Visual classification of braided and woven fiber bundles in X-ray computed tomography scanned carbon fiber reinforced polymer specimens

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A B S T R A C T

In recent years, advanced composite materials such as carbon fiber reinforced polymers (CFRP) are used in many fields of application (e.g., automotive, aeronautic and leisure industry). These materials are characterized by their high stiffness and strength, while having low weight. Especially, woven carbon fiber reinforced materials have outstanding mechanical properties due to their fabric structure. To analyze and develop the fabrics, it is important to understand the course of the individual fiber bundles. Industrial 3D X-ray computed tomography (XCT) as a nondestructive testing method allows resolving these individual fiber bundles. In this paper, we show our findings when applying the method of Bhattacharya et al. [6] for extracting fiber bundles on two new types of CFRP specimens. One specimen contains triaxial braided plies in an RTM6 resin and another specimen woven bi-diagonal layers. Furthermore, we show the required steps to separate the individual bundles and the calculation of the individual fiber bundles characteristics which are essential for the posterior visual analysis and exploration. We further demonstrate the classification of the individual fiber bundles within the fabrics to support the domain experts in perceiving the weaving structure of XCT scanned specimens. © 2016 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction and motivation

Advanced composites are promising materials, having low weight, high specific stiffness, high specific strength, as well as high corrosion resistance and comply, at the same, with today's industry needs for function orientation, high integration and cost-efficiency. In particular, carbon fiber reinforced polymers (CFRPs) have such material properties and were successfully introduced in aeronautic and automotive applications within the past years. To increase the usage, not only structural but also complex primary structures and highly loaded components have been manufactured from CFRP. As for today, besides commercial aerospace and automotive industry, CFRP is used in a wide range of industries, e.g., space/satellite, marine, sporting goods, automotive, civil engineering or wind energy [1,2].

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Fiber reinforced components consist of many individual textile layers, of which each is composed of various fiber bundles. The production of CFRP materials may follow different routines, such as the typical resin transfer molding (RTM) routine: first, the fiber layers are placed into a mold and stacked onto each other. Inside the sealed and heated mold a vacuum is built up and the heated resin is injected to impregnate the fiber layers. After a curing process at a constant temperature in an autoclave, the individual textile layers are connected.

For all fiber reinforced composites, the achieved material properties (e.g., the high stiffness and strength) are strongly influenced by the weaving patterns of the textiles and the orientation of the individual filaments or fiber bundles.

The increasing share of fiber reinforced polymers also generated a high demand for non-destructive testing (NDT) techniques [3]. The most wide spread method for NDT on fiber reinforced polymers required by various standards is still ultrasonic testing, which provides a quick and cost-efficient but low resolution and therefore imprecise overview. More recently industrial 3D X-ray computed tomography (XCT) has been discovered for NDT applications on fiber reinforced polymers [4], which allows e.g., to capture the individual carbon fiber layers.

XCT generates a 3D volumetric representation of the scanned specimen, reconstructed from a series of 2D penetration images, taken throughout a full rotation of the specimen. The specimen is placed on the rotary table between X-ray source and detector and penetrated by incident X-rays of the source. When passing through the specimen, the X-rays are attenuated by the materials present. The detector transfers the X-rays in its scintillator layer into visible light, which is then recorded in a 2D projection image. The process starts over at the next rotational step until the predefined number of projections is reached [5].

As XCT has been advanced to reach voxel sizes of below 500 nm in state of the art devices, it allows generating high resolution XCT volume data for comprehensive and detailed analyses of the test fiber reinforced composite specimens. Unfortunately, there is a trade-off between view port and image resolution. Due to the intrinsic concept of cone beam XCT setups, the reached scan magnification is determined by the specified distances between source and specimen as well as source and detector. Furthermore, the magnification directly influences both, resolution and viewport. A higher resolution decrease the viewport, while a lower resolution increases the viewport.

The inclination of the domain experts is increasingly shifting from high resolution studies [7] of the individual fibers towards studying the fiber bundles themselves. The domain specialists aim to integrate the real fiber bundle characteristics in finite element simulations either of the complete component or of regional subsets showing the recurring bundle pattern (unit cell).

This approach can be applied to a variety of problems, ranging from determining dry fabric permeability or draping characteristics to the composite mechanical response, including accurate prediction of stress-strain fields, macroscopic mechanical properties and the investigation of the non-linear behavior with damage initiation and development.

Understanding and capturing the structure of woven materials by looking at the XCT raw data using 3D volume renderings or 2D slices often turns out to be difficult. In this work we use the approach by Bhattacharya et al. [6] to calculate the geometric structures of XCT scanned woven carbon fiber reinforced components where the fibers are not visible or barely visible. Based on these results, the generated individual fiber segments (MetaTracts) can be manually clustered. The 3D visualization of the clustered MetaTracts gives an overview of the individual fiber bundles and allows the material specialists to better perceive the course and structure of the carbon fiber fabric. The workflow described above is shown in Fig. 1 and uses an example dataset for illustration.
Fig. 2. 3D and 2D slice view of the (a) raw dataset 1 (triaxial braid) and (b) dataset 2 (bi-diagonal layers).

Table 1
Scan parameters and important dataset properties.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>U (kV)</th>
<th>I (µA)</th>
<th>( T_{\text{int}} ) (ms)</th>
<th>Images</th>
<th>Scan time (min)</th>
<th>Voxel size (µm)</th>
<th>Averaging ZD (mm)</th>
<th>Evaluated dataset size X Y Z (voxel)</th>
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<td>1700</td>
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<td>6</td>
<td>5</td>
<td>300 500 220 500</td>
</tr>
<tr>
<td>Dataset 2</td>
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<td>190</td>
<td>500</td>
<td>1700</td>
<td>300</td>
<td>5.25</td>
<td>6</td>
<td>200 500 220 500</td>
</tr>
</tbody>
</table>

Fig. 3. Preprocessing workflow with the respective intermediate step results (example dataset).

2. Dataset descriptions and data acquisition

The techniques to extract and visualize the fiber bundles in an XCT scan are shown in this work by using two woven carbon fiber reinforced polymer datasets. Each dataset is a cutout from a larger specimen.

The raw dataset 1 consists of a CFRP-specimen produced with a total of four triaxial braid plies by resin infusion. Toho-Tenax® HTS40 F13 12K yarns for both, the axial and braider direction in combination with a Hexcel HexFlow® RTM 6 was used. The braid architectures, with a nominal braiding angle of 30°, were manufactured on a circular braiding machine with 176 bobbins [11]. The investigated sample size was \( \sim 10 \times 10 \times 2 \) mm\(^3\) (Fig. 2a).

The raw dataset 2 consists of a CFRP-specimen made from 16 plies of bi-diagonal (0°/90°) layers with 12k rovings and RTM6 resin (see Fig. 2b).

The XCT scans were performed on a GE phoenix X-ray Nanotom 180 NF. The device uses a 180 kV nano-focus tube and a full digital 2304\(^2\) pixel flat panel detector. Molybdenum was used as target material. No pre- or post-filters were used for the scans. The applied voltage on the X-ray tube was 60 kV at a voxel size of 6 µm\(^3\) for dataset 1 and 5.25 µm\(^3\) for dataset 2. Table 1 presents the XCT measurement parameters of the investigated specimens.

2.1. Preprocessing

In order to calculate the fiber bundles, we have to preprocess the raw data (see Fig. 3). First, we use intensity windowing [9] to enhance the contrast and to remove the air and most of the epoxy matrix, as we are only interested in the fiber bundle information. For this purpose, we delimit the material peak (in the gray value histogram) with the minimum and maximum window intensity value. All values below or above the interval of the intensity window are mapped to gray
value 0 or 65535. Second, we smooth the fiber bundle data with a $3 \times 3 \times 3$ median filter \cite{10} to reduce the ‘salt and pepper’ noise. The preprocessing results of dataset 1 and 2 are shown in Fig. 6b and Fig. 8b. The result of the smoothing step is used as an input to the MetaTracts calculation (see Section 3).

3. MetaTracts calculation

MetaTracts are a coarse and simple approximation of integral curves. Each MetaTract is a connected chain of cylindrical tubes which traverse the fiber bundles embedded in the data. MetaTracts form an abstract representation of the fibers composing the fiber bundles. Each MetaTract is not a single fiber but a small portion of the fiber bundle, a collection of MetaTracts thus forms a fiber bundle. The MetaTracts extraction consists of two major steps. First we extract a local orientation vector at each grid location. Second, we compute a set of poly-cylinders which traverse along these local orientations.

In the first step the local orientations are computed using eigenvalue analysis of the Hessian matrix computed at each voxel. Hessian matrix captures the local second-order structure in the data. The eigenvector associated with the smallest eigenvalue gives an approximation of the local orientation. Fig. 4a shows the example dataset where the computed local orientations are color coded according to the RGB color-scale mapped to the X-, Y- and Z-axis. We clearly see the computed orientation captures the local fiber bundle directions.

In the second step, starting from a grid vertex we generate a cylinder along the direction of the local orientation. All grid vertices within the cylinder form a set of candidate vertices which could be used to generate the next cylinder. Fig. 4b shows the MetaTracts in two dimensions (each MetaTract is a rectangle). $C_p$ is the start point of the current MetaTract and $N_p$ is the current local orientation. All grid vertices within the MetaTract (blue shade) are candidate vertices. We choose the vertex which is farthest from the current vertex and approximately along the direction of the local orientation of the current cylinder to generate the next cylinder and continue the computation. We densely seed the data and generate MetaTracts. We discard the MetaTracts whose length is below a threshold. \cite{6} provides extensive details of the MetaTract generation process.

Currently, the calculation of the MetaTracts is limited to small datasets (around $500 \times 500 \times 300$ voxels) cause of the long computation time ($\sim6$ hours). The MetaTracts calculation result serves as input to the characteristics calculation and the classification process (see Section 4).

4. MetaTracts characteristics calculation and manual classification

In order to display the fiber bundles of a woven CFRP specimen, the calculated MetaTracts (see Section 3) have to be classified. This requires the calculation of the MetaTracts characteristics: $X_m Y_m Z_m$-coordinates of a MetaTracts center point, the angle $\theta$ of a MetaTracts to the Z-axis and the angle $\varphi$ to the XY-plane. The MetaTracts characteristics calculation and the classification process use a scatterplot matrix to select the MetaTracts according to their specific characteristics and store a selection as a particular classification. The selections and classifications within the dataset are visualized with a volume renderer.

A typical selection and classification process is illustrated in Fig. 5a–k. Starting from the unclassified (gray) MetaTracts (a), a selection (b) is performed on the parameter $\varphi$ between $80^\circ$–$90^\circ$ and results in two (red) fiber bundles (c) perpendicular to the Z-axis. These two fiber bundles are shown as a light-blue classification (d) and can be identified in the scatterplot $Y_m - Z_m$ as two separated clusters (e). The top fiber bundle is selected in (e) and (f) and classified as a color-coded (light-orange) fiber bundle (see Fig. 5j and k). Starting from the left over blue classification (g) we select the other cluster in the
Fig. 5. MetaTracts selection and classification process (example dataset).
scatterplot (h) and (i), classify and color-code it (the remaining MetaTracts in the blue classification are released into the (gray) unclassified MetaTracts). Fig. 5j shows the front of the classified colored fiber bundles and Fig. 5k the back. Both, the dark-orange and the light-orange bundle point in the X-direction and are perpendicular to the Z-axis. To select and classify the data manually, $\sim 65$ minutes were required for dataset 1 and $\sim 20$ minutes for dataset 2.

5. Fiber bundle classification results

Based on the raw triaxial braid dataset 1 and bi-diagonal layers dataset 2 (see Fig. 6a and Fig. 8a) a preprocessing step (see Section 2.1) which reduces the noise and removes the epoxy matrix was performed to enhance the image quality (see Fig. 6b and Fig. 8b) and to better differentiate the individual fiber bundles from each other. The preprocessed results serve as input for the MetaTracts calculation, the MetaTracts characteristics calculation and the manual classification process. The color-coded classified MetaTracts are shown in Fig. 6c and Fig. 8c. The individual fiber bundles have unique colors and can be clearly distinguished from each other. Slicing through the volume of the colored fiber bundles allows verifying the MetaTracts generation and the manual classification process in more detail.

Fig. 7a and b shows a comparison between the two 2D slices of dataset 1, the preprocessed data and the classified MetaTracts data. The triaxial braid is clearly visible. The MetaTracts were classified according to their spatial position, angle to the Z-axis ($\vartheta \approx 80^\circ - 90^\circ$) and angle to the XY-plane ($\varphi$). Only a few gray MetaTracts could not be classified.

Fig. 9a and b shows the slice comparison of dataset 2 between the preprocessed data and the classified MetaTracts data. The vertical (blue, $\vartheta \approx 0^\circ - 20^\circ$) and horizontal (orange, $\vartheta \approx 70^\circ - 90^\circ$) fiber layers are clearly visible. A few MetaTracts
remain unclassified (gray). The small 'bent' fiber bundle (see Fig. 9a and b, lower right area) has not been detected by the MetaTracts algorithm, because of the small bundle thickness.

6. Conclusion and future work

In this work we have applied the approach by Bhattacharya et al. [6], to extract the fiber bundles in CFRP fabrics using the MetaTracts generation, to two different specimens. By using the scatterplots to classify the fiber bundles the generated MetaTracts were selected based on their previously calculated characteristics and classified to form the resulting fiber bundles. The visualization results show that the individual fiber bundles are clearly identifiable which helps to better understand the fabric structure.

One shortcoming of the current MetaTracts calculation implementation is that the MetaTracts generation takes a long time to complete. Therefore, only small datasets can be processed, at the moment. Furthermore, the MetaTracts algorithm produces a few false-oriented MetaTracts within a fiber bundle, which cannot be classified.

For the future work, we plan to parallelize the algorithm to reduce the computation time of the MetaTracts and improve the reliability of the algorithm to reduce the false-oriented fibers within a fiber bundle.

Based on the shown results, the derived individual fiber bundle data can be used in a further step as input data for numerical modeling using meso-scale finite-element (FE) unit cell models to study the material behavior of composites [8].
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