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# 3D tomographic characterization of sandwich structures

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ABSTRACT

Computed micro-tomography ($\mu$-CT) is widely used in non-destructive testing (NDT) of components and material characterization on the micro-scale. The investigation of industrial components is mainly concerned with the geometric characteristics and contour accuracy while in material science the focus is on the micro- and meso-structure of the applied materials or damage characteristics. The production of integrally formed sandwich materials poses a fundamental challenge for a separation of the scales and the successful measurement of characteristic features using $\mu$-CT. In this work we present several $\mu$-CT analysis techniques for a quantitative description of the processing parameters, the apparent micro- and meso-structure and impact deformation in sandwich structures. Therein the variations in honeycomb cell geometry and face-sheet fiber orientation are characterized using distribution functions extracted with 3D image analysis techniques. The knowledge of cell geometry thereupon allows the characterization of cell deformation due to varying impact loads. The detection of characteristic properties for an optimization of the process and a realistic localization of morphological weak spots and damage zones are demonstrated. Finally the restrictions of the methods are outlined and discussed with respect to the application range and application possibilities.

## 1. Introduction

The application of computed tomography (CT) in the field of NDT has proven to be especially useful in the investigation of micro- and meso-structures of composite materials [1]. Furthermore the realization of a three-dimensional representation of the structural composition allows, in contrast to traditional radiographic methods, the exact location of failure zones and irregularities. Due to the mostly lightweight composite structures and therefore the easy penetrability of X-rays several drawbacks of conventional tomography in material science like artefacts or sample thickness restrictions can be neglected. Since the fundamental mathematics for a simple reconstruction of the absorption contrast of an object from its 2D projections have been established in the 1980s [2,3], the implementation into modern computer hardware today additionally allows for high resolution and wide field of view imaging. Modern $\mu$-CT-systems with a focal spot size in the few micrometer range in combination with high dynamic range flat panel detectors provide a resolution down to 1 µm [4].

The application of a $\mu$-CT-analysis in the field of composite characterization is widespread. In case of fiber reinforced polymer matrix composites the spatial distribution and identification of single filaments, fiber bundles or fabric composition has been achieved (see e.g. [5]). For single fibers and fiber networks the fiber orientation and packing can be used to numerically model or calculate both conductive and mechanical properties of the composite [6,7]. For braided composites it is possible to characterize the shape and deformation in order to provide a realistic and micro-structurally exact input into finite element simulations [8].

For foam or resin components in composite matrices or adhesive joints especially the pore content is regularly analysed by $\mu$-CT measurements and is implemented as a standard operation in most $\mu$-CT analysis software packages. Furthermore it is also feasible to detect the pore shape and position to account for stress and strain effects beyond simple volumetric descriptions in the modelling of mechanical properties [9]. Recently even the in situ characterization of composites has been possible [10,11] providing the ability of 3D strain field measurements from $\mu$-CT data.

Nonetheless for sandwich components or hybrid lightweight structures there have been only few studies investigating the entire structure and not only single components. The focus in these studies has been mainly the qualitative assessment of structural properties as well as the investigation of failure initiation and failure progress [12]. The advantages of $\mu$-CT in the investigation of the core-face-sheet interface with respect to porosity could be first outlined in [13]. There the important advantages of the $\mu$-CT measurement methods have been

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highlighted and applied to different problems concerning sandwich material selection and design. One of these problems is the field of the non-destructive testing of impact events. The detection and shape description of deformations and delaminations in the vicinity of the impact point is essential for the investigation of damage evolution and damage mechanisms and has been employed by X-ray and microscopic 2D techniques in the last decades (see e.g. [14]). Here computed tomography provides a versatile tool-set for the characterization of the impact zone and the damage to the internal microstructure and mesostructure on a representative 3D basis [15,16].

However the analysis of the image data for hybrid material structures or lightweight composites often lacks the automation and comparability for a quantitative depiction of micro- and mesostructures or damage classification. At the same time the role of processing and handling is often not incorporated into the evaluation of the sandwich components which may otherwise reveal a close coupling between geometry, shape and microstructure formation. In this work we outline three methods with exemplary applications to honeycomb GFRP-sandwiches from an integral spray moulding technique. The goal of these methods is the automatic evaluation of user-defined characteristics and their representation in a form that explicitly reveals the relations between process setup and structural properties which determine the mechanical quality in the field of application.

## 2. Material and methods

### 2.1. Material properties, processing and mechanical testing

Sandwich composites are a combination of a stiff face-sheet carrying the tensile and compression load in the skin layer and a supporting core component separating the outer layers and bearing shear deformations. This combination offers an optimized bending stiffness of the entire structure. The sandwich manufacturing process is based on the recently developed, fully automated spray manufacturing of sandwich shell elements for automobile and railway vehicles. Therein the infiltration of the fiber architecture in the chopped strand mat (CSM) is simultaneous with the adhesion to the core component due to the penetration of excess polyurethane (PU) foam from the matrix into the open core cavities (see Fig. 1). A detailed description of the process parameters, polyurethane system and comprehensive mechanical properties of the sandwich can be found in [17–19]. The sandwich configurations investigated herein consist of a sinusoidal or hexagonal paperboard core with a 0.35 mm thick face-sheet layer.

The investigated face-sheet is build up from a CSM with a fiber volume fraction of 31% and an average strand length of 50 mm. The investigated core components are sinusoidal paperboard honeycombs (testliner paper 115 g/m$^2$) with a volume density of 57 kg/m$^3$ and hexagonal Nomex honeycombs ECA-I 4.8-32 [20]. The sinusoidal cell geometry, as provided by the manufacturer, is 8.97 × 4.97 mm$^2$ with a wall thickness of 180 μm. The core height in the initial state is 20 mm. For the polyurethane (PU) matrix deposition on the face-sheet an amount of 1160 g/m$^2$ was sufficient to achieve a rigid connection between face-sheet and core. The processing steps for the composite sandwich include the sandwich preforming of the face-sheet on the core and a subsequent robot controlled spraying with a low viscosity polyurethane system. The positioning in the compression mold and curing of the PU matrix at an elevated mould temperature of 150 °C finalize the process chain (see Fig. 2).

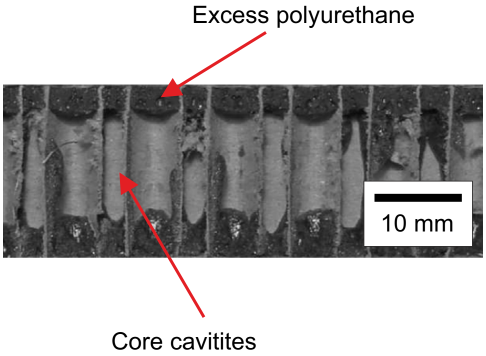

**Fig. 1.** Micrograph of the infiltrated core cavities for sinusoidal honeycomb cores.

For the impact testing of the sinusoidal sandwich an Instron Dynatup drop tower with a drop cage weight of 5.24 kg has been used. The impact energy was calibrated to 5, 10 and 20 J. The quadratic (140 × 140 mm$^2$) sandwich samples were clamped between two metallic plates with a circular cut-out of 100 mm diameter. The samples were struck at the center by a hemispherical indenter fixed on a load cell underneath the drop cage.

### 2.2. Computed tomography

The measurement process for tomographic data can be divided into two main tasks. Usually in a laboratory source radiographic projections are taken for a fixed angle increment over 360°. In a subsequent step the projections are reconstructed using the FDK algorithm [2] to obtain three dimensional image data sets. The $\mu$-CT measurements of different sandwich samples have been conducted on an YXLON Y.CT Precision $\mu$-CT System. The X-ray tube was operated at an acceleration voltage between 90 and 145 keV with a target current of 0.03–0.06 mA on a tungsten transmission target. The scanner gantry was set up in such a way as to obtain a maximum resolution (20–70 μm) whilst preserving the representative sample volume according to the characterization tasks. The reconstructed data sets from 2010 projections have a volume edge length of 2048 pixels and a varying volumetric picture element (voxel) size according to Table 1.

The projection data and the reconstructed slices of the 3D volume are finally stored as 16-bit 2D image stacks providing raw data with a size of approximately 32 Gb for the visualization and image analysis on a workstation equipped with four Xeon Quad-Core CPUs and 96 Gb of RAM as well as sufficient graphics hardware.

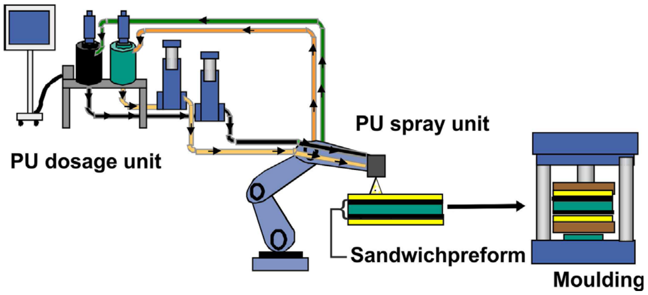

**Fig. 2.** Illustration of the integral processing steps.

**Table 1**
Setup of the $\mu$-CT-system for the different measurement tasks.

| Application | Voxel size (μm) | Voltage (kV) | Current (mA) |
|---|---|---|---|
| Core cell geometry/Wall thickness | 20.3 | 95.0 | 0.05 |
| Roving orientation | 31.0 | 90.0 | 0.03 |
| Impact damage | 69.0 | 148.0 | 0.06 |