Capabilities and Application of Specialized Computed Tomography Methods for the Determination of Characteristic Material Properties of Fiber Composite Components

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Abstract
Within last years, the proportion of used fiber composite materials in various areas of industrial production rose steadily. Beside aviation industry also automobile manufacturer realized the advantages of light weight design and identified it as a key feature to vehicle production of tomorrow. Fiber composite materials are characterized by several advantageous properties like high specific stiffness and strength which make them ideal for lightweight applications. Since several questions of automatic production and testing are still open, fiber composites are not yet used in mass production.
Testing methods which allow complete material characterization and non-destructive troubleshooting with adequate effort are still a field of current research. Due to its ability of exact three-dimensional cross sectional imaging of the entire part, X-ray computed tomography (CT) is the ideal technology for that purpose. Fiber composite components are often large in size paired with an extreme cross sectional aspect ratio which makes it necessary to step beyond the procedural limitations of conventional 3D-CT. Therefore, advanced CT techniques (e.g., helical CT, transversal CT and 3D-CT with limited angular range) have been developed. Thanks to special 3D reconstruction and evaluation algorithms these methods allow determination and visualization of relevant material properties and characterization of defects and damage.
In the presentation scanning methods and their industrial applications are illustrated by numerous examples. The results of typical errors and damage patterns and quantitative and qualitative evaluations of characteristic material properties (e.g. porosity, fiber volume fractions) are presented.

1 Introduction

Fiber composites are materials made of a polymer matrix reinforced with fibres. Most common fibre materials are glass and carbon. The polymer matrix usually consists of epoxy, vinylester or polyester plastics. Fiber composite materials are characterized by several advantageous properties like high specific stiffness and strength which make them ideal for lightweight applications. By variation of fibre and matrix material, fibre orientation and thickness numerous applications are possible. Typical errors and damage patterns of fibre composites are delaminations, undulations, porosities, fibre cracks or impact damages. Figure 1 shows representative CT images for these different kinds of materials defects.

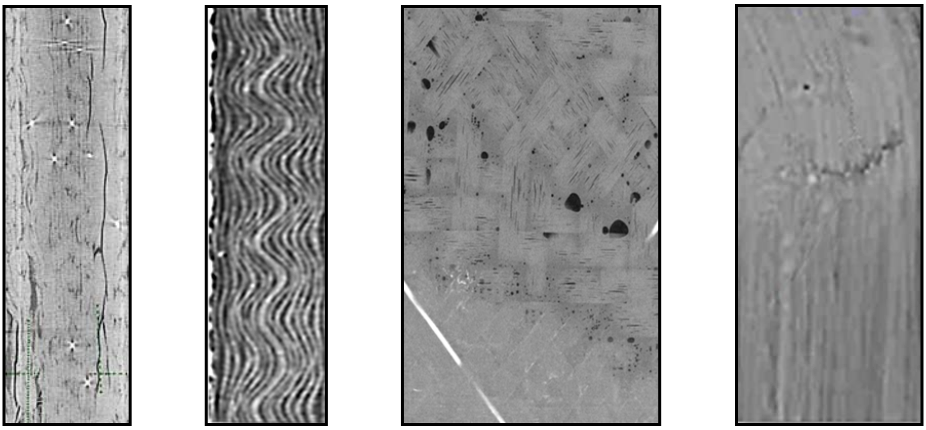

Figure 1: Different kinds of defects in fibre composite materials. From left to right: delamination, undulation, porosity and fibre crack.

Testing methods which allow complete material characterization and non-destructive troubleshooting of fibre composite materials with adequate effort are still a field of current research. Due to its ability of exact three-dimensional cross sectional imaging of the entire part, X-ray computed tomography (CT) is the ideal technology for that purpose [7].

2 Method

Computed tomography is an imaging method based on X-ray attenuation which allows exact three-dimensional cross sectional imaging of an object under investigation. It is based on the assumption that a cross section of an object can be computer aided reconstructed out of a finite number of measured radiographic projections of different directions of the object. Usually a circular orbit is chosen which implies that either X-ray source and detector move around the object or the object is rotated on a turntable (see figure 2). Side condition of 3D-CT is the limitation that the object has to be measured and penetrated completely in each direction during the CT scan. This scan method is called conventional 3D-CT.

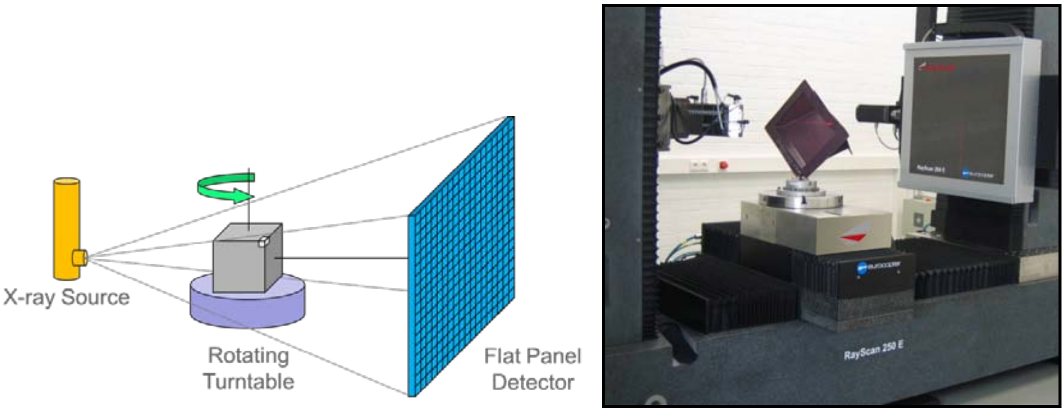

Figure 2: Conventional 3D computed tomography: left: Schematic view, right: CT system RayScan 250 E

In addition to the fact, that only a small portion of the object can be measured, the image quality of conventional 3D-CT decreases with increasing distance to the center horizontal cross sectional plane of the CT image. Helical CT encounters these limitations with a helical shaped orbit around the object [5]. The image quality is as good as in the center plane of 3D-CT all over the CT image and the size of the object is only limited by the CT scanner and the accuracy of the underlying manipulation system (see figure 3).

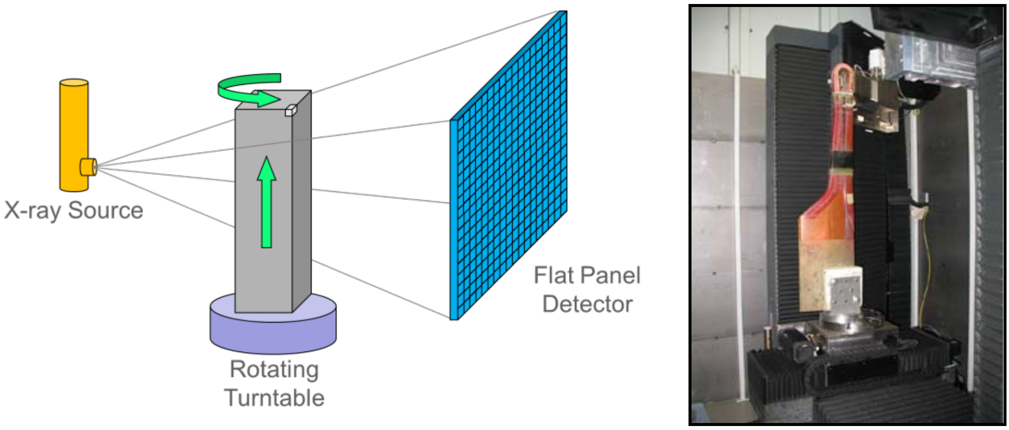

Figure 3: Helical computed tomography: left side: Schematic view, right side: CT system RayScan 250 E

As long as measurement objects have a size which allows for rotating the object 360° within the measurement field, 3D-CT or helical CT deliver good results. Objects with large extension in two dimensions like plates, boards, tablets or other layered structures sometimes prevent 360° orbits. Additionally, the X-ray attenuation depends extremely on angle at which die X-rays impinge on the objects surface and often exceeds the dynamic range and the contrast sensitivity of the X-ray detector. Transversal-CT is able to overcome these limitations by using a different scan geometry [5]. Here, source and detector move in opposite directions more or less parallel to the objects surface while continuously focusing a certain region of interest (ROI) within the object (see figure 4). The reconstructed CT image has a certain amount of clear CT cross sectional slices depending on the focal point. An increasing distance to that focal points manifests in defocused and blurred images, which is the drawback of this scanning method.

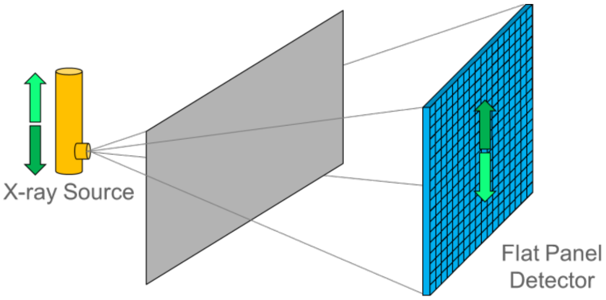

Figure 4: Transversal computed

Figure 5: CT system RayScan 250 E equipped with fibre composite parts, left: helicopter side panel, middle: frame part, right: floor element

Fibre composite components are often large in size paired with an extreme cross sectional aspect ratio which makes it necessary to use advanced scanning methods as described before.

Once the 3D-images are reconstructed, 3D image processing has to take place in order to obtain the required information. Various image processing algorithms and evaluation schemes for porosity determination [4][5], fibre orientation[1], texture analysis and other operations can be found in literature.

3 Experimental setup and results

The following paragraph shows the results of different kinds of measurements applied to fibre composite materials. The first measurement was performed on a RayScan 250 E CT System (see figure 5). The CT scanner has a 225 kV open micro focus X-Ray tube and a 16 bit 4MP digital flat panel detector mounted to a granite based 6 axis manipulation system. Different samples of a carbon fibre reinforced composite were measured in order to determine the porosity. Table 1 shows the measurement parameters.

Parameter	Value
Tube voltage / kV	200
Tube current / µA	100
Voxel size / µm	17
Number of projections	1890
Reconstructed voxels	2048^3
Scan method	3D-CT

Table 1: Measurement parameters

As the visual impression of the following images in figure 6 already indicates, the evaluation of the CT images revealed different porosity values of 5 %, 1.3 % and 0 %. For this purpose 3D-CT images give satisfying results.

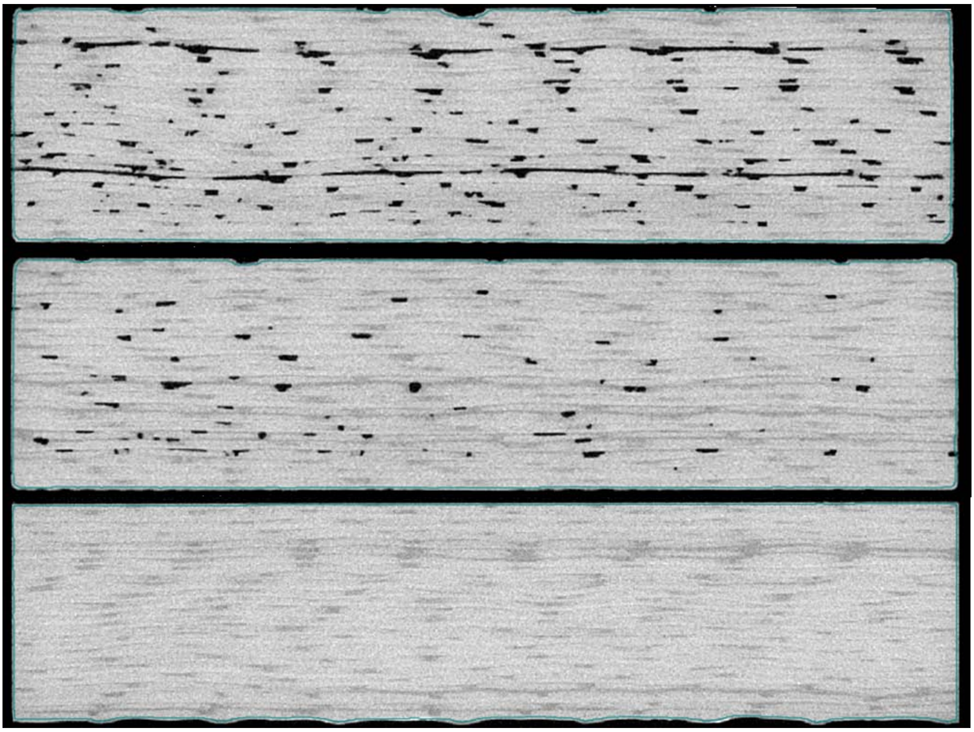

Figure 6: Different samples of a carbon fibre reinforced composites measured with 3D-CT. Porosity values were determined to 5 %, 1.3 % and 0 %.

The next measurement was made on a RayScan 200 XE CT-System. This CT scanner also has a 225 kV open micro focus X-Ray tube and a 16 bit 4 MP digital flat panel detector mounted to a granite based 5 axis manipulation system (see figure 7). In this case the measurement task was the non-destructive testing of a complete car body made of a carbon fibre reinforced polymer. Task was the evaluation of different damages to the structure and assessment of structural integrity of stressed regions.

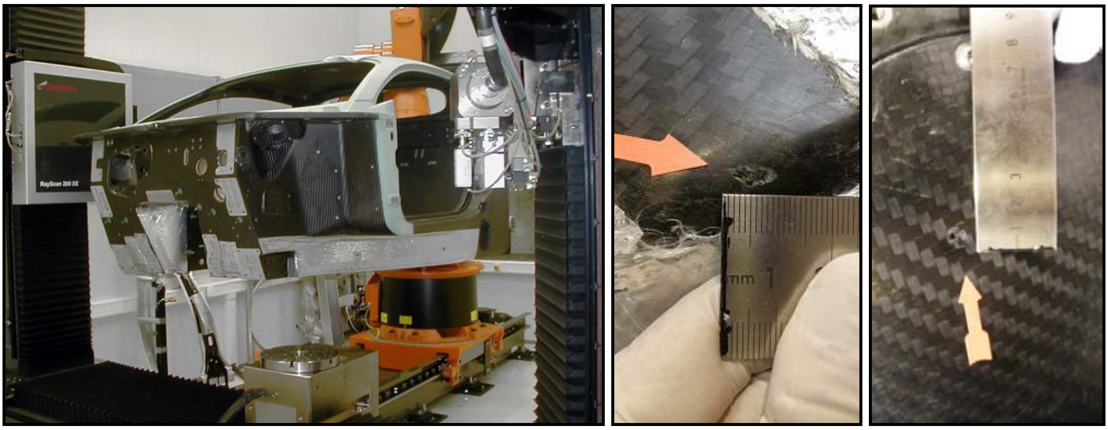

Figure 7: Experimental setup of a measurement of a complete car body made of fibre reinforced composite materials on a RayScan 200 XE CT-System. Left: Placed car body in the measurement field, middle: surface damage caused by a scratch, right: surface damage caused by an impact.

The results of these measurements revealed that the structural health of the car body was not at risk. As in figure 8 depicted, the surface damage caused by a scratch did not deform the underlying honeycomb structure. A little different are the results of the impact damage shown in figure 9. Here, the top layer of carbon fibres is broken and a damage of the underlying honeycomb structure can be found. Because of the very good spatial resolution of detail the defect propagation under the object surface can be examined very precisely.

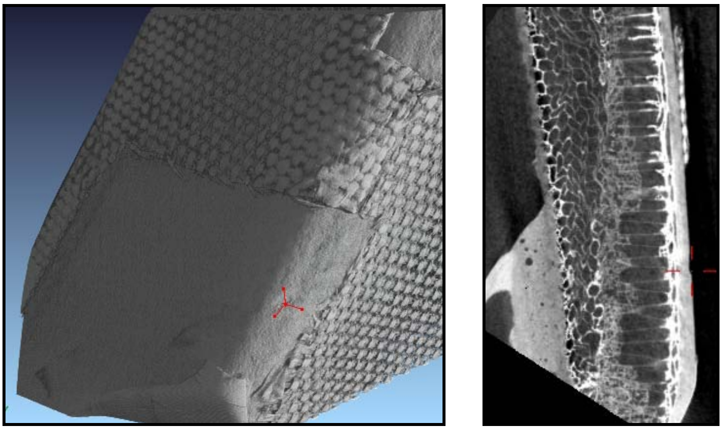

Figure 8: Results of the CT measurement of a part of a complete car body made of fibre reinforced material. Left: 3D visualization of the region under investigation, right: cross sectional slice of the damaged region.

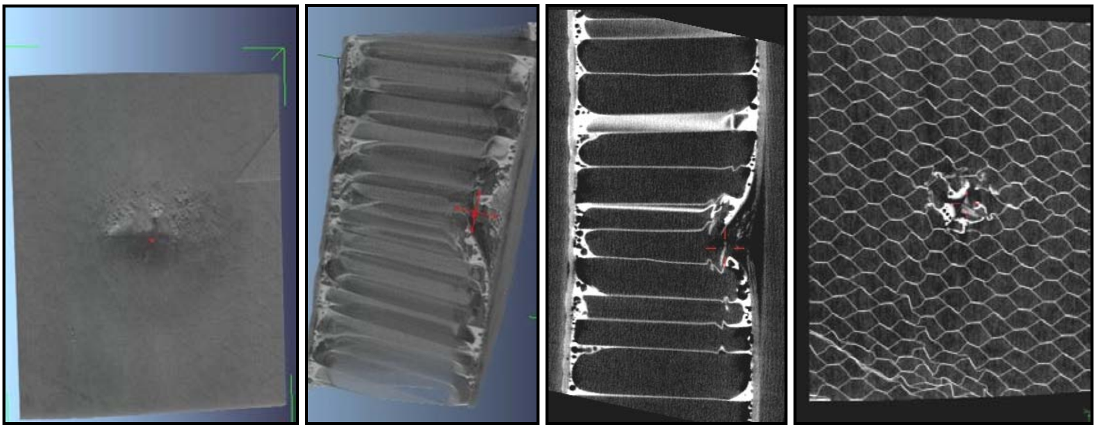

Figure 9: Results of the CT measurement of a part of a complete car body made of fibre reinforced material. Left most images: 3D visualization of the region under investigation, right most images: cross sectional slices of the damaged region.

The last measurement presented here, was also made with a RayScan 250 E CT-System according to the first measurement. The measurement task was to check the part for cracks and pores respectively air or resin inclusions. The experimental setup is shown in figure 10. Measurement parameters are given in table 2.

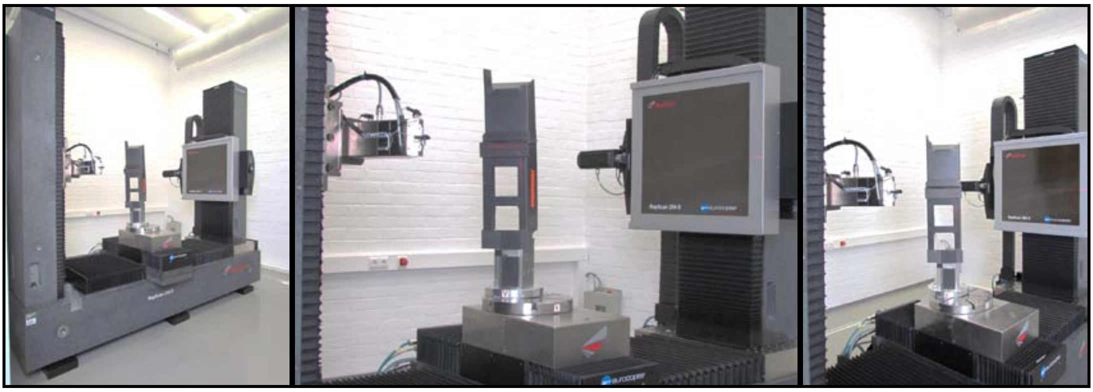

Figure 10: Different views on an experimental setup of a measurement of a carbon fibre reinforced composite part on a RayScan 250 E CT-System.

Parameter	Value
Tube voltage / kV	120
Tube current / µA	230
Voxel size / µm	23
Number of projections	1890
Reconstructed voxels	2048^3
Scan method	3D-ROI-CT

Table 2: Measurement parameters

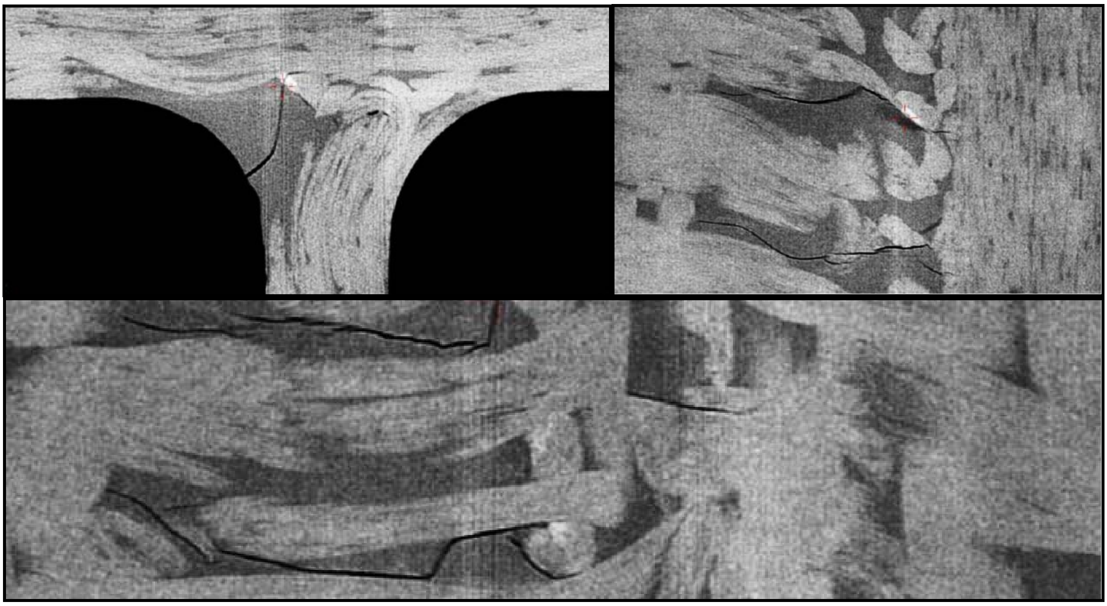

Figure 11: Different views on a CT image of a carbon fibre reinforced composite part. Several cracks can be found near the surface caused by a resin inclusion. Top left: XY-slice, top right: YZ-slice, bottom: zoomed XZ slice.

The results in figure 11 show that several cracks are present in a stressed region of the part. Reason for these cracks is a rather big resin inclusion near the object surface. The missing fibres reduce the toughness of the material in this region and lead to cracks within the structure.

3 Conclusion

The results show that typical errors and damage patterns of fibre component materials can be measured and visualized very well in most cases. Although parts are often large in size in either one or two dimensions and therefore have rather big aspect ratios, recent CT methods are able to solve the required measurement problems. Fields of ongoing research will be methods for metal artifact reduction in CT images of regions within the part where metal insets like bushes, plugs or rivets are present. But also alternative reconstruction methods for special orbits will be part of the future work.

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