ARTICLE IN PRESS
CSNDT:40

Case Studies in Nondestructive Testing and Evaluation ••• (••••) •••–•••

Contents lists available at ScienceDirect

Case Studies in Nondestructive Testing and Evaluation

www.elsevier.com/locate/csndt

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

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ARTICLE INFO

Article history:
Available online xxxx

ABSTRACT

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.

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].

DOI of original article: http://dx.doi.org/10.1016/j.csndt.2016.04.002.
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http://dx.doi.org/10.1016/j.csndt.2016.05.006

Please cite this article in press as: Weissenböck J, et al. Visual classification of braided and woven fiber bundles in X-ray computed tomography scanned carbon fiber reinforced polymer specimens. Case Stud Nondestruct Test Eval (2016), http://dx.doi.org/10.1016/j.csndt.2016.05.006

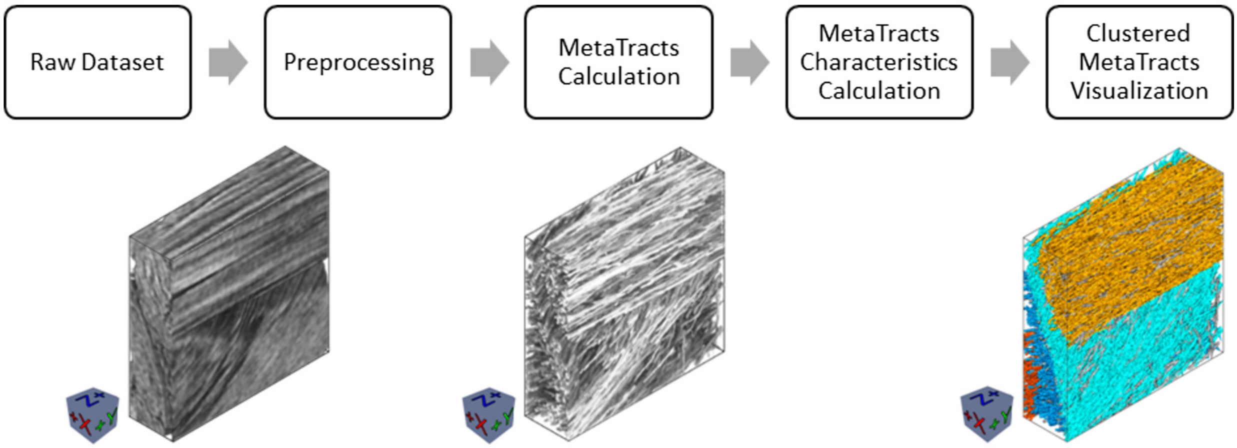

Fig. 1. Fiber bundle extraction workflow (raw example dataset, calculated MetaTracts and classified fiber bundles).

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.