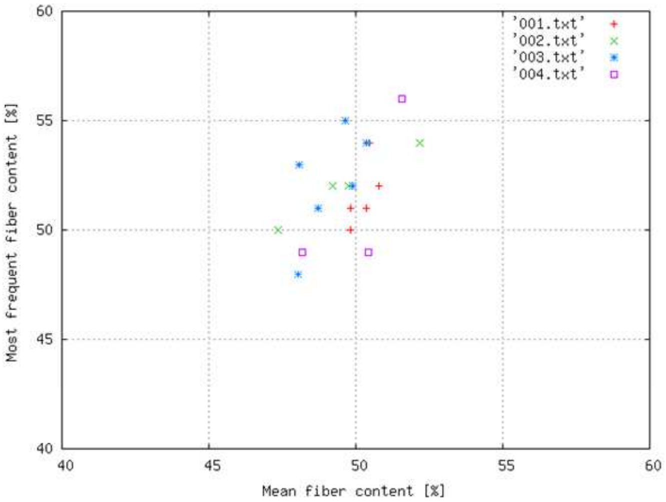


Figure 5: Distribution of the mean fiber content and the most frequent fiber content values of the 19 preform samples.

3.4 Further investigations on a thick sample

In order to estimate of the influence of beam hardening and missing angle acquisitions, another measurement series was performed. For that pupose, 24 preform patches were prepared, two-layered MAG with a size of 5 by 5 cm². Projection measurements of all thicknesses between 1 and 24 patches were acquired for generation of beam hardening correction information. Furthermore, a CT measurement of a block of all 24 patches sewed together was performed (fig. 6, left).

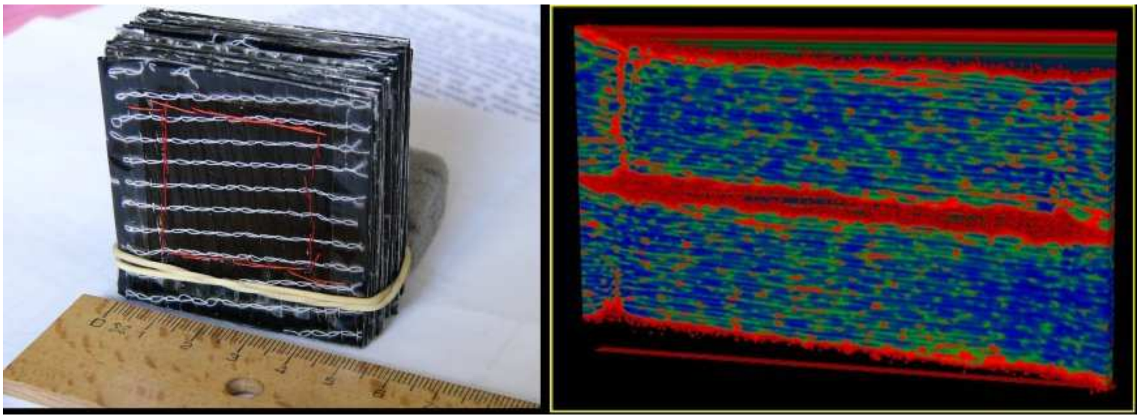
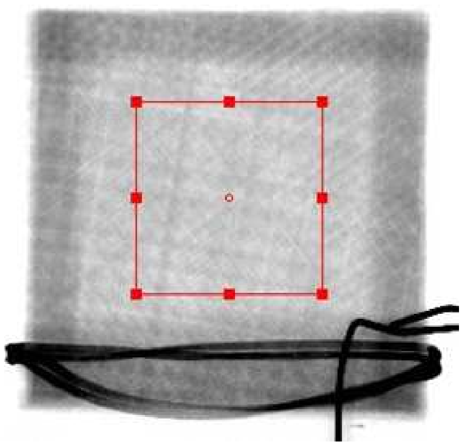


Figure 6: Several preform patches bound to one block (left) and a cut through the three-dimensional color coded volume (right).

The measurements were acquired at 80 kV with 1200 projections. The reconstructed voxel size was approximately 50 µm. The right image in fig. 6 shows a slice through the three-dimensional fiber content distribution of the patch block, with a color coded local fiber content. The stitching area in the upper left corner can be seen clearly. In that case, a color table was used, where voxels with fiber contents below 30% are colored red, those with fiber contents above 60% are colored blue.

3.4.1 Influence of material calibration

Goal of that investigation is the determination of the influence of material calibration to the computed fiber content. The projection images of 24 different thicknesses of preform patches are acquired. The measurement with a thickness of eight layers is shown on the left side of fig. 7. Within the marked red rectangle, the mean intensity is determined. These measurement values are shown as red points within the right graph of fig. 7. As it could be expected from the X-ray tube voltage of 80 kV, there is a rather linear behaviour between intensity and thickness. These support points were fitted into an exponential model, shown as a green line in the graph. The higher thicknesses are fitted with less error. However, the support points of the model do not cover all the thicknesses in the CT measurement of the thick sample, as the sample comprises all 24 used preform patches. Therefore, thickness calibration works in extrapolation mode.



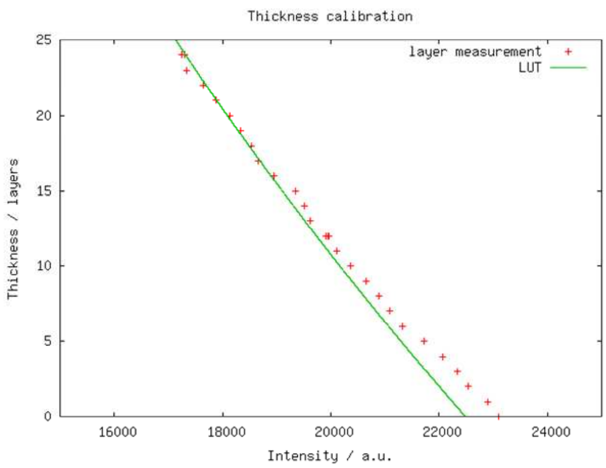


Figure 7: Projection image of eight layers of perform patches, used for material calibration (left), measured intensities and fitted model curve (right).

The effects of using a material thickness calibration are marginal, as can be seen in the Figure 8 at the right, which shows a comparison of the local fiber content distribution with and without material calibration. The deviation of the global fiber content is 0.68 %-points. At the left, the fiber content difference within one slice is shown.

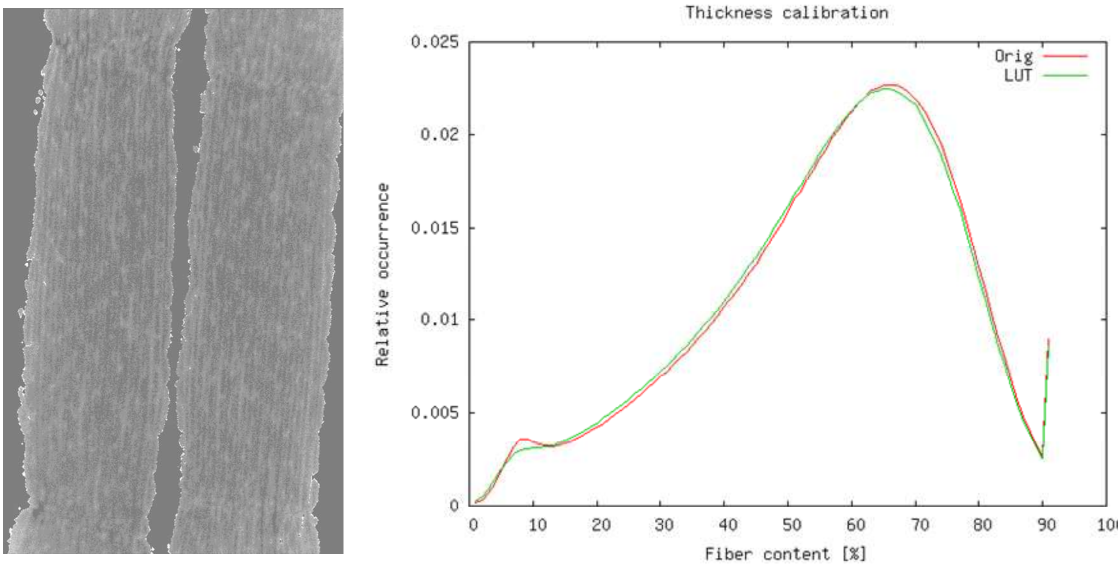


Figure 8: Effect of the material calibration. The difference is shown in the left image. The right image shows the distribution of the fiber content in the original and the calibrated data.

3.4.2 Influence of limited angle acquisition

The influence of limited angle projection data was investigated, in order to evaluate the possibility to scan larger samples, which cannot be rotated completely within the X-ray beam. In that test, ±30° of the projection data were omitted, using the conventional filtered backpropagation reconstruction mode. The results are shown in fig. 9. The global fiber content value deviates more than 22 %-points from the reconstruction using all projections.

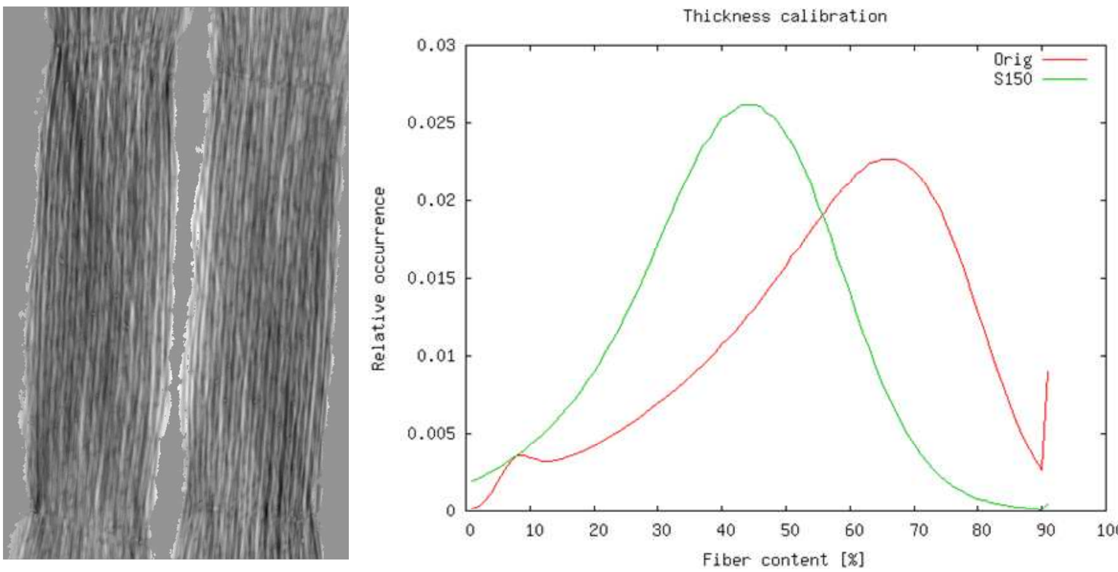


Figure 9: Influence of limited angle projection data. The left image shows a slice of the difference volume, which is calculated between the original and the limited angle volume. The right diagram shows the computed fiber content of the original and the limited angle volume.

3.5 Discussion and outlook

The verification of the method was carried out on only few samples with very small sewing parameter variations. The different sewing parameters showed no influence on the computed global fiber content. The calibration of the method to the real fiber content of the samples is not carried out yet. In this respect, the flexibility of the samples is a big problem, because the true volume of the samples has to be determined.
The influence of the beam hardening effect was investigated, but with respect to the applied conditions, its effect seems to be negligible.
In contrast, the influence of limited angle acquisitions in connection with the applied filtered back projection is enormous. This fact becomes important as soon as large samples have to be evaluated with the presented method. In this regard, reconstruction methods have to be found out, which keep their quantitative behaviour even under restricted acquisition conditions.
For advancement of analysis of the fiber content by means of CT, the following steps are planned during the remaining project runtime:

- Verification of the method on a larger test sample.
- Trials to calibrate the results to the true fiber content.
- Investigation of the influence of the sewing parameters on a more local scale.

4. Conclusion

Using micro CT reconstruction, the presented method allows for small sewed preform samples the quantitative estimation of the global and local fiber content. The basic assumption, which has to be met, is that the scaling of the reconstructed values to the theoretically maximum possible fiber content is valid. Under these conditions, the proposed method may be useful to investigate the influence of different sewing settings.

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