Composites Science and Technology 110 (2015) 62–68

Contents lists available at ScienceDirect

Composites Science and Technology

journal homepage: www.elsevier.com/locate/compscitech

# A quantitative comparison of the capabilities of *in situ* computed tomography and conventional computed tomography for damage analysis of composites

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ARTICLE INFO

*Article history:*
Received 14 May 2014
Received in revised form 6 January 2015
Accepted 8 January 2015
Available online 7 February 2015

*Keywords:*
A. Textile composites
B. Fracture
D. Non-destructive testing
*In situ* computed tomography

ABSTRACT

The so called *in situ* computed tomography is a powerful non-destructive testing method to study the damage phenomenology while a material is loaded. However, the difference in the detected amount of damage compared to conventional CT scans after unloading of the specimen has not been reported so far and is therefore the focus of this study. Three different textile-reinforced composite materials have been experimentally investigated for that purpose. Carbon fibre reinforced epoxy composites with multi-layered flat bed weft-knitted fabrics and multi-axial non-crimp fabrics were uniaxially loaded in tension. *In situ* CT scans were taken at different load levels and conventional CT scans after unloading. The experiments have shown that the observed crack lengths and delaminated areas are significantly larger while the load is applied because of crack closure effects during unloading. Any damage diagnosis should therefore be performed under load. A ceramic C/C composite with woven reinforcement was taken as a third example. This composite was loaded by compression in thickness direction. It was found that the decrease of total porosity with increasing load can only be predicted by *in situ* CT measurements.

## 1. Introduction

The damage behaviour of composite materials has been the subject of extensive research during the last decades. Along with the development of material models which describe the different aspects of damage, the study of the damage phenomenology using suitable non-destructive testing (NDT) methods has been one major research focus [1]. Various NDT techniques and damage assessment methods are used for material model verification purposes or simply to achieve a better understanding of damage growth in composites. Crack density measurements [2,3], micrograph analysis [4,5], acoustic emission [6–8], thermography [9], ultrasonics [10,11] and video studies [6] are among the different used approaches. Their advantages and disadvantages are widely reported in the literature. Some of those NDT methods are frequently replaced by different non-destructive X-ray tomographic techniques in recent years. Compared to the NDT techniques and damage assessment methods mentioned above, microfocus computer tomography (CT) and synchrotron radiation CT offer significant advantages [12–14]. The different damage phenomena like matrix cracks, delaminations, fibre breaks or voids can be assessed with a very high resolution (up to 1 μm) and, probably more important, as a 3D visualisation.

The conventional procedure to use CT for damage analysis involves CT scans of specimens that have been loaded and unloaded before. The obvious disadvantage of this *ex situ* CT approach is that the observed damage status is inaccurately reflected because of crack closure effects. Due to that reason, novel developments focus *in situ* CT measurements where a CT scan is performed while the specimen is loaded [15–17]. The arising questions regarding design, construction and operation of such test devices are discussed in [17]. *In situ* CT measurements enable a very accurate damage assessment even at very critical loading conditions. Transverse ply cracks, splits, delaminations and even the break of single fibres in $[0/90]_s$-laminates that have been loaded up to 94% of the tensile strength are analysed in [18] using *in situ* CT. Void growth and crack growth in textile composite specimens loaded in thickness direction are studied in [17]. Apart from the composite field, *in situ* CT is additionally used in manufacturing engineering [19] and in biomechanics [20] as well as to quantify damage in alloys [21] and foams [22].

However, it has to be mentioned that the generation of high-quality results with *in situ* CT measurements requires a high

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http://dx.doi.org/10.1016/j.compscitech.2015.01.020

experimental effort. An important question is raised in that context: how large is the difference in damage amount that is observed with *in situ* CT compared to conventional CT measurements? This question becomes crucial in every damage study where a weighting between experimental effort and aspired accuracy has to be carried out. Such a quantitative comparison has not been reported so far and is therefore the aim of this paper. Three different composite materials are chosen: two textile-based CFRP composites with different textile preforms and a ceramic composite. The two textile-based CFRP high-performance composites are chosen because the damage phenomenology in textile composites is still not fully understood compared to classical UD-based composite. The ceramic composite was chosen in order to evaluate the potential of *in situ* CT measurements to deal with a large amount of initial damage. Different loading conditions are addressed: in-plane tensile loading and out-of plane compression. The damage process is evaluated with *in situ* CT and for quantitative comparison with the conventional CT method described above. All measurements (*in situ* and *ex situ*) for a given material were performed on one and the same CT without any modification on the test setup. Crack densities, delaminated areas and total void volumes are determined with both approaches: *in situ* and *ex situ* CT measurements.

## 2. Damage characterisation by *in situ* computed tomography

Because *in situ* computed tomography is a relatively new test procedure, standardised test devices do not exist by today. Two different *in situ* CT test devices have been especially developed and were used within this study. The *in situ* CT device which is used for tensile testing has been developed in previous studies [17]. Several details of the device are adjusted and continuously improved since that study. A 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 was combined with a small mobile uniaxial testing machine. The CT consists of a flat panel detector with $2048 \times 2048$ 14 bit pixels whereat one pixel is $200 \times 200\ \mu m^2$. Due to the large geometrical magnification, the maximal resolution of the CT is 1 µm. The testing machine is fixed to the rotary table of the CT. The whole *in situ* CT test device is shown in Fig. 1.

Due to insufficient resolution in the previous study, see [17], the load introduction element was modified. Originally, a stepping motor with a cumbersome and huge bevel gear has been used. This motor was replaced by a more compact wheel and the load is applied manually now. The distance between the X-ray tube and the test device was reduced from 300 mm to 60 mm by this modification. Thus, the scanning time could be reduced or the voxel resolution can be improved from 25 µm to 5 µm. The clamping adapter for flat tensile or compressive specimens can handle specimens with a maximum width of 30 mm and a maximum thickness of 12 mm. The specimen has to be fixed in the clamping unit outside the test device. To ensure a good force transmission, the clamping jaws have transversal grooves and a bolt to center the specimens. After fixing, the clamped specimen is assembled into the test device, see [17].

A novel *in situ* CT machine was used for the compression tests in thickness direction. The *in situ* CT device FCTS 160 which was developed in cooperation with Zwick/Roell enables CT scans while a specimen is multi-axially loaded. Fig. 2 shows the multi-axial *in situ* CT device together with a schematic description of its technical components. In contrast to the device described above where the CT is fixed and the specimen rotates on the rotary table, the whole CT unit of the FCTS 160 rotates around a fixed specimen. The FCTS 160 consists of a 160 kV microfocus X-ray tube with a minimum focal spot of lower than 3 µm and a flat panel detector with $3200 \times 2300$ 14 bit pixels whereat one pixel is $127 \times 127\ \mu m^2$. The Zwick/Roell Z 250 tension/compression-torsion test machine enables maximum forces of 250 kN and maximum torsion moments of 2000 Nm to be applied. Both approaches (rotating sample/rotating CT) have assets and drawbacks. With a rotary table, stationary conditions for the X-ray tube can be guaranteed and the distance between source and detector can be larger. On the other hand, load introduction elements like the used aluminium cylinder are arranged in the beam path and specimen vibrations could possibly influence the measurement. When a system with rotating CT and stationary sample is used, no additional movement of the specimen occurs but the variable conditions for the X-ray source could possibly lead to blurrings due to the moving focal spot.

## 3. Experiments

### 3.1. Materials and specimen geometry

Three different materials were examined within this study: two carbon fibre reinforced epoxy composites, one reinforced with a

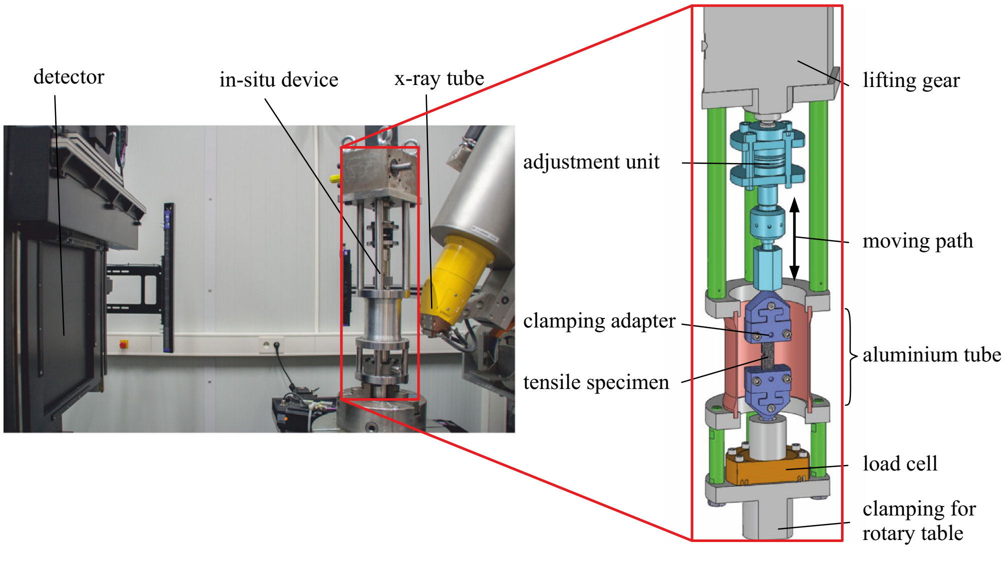

**Fig. 1.** *In situ* CT test device (left) and scheme with technical components (right).