XXL-Micro-CT
Comparative Evaluation of Microscopic
Computed Tomography for Macroscopic Objects

Wolfgang HOLUB ¹, Ulf HAßLER ¹, Christian SCHORR ², Michael MAISL ²,
Philipp JANELLO ³, Peter JAHNKE ³

¹ Fraunhofer Development Center for X-ray Technology EZRT; Fürth, Germany
Phone: +49 911 58061 7541, Fax: +49 911 58061 7599; e-mail: {wolfgang.holub,ulf.hassler}@iis.fraunhofer.de
² Fraunhofer Institute for Nondestructive Testing IZFP; Saarbrücken, Germany;
e-mail: {christian.schorr,michael.maisl}@izfp.fraunhofer.de
³ Materials Technology Nonmetal, BMW Group; München, Germany;
e-mail: {philipp.janello,peter.jahnke}@bmw.de

Abstract
Computed tomography (CT) is one of the most powerful means to inspect and characterize composite materials. However, the method in its basic approach is limited to objects whose projection images can fit on the used X-ray detector. In typical setups, the measurement volume limits the diameter of the object to no more than 400 mm. Motivated by the largest object of BMW’s i3, the car’s side frame, we investigated the applicability of different methods for Micro-CT of regions-of-interest (ROI) of this object with the objective to visualize structures like CFRP rovings in the composite material. We compared axial CT from limited acquisition angles with Tomosynthesis, CLARA laminography and RoboCT.

Keywords: CT, limited angle CT, short scan CT, laminography, tomosynthesis, CLARA, RoboCT, multi-angle radiography, defect detection, carbon fiber reinforced polymers, car body

1. Introduction

Today’s engineering uses composite materials like carbon fiber reinforced polymers (CFRP) for the lightweight and at the same time very strong construction of aerostructures or automobile components. The inhomogeneous structure of these composites requires NDE methods to be capable of displaying small features from few hundred microns for the inspection of porosities, inclusions and orientation of the larger structures (e.g. of fiber rovings) down to three to five microns for the visualization of single carbon fibers. Regular Micro-CT systems offer to acquire computed tomographies in the range from 200 µm voxel size at 400 mm diameter scan range down to few microns or even below for specimens of few millimeters in diameter. With these capabilities, Micro-CT is one of the most powerful means to inspect and characterize composite materials as long as the objects fit the laboratory scale. In their new electric vehicle (EV), the BMW i3, BMW’s engineers take advantage of these new materials’ properties by building the complete life-module from CFRP. The side frame is made of one single component with bounding box dimensions of approximately 3100 · 1500 · 200 mm³ and thus the largest single CFRP component of that car. For in-line or close-to-line inspection of these components it is of course unacceptable to cut out regions of interest (ROI) that fit in regular CT devices. This is why we have evaluated the applicability of different CT methods which are capable to deliver high-resolution three-dimensional cross-sections with not more than 100 µm voxel size of ROIs of the whole side frame.
2. Materials and Methods

2.1 Specimens

The idea of the study was to examine the detectability of small structures in feasible measurement setups for very large objects. For reproduction of the testing condition, small specimen platelets were attached to several components from the car frame.

2.1.1 Circular Carrier

The Circular Carrier (Figure 1) is the second largest object of the BMW i3. This component covers the range extender motor in the car’s trunk. The bounding box of that specimen is 1250 \cdot 900 \cdot 200 \text{mm}^3. It comes with 18 prepared positions where the specimen platelets can be attached to. There are several positions around the frame of the object, approximately parallel to its first principal plane and one additional position in the critical orientation for laminography, approximately orthogonal to the principal plane. The measurements were performed at one horizontal and at the orthogonal position.

![Figure 1: Circular carrier of BMW i3](image1)

2.1.2 Side Frame

The side frame (Figure 2) with bounding box dimensions of 3100 \cdot 1500 \cdot 200 \text{mm}^3 is the car’s largest component. There are prepared positions all over the side frame from which we chose one parallel and one orthogonal to the principal plane.

![Figure 2: Side frame of BMW i3](image2)

2.1.3 Platelets

For examining the detectability of different features in a test specimen, we selected a set of four out of many cut-outs with different material features or defects that were available at the materials technology lab of BMW. The cut outs have sizes in the range of 40 \cdot 80 \text{mm}^2 to
40 · 120 mm². They can be mounted to the different testing positions by plastic screws. Here, we present the comparison of the different methods on specimen #28 (Figure 3). This cut out is made from CFRP with layers of 0° and ±45° and shows severe in-plane undulations. For ground-truth, we performed a regular axial Micro-CT scan of the platelets at 45 µm voxel size. The CT image (Figure 4) shows the undulations of the carbon fiber rovings in the 0° layer of the textile. The platelet is slightly bent on its right side why we see glass fibers on the specimen surface close to the right screw.

![Figure 3: CT volume rendering of platelet #28 with mounting screws](image)

![Figure 4: Micro-CT slice through the 0° layer of specimen #28 with in-plane undulations](image)

2.2 CT Systems and Methods of Acquisition

Computed tomography systems do usually have measurement volumes with diameters of up to 400 mm due to the width of typical X-ray detectors. EZRT built the world’s largest computed tomograph, the XXL-CT [1] that is capable of acquiring full CT for a measurement volume of 3100 mm in diameter and 5000 mm in height. Such a measurement is too complex to be applied frequently in a laboratory environment and the resolution of the XXL-CT is still limited to 340 µm voxel size which does not suffice the requirements for visualizing small structures in composite materials. Laminographic methods like tomosynthesis or CLARA laminography allow the three-dimensional acquisition of ROIs from rather planar objects, i.e. of objects with one dimension significantly smaller than the others. Laminographies are limited information methods based only on a subset of the perspective data that is needed for full CT. This leads to anisotropic resolution in the object with limited in-depth information and results in different quality depending on the orientation of the ROI. Cutting-edge technologies like robot based CT allow extremely flexible trajectories for laminography and even full CT.

The different systems used in this study have a huge variance regarding their X-ray sources and detectors and focus detector distances. With respect to these basic conditions, aim of the study was not to compare the final systems in terms of speed, efficiency or cost but to compare the potential of the acquisition methods.
2.2.1 Axial Short Scan CT with Tomosynthesis Micro-CT System

EZRT’s new tomosynthesis system (Figure 5) is equipped with a regular microfocus tube with exchangeable heads both for reflective operation and transmission. For this study, the system was being used with a 3k × 3k detector with 148 µm pixel pitch. The specialty of this system are the very long axes of the manipulation system. The detector can be adjusted from 250 mm focus-detector-distance to 1700 mm, source and detector can be moved vertically by 2000 mm and there are horizontal axes of ± 750 mm for the detector and ± 130 mm for the source. Altogether this allows to perform Micro-CT scans down to 1 µm voxel size or up to 1700 mm scan diameter with measuring field enlargement. The long horizontal and vertical axes allow tomosynthesis under high angles and with very high resolutions.

In this study we used the tomosynthesis system for axial short scan CT (Figure 5) where the object is not rotated by full 360° but only by at least 180° plus opening angle of the cone beam. This allowed us to perform the scan with the object ROI close to the detector to achieve the planned resolution of 100 µm while adjusting the focus-object-distance so that the object can just pass by the head of the tube during rotation. With the same setup but with the ROI close to the source we performed another measurement at 40 µm voxel size for comparison.

Figure 5: Tomosynthesis Micro-CT system with side frame on the rotation stage

Movie: www.ndt.net/events/DIR2015/app/content/Movie/63_Holub.mp4

2.2.2 Tomosynthesis with Tomosynthesis Micro-CT System

One form of laminography is tomosynthesis [2], i.e. coplanar translational laminography. This means that X-ray source and detector move along translatory trajectories parallel to each other and parallel to a tomosynthesis plane in the object (Figure 6). The angle, i.e. here the radii of the circular trajectories influences the in-depth resolution. Both, side frame and circular carrier are rather flat, semi-planar objects. This enables scans with rather short focus-detector-distances.
2.2.3 Laminography with CLARA

With CLARA [3], Fraunhofer IZFP implemented a different setup for computed laminography. Figure 7 shows the CLARA device with the circular carrier on the turntable. Here, the object is rotated on a horizontal stage while X-ray source and detector are mounted to a frame tilted at an angle to the vertical axis. The perspective information collected by this setup is almost identical to the tomosynthesis approach. The main advantages of CLARA are the fact that less complicated manipulation effort has to be taken and that the detector is exposed to the central beam of the X-ray tube what makes exposure more efficient. One disadvantage is that the trajectories are not as flexible as with the Tomosynthesis setup.

2.2.4 Limited Angle CT with RoboCT

EZRT researches and develops robot based computed tomography. RoboCT uses industrial robots to manipulate X-ray source and detector. The step from cartesian axes systems to robots offers extreme flexibility in the implementation of scan trajectories for hardly accessible regions of interest and promises to give a wide potential in future mobile applications. Figure 8 shows the setup with two industrial robots and the side frame in one position from a circular limited angle acquisition around the tilted axis of the A-pillar. Algebraic reconstruction techniques allow to reconstruct those arbitrary trajectories. While still under development, RoboCT reached a technological level so that it is now being used for evaluation and for first prototypes in the industry.
2.2.5 Laminography with RoboCT
We used the same RoboCT setup to acquire data on a coplanar laminography trajectory as can be seen in Figure 9. We used our tool for trajectory planning to reproduce coplanar circular trajectories similar to tomosynthesis.

3. Measurements

3.1 Axial Short Scan CT
With the axial short scan CT, we could acquire a CT of a ROI volume with 267 mm diameter around the platelet at 100 µm voxel size. Figure 10 shows the measurement volume with truncated parts of the wooden rack that was used for positioning. Figures 11 and 12 show the corresponding slices from the 100 µm scan with the object close to the detector and from the 40 µm scan with the object close to the source. Both acquisitions were made with 800 Projections, i.e. an angular step of 0.3° and reconstructed with filtered backprojection. The structures in the platelet can be seen with almost identical quality as in the regular Micro-CT.
3.2 Tomosynthesis

Tomosynthesis was acquired at the resolution of 40 µm with a circular trajectory of 30° tomosynthesis angle and 100 projections. Figure 13 shows the resulting slice from the platelet mounted parallel to the trajectories of focus and detector. There is good contrast between fibers and matrix and the undulations can be recognized.
Figure 14 shows the same specimen mounted orthogonally. This is the crucial orientation for tomosynthesis where it suffers from missing in-depth information. In the image, we can still see the glass fibers, but the rovings are hardly visible. Only high contrasted or rather large structures can be identified in this case.

3.3 CLARA Laminography

A very similar geometry was used for the acquisition with the CLARA setup of Fraunhofer IZFP. 400 projections were taken from an acquisition angel of 30°. Figures 15 and 16 show the results of specimen #28 in parallel and orthogonal orientation. The noticeable difference to tomosynthesis is that here the orthogonal specimen orientation seems to be superior for the task of detecting single fiber rovings and undulations within. Parallel orientation shows much sharper contours while losing the actual attenuation information in the platelet. Orthogonal orientation misses contours in depth (missing horizontal edges in the image) while delivering good reconstruction of the attenuation in the object. Speculatively, that effect is due to the nature of algebraic reconstruction having difficulty dealing with limited information and truncated projections at the same time.
3.4 RoboCT Laminography

For laminography with the RoboCT setup, we parametrized circular coplanar trajectories with 100 projections on circles with 300 mm radius at a distance between focal- and detector-plane of 500 mm, i.e. at a laminographic angle of 17° (Figure 9). Figure 17 shows the reconstruction of the specimen. Similarly to CLARA laminography in this orientation, one can see the high contrasted structures like glass fibers and also the larger objects like the plastic screws but the contrast does not suffice to recognize single carbon fiber rovings.

![Figure 17: Slice of the 0° layer from the RoboCT Laminography at 50 µm specimen orientation parallel to the trajectories of source and detector](image)

3.5 RoboCT Limited Angle CT

We also used RoboCT to examine its capabilities towards full CT. The aim was to implement an axial limited angle CT with as much angular range as was possible. Since parametrization of a circle with arbitrary axis and diameter in space is not yet done in our tools, we ended up with a manually taught approximately circular acquisition of 120° angular range with 100 projections. Figure 18 shows the result of the reconstructed slice. Geometric deviations are obvious. The planar structures of the platelet are located on curved surfaces in the reconstructed volume. Speculatively, this is due to the combination of a manually taught trajectory and the high residuum for the geometrical calibration that comes from the robots working at the farthest points in their reach.

![Figure 18: Slice of the 0° layer from the RoboCT limited angle CT at 50 µm](image)

4. Comparison of Results

We identified one region of the specimen platelet that reflects all the facets that shall be detectable in these scans. This is the undulated region with a formed cavity without fibers close to the left screw of the CT slices. Figure 19 shows the comparison of cut-outs of this region with all the examined modalities.
As expected, the axial short scan CT performs best of all methods. Apart from minor artifacts from truncated data, it uses the same information as a regular Micro-CT. RoboCT gave promising and impressive results but also showed that there is still some work to do to be competitive also at these conditions with low contrast and small structures that are found in composite materials. Nevertheless, it is the most flexible of all methods in regard to accessibility of complex parts and flexibility for different objects. The laminographic methods showed their dependence on the orientation of the relevant ROI. Both methods provide good results for well orientation but drop off otherwise.

5. Conclusion

In this study, we could demonstrate applicable methods for the inspection of large objects that could not be handled by conventional Micro-CT systems. Especially methods that acquire data for full computed tomography without missing information can deliver CT images with hardly any trade-off in image quality compared to regular lab CT. Laminography can provide the same information as long as the acquisition can be set up so that the specimen is well oriented for the methods. It is very noticeable, that both methods give the relevant results with contrary orientation of the specimen although they are based on almost identical data. This might be connected to the different reconstruction techniques. Algebraic reconstruction and tomosynthesis could be improved by deeper knowledge of the causes.

Acknowledgments

This study was developed together with and funded by BMW Group.
The study contributes to MAIzfp, the NDT project in the German Leading-Edge Cluster MAI Carbon funded by the German Federal Ministry of Education and Research.
This study is partially based on results from the EU project QUICOM (Quantitative Inspection of Complex Composite Aeronautic Parts Using Advanced X-ray Techniques) funded by the 7th Framework Programme.

References