IN SITU CT BASED DAMAGE CHARACTERISATION OF TEXTILE-REINFORCED CFRP COMPOSITES

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Abstract
With the aim of damage tolerant design of textile-reinforced composite structures, computer tomography (CT) based damage detection methods proved to be very promising if an in-situ measurement can be realised. For that purpose, an in situ CT test device has been developed using a high resolution CT-system in combination with a multi-axial test machine. The novel test device was used to study the damage phenomena in different textile-reinforced composite materials.

1 Introduction
In the field of lightweight engineering, basic design routines and methods of constitutive material modelling have consistently been enhanced in the past and considerable progress has been made to predict individual failure modes of textile composites [1-5]. However, a reliable damage evaluation, the persistent modelling of damage induced failure phenomena as well as approaches for classifying the failure interactions are still missing especially for carbon fibre reinforced textile composites [6]. Subsequently, this lack of knowledge results in considerable over-dimensioning in most of today's in-service textile-based lightweight structures [7,8]. Accordingly, a fundamental understanding of the complex relations between materials damage and failure behaviour and composite architecture must be used for an improved performance.
Promising results are expected if the damage behaviour of composites is analysed by computer tomography. In this context, the fundamental decision need to be taken whether classical CT scans or novel in situ CT scans should be used. Classical CT analysis shows a lot of disadvantages (hysteresis effects due to loading and unloading, crack closure during unloading etc.). Novel approaches try to establish in situ CT measurements for damage diagnostics [9-13]. However, these publications concentrate on experimental results and only give rare information about the experimental setup itself.
The presented study therefore proposes an experimental setup for in situ CT in order to analyse the damage in textile composites. A multi-axial test machine and a computer tomography are combines as described below. In this context, questions with regard to experimental practicability and reliable data generation need to be answered. The paper discusses the problems that arise from the chosen experimental concept (load transfer, specimen clamping, scanning time etc.). The failure behaviour of textile composites that are

loaded in thickness direction has been chosen as an example in order to discuss advantages and limitations of the novel in situ test device.

2 In situ computer tomography

2.1 Computer tomograph

For damage analysis of textile composites, an in-situ CT test device has been developed using the high resolution CT-system V|tome|x-L 450 (GE Phoenix X-Ray) with a 300 kV microfocus and a 450 kV macrofocus X-ray tube. The CT consists of a flat panel detector with 2048 x 2048 14 bit pixels where one pixel is 200 x 200 µm². Due to large optical scaling, the maximal resolution of the CT is 1 µm. Fig. 1 shows the used CT with the novel in situ device.

Figure 1. Computer tomograph V|tome|x-L 450 (left); In situ CT test device (right)

To observe the damage evolution in CFRP textile composites, it is necessary to perform a 3D CT-scan while the specimen is under load so that evolving cracks can be observed in its opened state.

2.2 In situ test device

To realise the constant load transfer during the scan of the specimen, a special test device was developed which fits into the rotary table of the CT. The device has to secure a X-ray transparent view onto the specimen from 360° while the testing machine is rotated during the CT scan. Additionally, the necessary load must be applied and measured in very small increments. For that purpose, a specially formed cylinder made of high strength aluminium is used since aluminium has a good X-ray transparency due to its low density and high mechanical properties to achieve a minimal wall thickness [14]. By using this homogenous tube, artefacts in the 3D-image can be avoided. The load is applied using a lift gear powered stepping motor with an additional planetary gearing so that a load increment of 45 nm can be theoretically realised.

Fig. 2 shows the realised load transfer unit for out-of-plane loading together with the difficult specimen clamping situation. For the planned tests in composite thickness direction, already small misalignment of the coaxiality of the test string can have larger effects on the observed failure behaviour. Due to the fact that such misalignments cannot be excluded because of specimen manufacturing tolerances, an adjustable compensation unit made of cone pulleys was additionally integrated into the test string. When in-plane loading should be investigated, the same load transfer unit is used. However, in this case, the load clamping system has to be adapted (Fig. 3).

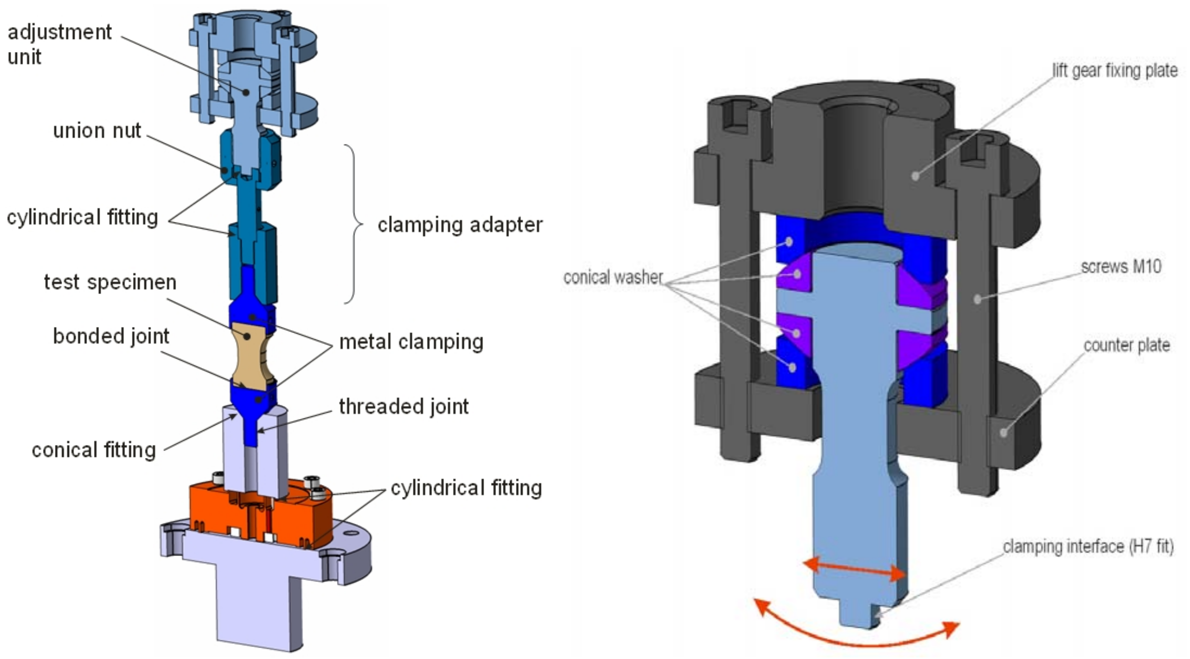

Figure 2. Load transfer unit and specimen clamping system within the in situ CT test device [22]

Figure 3. Clamping system for in-plane loading

3 CT based damage characterisation of textile-reinforced composites

3.1 Material

Multiaxially reinforced weft-knitted fabrics (MKF's) [15] are chosen as example for high-performance textile composites. Here, MKF's with biaxial reinforcement [0/90] are used. The reinforcing warp and weft yarns are fixed to each other with one or two stitching yarn systems. Fig. 4 shows the textile architecture determined by CT.

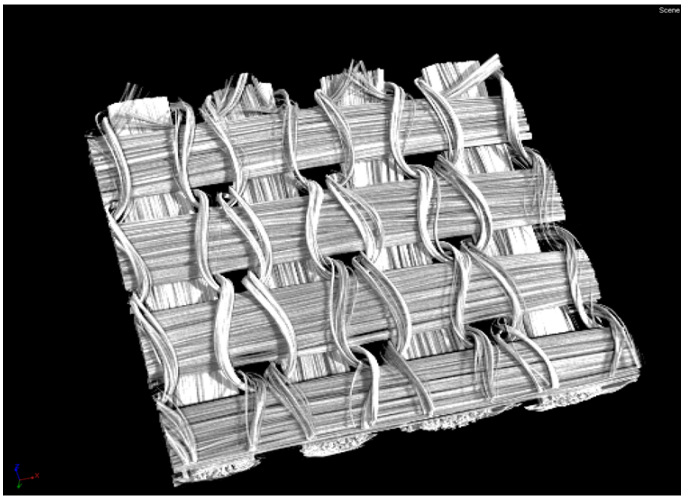

Figure 4. Textile architecture of the MKF-based composite determined by computer tomography

MKF's combine the advantages of stitched structures and reinforcing yarns with almost no ondulations. They feature high stiffnesses and strength values as well as very good draping behaviour and excellent crash properties. In this case, carbon fibre MKF's are infiltrated to CF/EP composites using RTM technology.

3.2 In-plane loading

As a preliminary study, stepwise in-plane tensile tests have been performed with subsequent damage analysis by CT. Tensile tests in 0°, 30°, 45° and 90° direction were conducted on $[0/90]_s$ specimens and stiffnesses and strengths have been determined according to the usual guidelines. Three specimens are tested in every direction up to total failure in order to determine the onset of damage (by acoustic emission) and the tensile strength. The load between onset of damage and failure is subdivided into 5 sectors which are also the CT scan levels. The final scan level was set to 95% of the strength in order to prevent failure during the CT scan itself.

Figure 5 exemplary shows three CT scans of a specimen tested in 0°-direction. The width of the tomograms also indicates the loading direction. The pictures clearly indicate the crack growth with increasing load. The results can be used to determine the crack density distribution which usually is an essential key parameter for analytical or numerical damage analysis. The results reported here are in good correlation with published data about the crack distribution in CFRP composites [16].

3.3 Out-of plane loading

Through-thickness loading was investigated with the in-situ test device shown in Fig. 2. The corresponding cylindrical specimens have been manufactured according to ASTM D7291. 135 MKF layers were used to infiltrate a 100 thick specimen with 47.1 % fibre volume content. Tensile tests have been performed in thickness direction with intermediate in situ CT scans at four different load levels. Selected specimens have been tested to failure without CT scans as reference values.

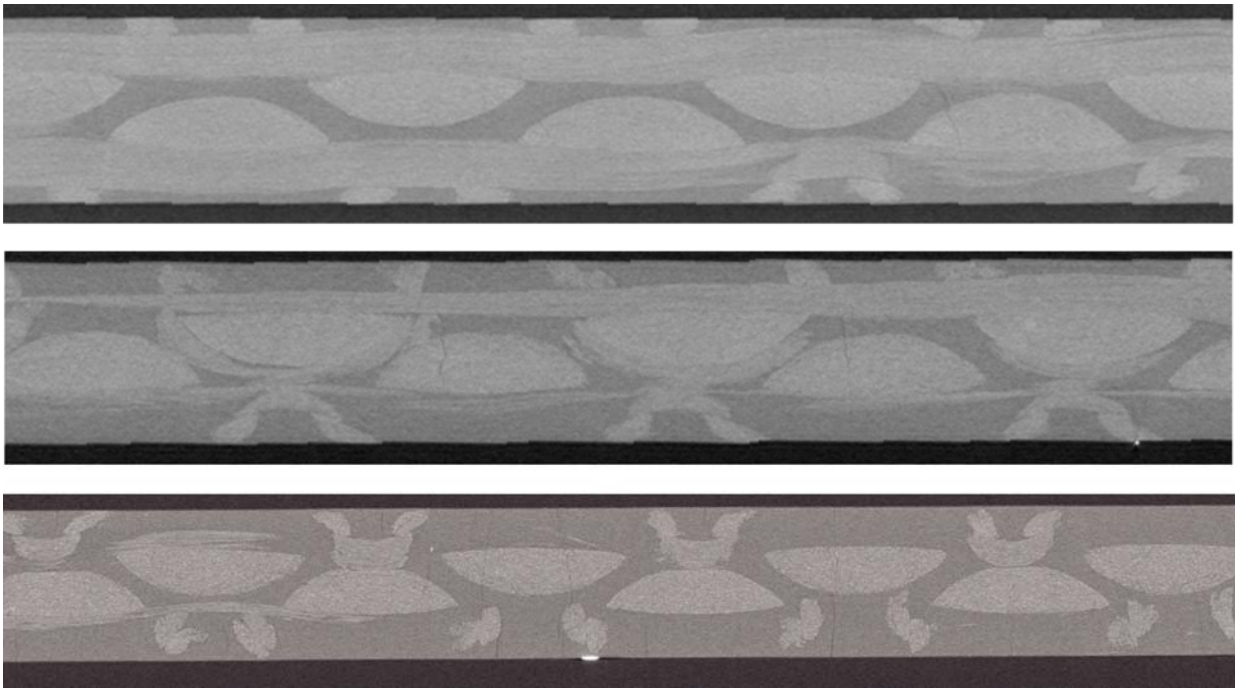

Figure 5. Tomograms of a MKF-CF/RP tensile specimen at different load stages: 375 MPa (top), 476 MPa (middle), 550 MPa (bottom)

Because the reference stress-strain curve is almost linear, the first CT scan was performed at 50 % of the reference strength. Every further tomogram was taken after a loading increment of approx. 1.5-2.0 kN. Figure 6 shows the CT scans for the same specimen at the four chosen load levels together with the initial scan. Pictures are given in all three axes of orthotropy.

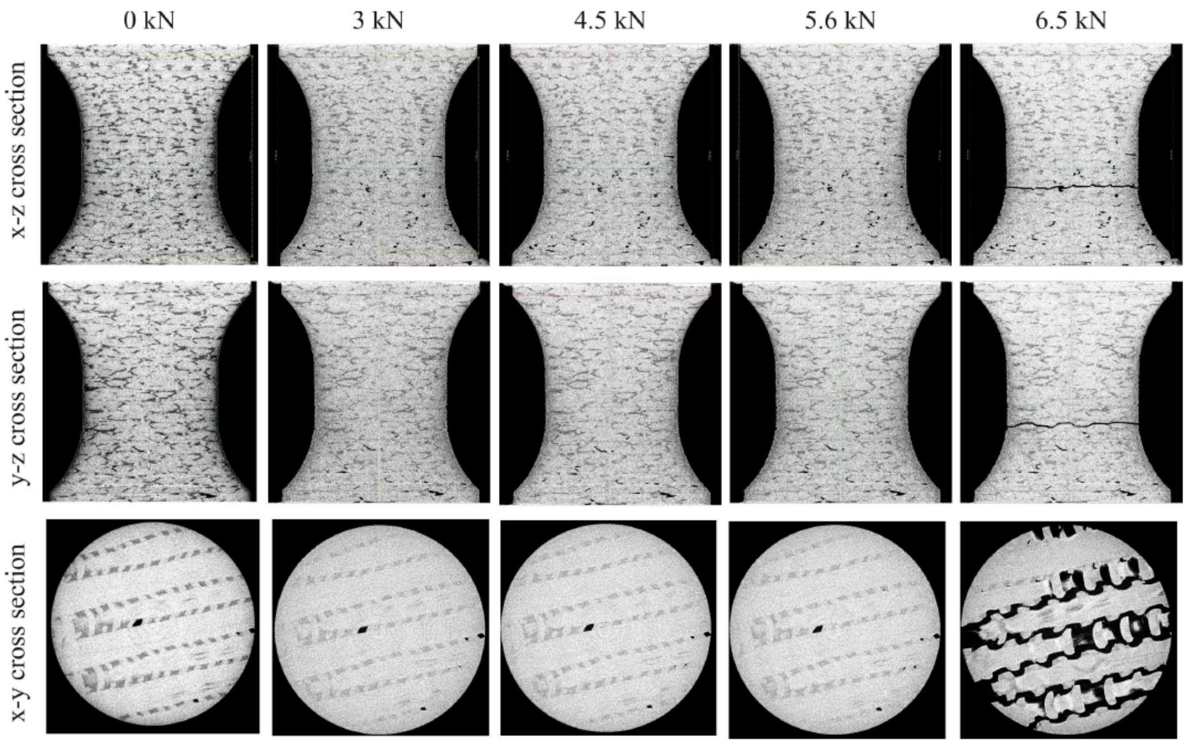

Figure 6. In situ CT scans of a through-thickness tensile MKF-CF/RP specimen at five different load levels [14]

In the case of through-thickness loading, purely brittle failure was observed. Before cracking, no damage was observed despite from voids which arise due to manufacturing restrictions.

The pictures indicate that the amount of initial damage within the specimen plays an important role for the localisation of brittle failure. Fig. 6 shows that the brittle crack is connected with the largest void in the specimen. This effect has been observed in all tensile tests.
The stacking sequence of the [0/90] MKF's causes two different interfaces in the specimen: one interface where the warp threads are located next to each other and one interface where the weft threads touch each other. In every tensile test, the crack surface is formed between the warp threads because this interface is significantly higher undulated. Due to the fact, that the void distribution is relatively homogeneous over the whole specimen, these two conclusions are not contradictory.

4 Conclusions

In situ computer tomography can be used as a quick and efficient method to determine damage mechanisms in composites. Especially for non-transparent materials, this method is the only way to detect matrix-dominated damage phenomena like matrix cracks or delaminations while a load is applied.
Novel textile composites with multiaxially reinforced weft-knitted fabrics have been investigated with an especially developed in situ test device. Specimens with $([0/90]_s)_n$ layup have been loaded in tension and the damage phenomenology was reported by CT scans. The obtained results of in-plane tests can be used to determine crack densities that are necessary for damage tolerant design studies. The proposed experimental setup is therefore of vital importance for advanced failure analysis of composites.
Beside purely phenomenological conclusions, the in situ test device can perspectively be used also for process analysis by finding correlations between initial defect volume and tensile strength. If void-free specimens can be manufactured, a significant strength increase can be expected.

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