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COMPOSITES THEORY AND PRACTICE

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COMPUTER TOMOGRAPHY-AIDED NON-DESTRUCTIVE AND DESTRUCTIVE TESTING IN COMPOSITE ENGINEERING

The inner material structure as well as voids and damages in composite materials have a significant influence on mechanical material behaviour. Thus, for a reliable application of composites in safety relevant lightweight structures, knowledge of the inner material structure is of utmost significance. Computer tomography is an especially important part of non-destructive testing (NDT) both in research and industrial applications for non-transparent composites. Besides that, a novel in situ CT which enables the preparation of tomograms of specimens under loading conditions offers a better understanding of damage processes in composites. The paper gives examples for the advanced analysis of fibre-reinforced composites and their degradation behaviour using novel CT systems. The advantages of high resolution CT scans as well as corresponding FEM results are shown and an overview of the numerous application possibilities is given.

Keywords: textile composites, fibre reinforcements, non-destructive testing, in situ computed tomography

TOMOGRAFIA KOMPUTEROWA WSPOMAGAJĄCA NIENISZCZĄCE I NISZCZĄCE BADANIA W TECHNIKACH KOMPOZYTOWYCH

Zarówno struktura wewnętrzna materiału, jak również nieciągłości i uszkodzenia w materiałach kompozytowych mają znaczący wpływ na właściwości mechaniczne materiału. Dlatego w celu bezpiecznego zastosowania kompozytów jako struktur lekkich znajomość wewnętrznej struktury materiału ma ogromne znaczenie. Szczególnie tomografia komputerowa jest ważną częścią badań nieniszczących (NDT), zarówno w przemyśle, jak również w wykorzystaniu kompozytów nieprzeźroczystych. Poza tym nowoczesna technologia badania in situ CT, która umożliwia wykonanie tomogramów badanych obiektów w warunkach obciążenia, pozwala na lepsze zrozumienie procesów powstawania uszkodzeń w kompozytach. W artykule przedstawiono przykłady zaawansowanej analizy struktury kompozytów włóknistych z wykorzystaniem nowych systemów CT pozwalających na zaobserwownie procesów ich niszczenia oraz zaprezentowano zalety wysokorozdzielczej tomografii komputerowej wraz z wynikami MES oraz przykładami jej praktycznego zastosowania.

Słowa kluczowe: kompozyty włókniste, wzmocnienie włóknami, badania nieniszczące, tomografia komputerowa in situ

INTRODUCTION

Non-destructive x-ray testing methods including CT present a unique combination of advantages. On the one hand, they are easy to use and the basic principles are very well understood. On the other hand, they enable a look inside components and samples of various materials, sizes and shapes to identify, quantify and evaluate internal structures, voids and damages induced by production, processing or loading [1-3].

Because of these advantages, 2D and 3D x-ray imaging techniques are extensively used in manufacturing for failure detection and metrology as well as in research for identifying damage mechanisms. The possible types of failures in fibre-reinforced composites after production include pores inside the matrix as well as insufficient infiltration of fibres or textiles. Furthermore, delaminations, fibre pull-outs and different types of cracks can be expected after loading previously undamaged parts.

CT systems are becoming increasingly more powerful as new developments in beam generation and detector technologies are available: So-called diamond window targets allow for higher intensity and better contrast while lowering the required power and therefore enhancing the resolution [4]. This in addition to increasing detector sensitivity leads to a significant decline in acquisition time and also costs.

At the same time, new fields of application are unlocked for computer tomography: in-line CT systems are improving the process control of casted components in the automotive industry [5] while in situ scans of fibre-reinforced polymers deepen our understanding of composites and their failure behaviour [6, 7].

This paper gives an overview of the broad potential of CT in composite engineering starting from the analysis of the inner structure and its modelling to the damage and degradation analysis of composite materials and complex structures.

BASIC PRINCIPLE OF X-RAY TECHNOLOGY

Inside a vacuumed x-ray tube, thermal electrons are emitted from a heated tungsten filament and are accelerated and focused onto the target. Entering the target material, the electrons are decelerated via deflection in the atom force fields resulting in a continuous spectrum that is called bremsstrahlung. The maximum energy of the spectrum is limited by decelerating an electron in only one step transforming its entire kinetic energy into one single photon. This limit energy E_{max} is given as

$$E_{\max} = e * U_a = h * \nu_{\max}$$

Here, U_a is the acceleration voltage, ν_{max} the maximum of the frequency and e and h are the charge of an electron and Planck's constant respectively [8].

It may occur that an incoming electron collides with one of the target atom electrons leaving a void that is filled by an electron of a higher energy level. The energy difference is emitted as a photon of discrete energy and therefore wavelength. The entity of these discrete peaks forms the characteristic x-ray spectrum which is superimposed with the bremsstrahlung but contributes only a little to the overall intensity. The acceleration voltage and the target material define the shape of the spectrum which is the energy distribution of the emitted photons. The higher the acceleration voltage, the higher the maximum energy of the photons. A target material with a higher atomic number will lead to a faster deceleration of the atoms and therefore result in a narrower spectrum with a higher average energy. The x-ray cone beam exits the tube through a window made of beryllium. Afterwards, the radiation is absorbed, scattered or transmitted by the specimen. The amount of absorption on a path through the specimen depends on the initial intensity, the specimen materials (atomic number, density) and their thickness:

$$I = I_0 * e^{-\mu * l}$$

with I_0 as the initial intensity, μ the linear absorption coefficient and l the path of the beam inside the material.

Nowadays, flat-panel x-ray detectors are commonly used. They consist of an array of elements made of a photodiode and a thin-film transistor (TFT). The detector itself is covered with a scintillator layer which transforms x-ray radiation into visible light.

CT TECHNOLOGY AND SYSTEMS

A typical CT scanner consists of an x-ray tube, a detector and a sample holder including a rotation unit (Fig. 1). Whereas in medical CT scanners the tube and the detector are rotated around the object, in industrial CT scanners the position of the tube and the detector is fixed and the object rotates. At each step of the rotation, a radiographic image is gathered and saved. These projections are then used to reconstruct the volume after the scan.

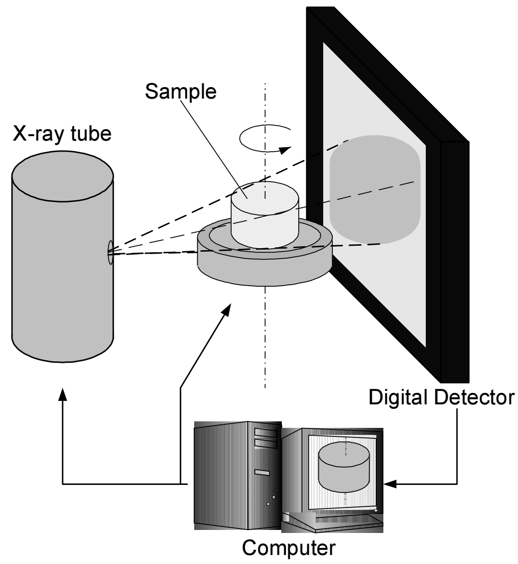

Fig. 1. Setup of industrial CT system

Rys. 1. Konfiguracja systemu CT przemysłowej

At the Institute of Lightweight Engineering and Polymer Technology (ILK), two dedicated CT systems are installed: the GE phoenix v|tome|x L 450 and the phoenix|x-ray nanotom 180NF. The v|tome|x L 450 is a large CT system that is capable of holding and scanning specimens up to dimensions of (2500 x 920 x 920) mm³ and a weight of 200 kg. In combination with a high-power x-ray tube, it enables one to evaluate even very large components such as fan blades or structural parts made for the aerospace or automotive industry. It is equipped with two x-ray sources: the first one is a 300 kV microfocus tube mostly used for quality assurance and damage assessment of components made of fibre-reinforced polymers. The second one is a 450 kV macrofocus tube mainly used for the analysis of highly absorbing materials like steel. Furthermore, there are two different types of detectors: A large, high-gain flat-panel detector with a pixel size of 200 µm which allows for short acquisition times combined with high contrasts providing either high resolutions of up to 1 µm or a large volume of about (330 x 330 x 330) mm^3 in one scan.

On the other hand, there is a line detector that is less susceptible to scatter and therefore provides an even better contrast while only scanning a very small disc of the specimen. Hence, the complete scan of a large component will take significantly longer compared to examining the same component with the flat-panel detector.

The nanotom 180NF is equipped with a flat-panel detector with a pixel size of 50 µm and a nanofocus x-ray tube providing a maximum acceleration voltage of 180 kV. Depending on the sample size and required power, CT scans with a resolution of up to 0.5 μm are possible. The size of the samples is limited to (150 x 120 x 120) mm³ and the CT system supports a maximum mass of 2 kg. Each CT system is equipped with a dedicated workstation for data handling, reconstruction and visualisation using datos|x 2.0 and VGStudio MAX 2.1 or VGStudio MAX 2.0.

Recently, an in situ apparatus that can be mounted into the v|tome|x L 450 system was developed (see Fig. 2). Its construction principles have been published in detail [7, 9]. It allows for compression, tension and bending tests with maximum forces of 50 kN depending on the used adapter. The in situ CT system enables for the first time, the recording of tomograms of specimens and structures while being loaded.

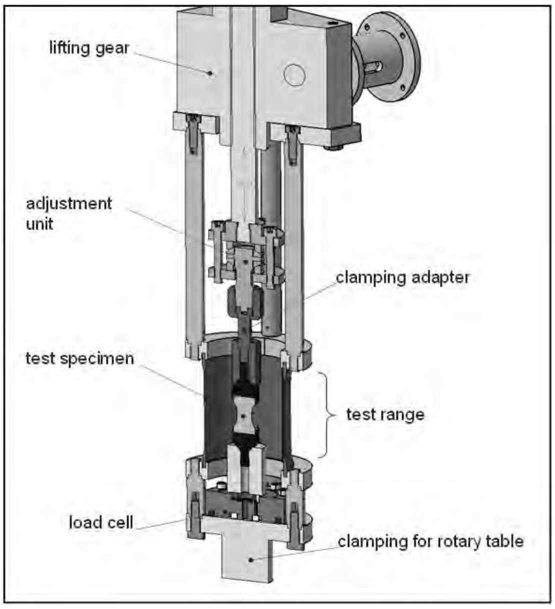

Fig. 2. Design of in situ apparatus developed at ILK

Rys. 2. Konstrukcja urządzenia in situ opracowana w ILK

Currently, a third CT system is being developed, which is a combination of a Zwick testing machine with a maximum tension/compression force of 250 kN and a maximum moment of torque of 2000 Nm and a high-resolution CT system inside the testing device. The CT system itself will be mounted on a turning table and will provide a maximum resolution of up to 1 μm with a maximum acceleration voltage of 160 kV.

EXAMPLES OF APPLICATION

Quality assurance

The mechanical properties of fibre-reinforced polymers are very susceptible to changes in their inner structure. The quality assurance of as-produced components and parts is vital to ensure their performance and their reliability. For opaque components, where optical examination might not be sufficient, computer tomography provides detailed information about the orientation and the volume fraction of fibres as well as the size, volume fraction and location of voids.

As an example, high resolution CT scans with a resulting voxel size of 3 μm were conducted on glass fibre-reinforced polypropylene with a three-dimensional multilayered weft-knitted textile fabric (MLG) reinforcement structure (Fig. 3). It could be shown that after infiltration with resin transfer moulding (RTM), the majority of voids were situated in the area between the rovings of adjacent layers, while the rovings were satisfactorily infiltrated.

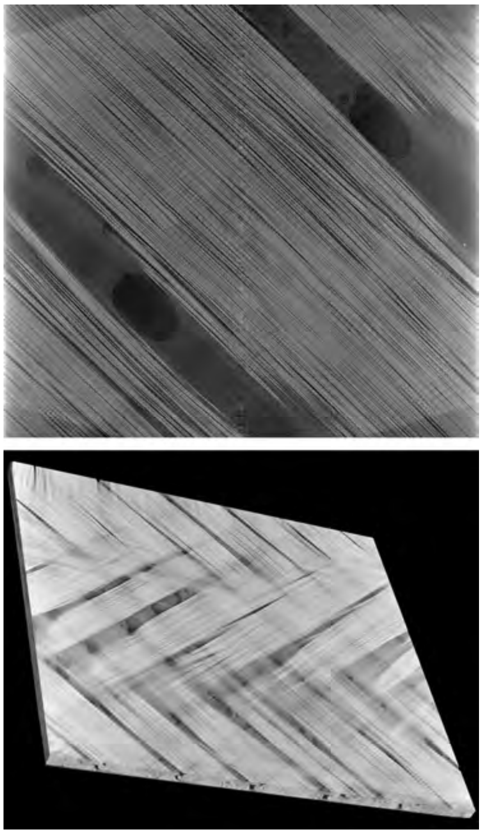

Fig. 3. Textile-reinforced GF-PP sample and voids in between rovings

Rys. 3. Próbki GF-PP wzmocnione włóknem szklanym wraz z nieprzeinfiltrowanymi przestrzeniami pomiędzy rowingami dzianiny wątkowej

CAD and FE model generation

For the numerical simulation of the deformation and damage behaviour of composites with complex textile reinforcements, modelling via representative volume elements (RVE) is advantageous. Here, CT can be used to gain a CAD model of the inner structure of real composite specimens including their manufacturing effects. On the example of carbon fibre-reinforced aluminium, this procedure is illustrated in Figure 4 in which the complex textile-reinforcement architecture can be seen. Textiles made from different types of carbon fibres were infiltrated via gas pressure infiltration with magnesium alloys of varying aluminium content. To evaluate the quality of the specimens aside from mechanical testing, small samples were prepared which then were examined in the v|tome|x L 450 CT scanner. The used parameters were an acceleration voltage of 160 kV, a beam current of 150 μA and a voxel size of 9.60 μm. Because of the high resolution, it was possible to extract the interface between the fibre and the matrix and export this surface to a CAD model. The containing information led to the generation of a unit cell which then was integrated into a FEM model allowing further investigations and improvements concerning the design and production of those metal matrix composites.

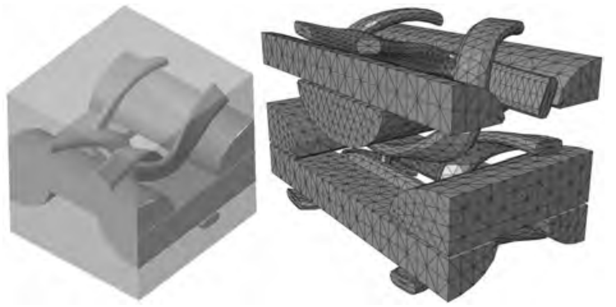

Fig. 4. Resulting reinforcement structure after manufacturing (left) and associated CAD and FE model (right)

Rys. 4. Struktura zbrojenia po procesie produkcji (z lewej) oraz model CAD i MES (z prawej)

One of the biggest advantages of reinforced polymers is the possibility to tailor their properties depending on the application. Usually this is done by adjusting the component structure regarding the type and orientation of the fibres as well as their positioning in the component and to each other. Once the structure is manufactured, there is little possibility to change these inherent properties. Magnetoelastic composites (MEC) are an interesting way of influencing the stiffness of a component online. Through a magnetic field, the stiffness can be adjusted to different loading conditions and therefore various scenarios of application. To assess the possible advantages of MEC as well as modelling their reaction to magnetic fields of different magnitudes, detailed knowledge of the as-produced structure is required. For that purpose, CT scans of log fibre-reinforced polyurethane (LFT-PUR) specimens were obtained to relate their structure to their properties (Fig. 5).

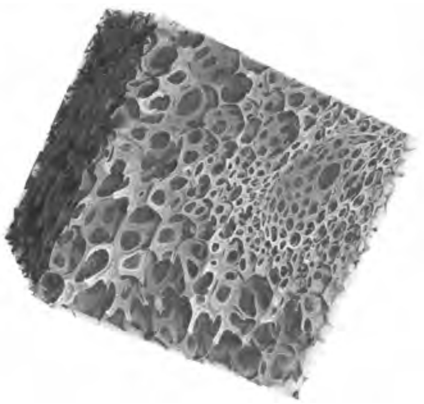

Fig. 5. Cellular LFT-PUR specimen after manufacturing

Rys. 5. Próbka komórkowego LFT-PUR po procesie produkcji

Damage analysis

Besides small specimens, larger lightweight structures can also be analyzed regarding their manufacture quality or damage phenomena after loading. As an example, a lightweight seat pan with integrated stiffeners and dimensions of about (1000 x 500 x 70) mm³ was developed and fabricated at the ILK using a combination of organo sheets made of glass fibre-reinforced polypropylene and a structure made of long fibre-reinforced thermoplastic (LFT). The technology and the used materials were published in [10]. The structure was scanned before and after mechanical testing with the v|tome|x L 450 CT system (Fig. 6). As this component consists of two different types of material combined in a hot pressing process with a 3000 t press, the interface between both phases and the orientation of the long fibres were of special interest after mechanical loading. The aim was to assess the degree of damage, examine the main modes of fracture, conduct topographic measurements and export the CAD volume. In both cases, the specimen was scanned with a 300 kV x-ray tube using an acceleration voltage of 230 kV and a beam current of 200 μA. A voxel size of 40 μm could be obtained using a magnification of 5 times.

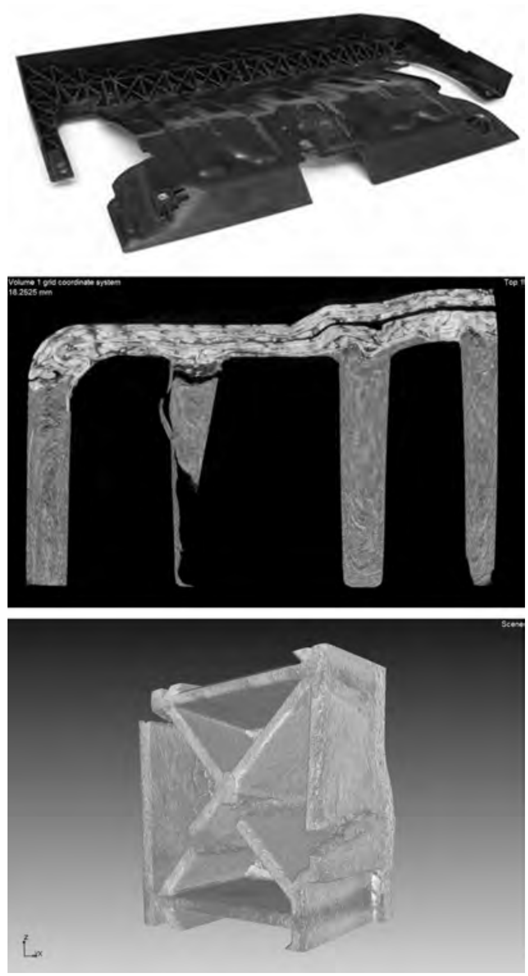

Fig. 6. Stiffened lightweight seat pan and associate tomograms of stiffened area showing cracks and delaminations

Rys. 6. Użebrowanie struktury nośnej lekkiego siedzenia polimerowego oraz jego tomogramy pokazujące pęknięcia i rozwarstwienia

A further example shows the predominance of CT versus ultrasonic testing. A curved composite plate made from TWINTEX was examined after impact testing using an air-coupled ultrasonic C-scan. The analysis revealed that the impact resulted in delamination in a specified area. However, due to the limitations of ultrasonic testing, one has no information regarding the distribution of the delamination across the thickness of the specimen. Computer tomography offers a huge advantage when dealing with this kind of damage: it enables the user to not only detect the cracks, but also to locate them and measure their extensiveness. To allow for this kind of analysis, a scan with a high contrast and a high resolution is necessary. A beam current of 300 μA and an acceleration voltage of 120 kV were chosen to ensure a high contrast while minimizing the power. In combination with the small sample size that allows for a high magnification, a resolution of 16 μm has been achieved (Fig. 7). Due to the high quality of the CT scan, it was possible to determine the sample depth where the cracks were situated and their thickness with a maximum value of 70 μm as well as their length. This knowledge can be used in FEM models to evaluate the damage tolerance of composite components and to improve their design.

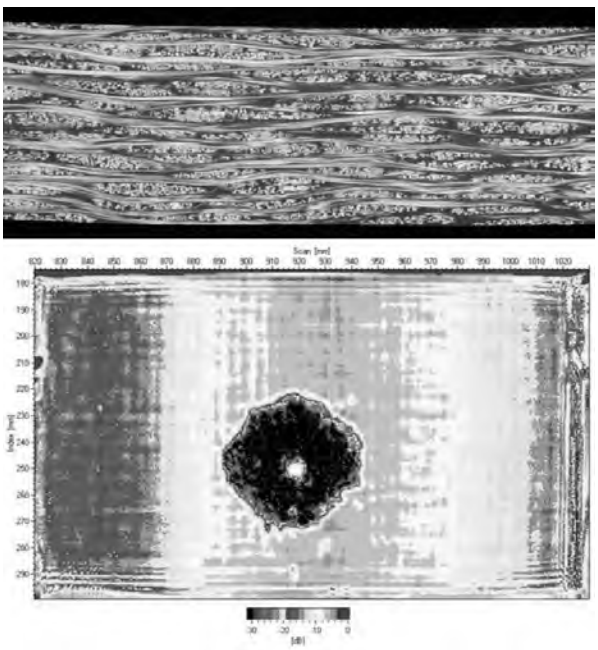

Fig. 7. Comparison of CT scan (top) and ultrasonic C-scan (bottom) of impact-induced delamination

Rys. 7. Porównanie wyników tomografii komputerowej (na górze) analizy ultradźwiękowej w postaci C-SCANu (na dole) rozwarstwiania powstałego po uderzeniu

Advanced damage analysis by in situ CT

In situ computer tomography can be used to assess the crack development and progression of carbon fibre-reinforced specimens for in-plane loading. For that purpose, a small in situ apparatus was developed and built at the ILK. The specimen is fastened inside the apparatus and both are fixed inside the CT. A scan without force serves as a reference. A defined tensile force is applied and the next scan is started once the desired load is reached. Successively, the load is increased and the sample is scanned, without the need of removing the specimen from the CT. Apart from saving time, the in situ approach is also advantageous concerning the detectability of resulting cracks. Since the load is kept steady during the scan, it is less likely for cracks to close and become unverifiable due to their small size. The acceleration voltage for the +45°/–45° sample was set to be 200 kV and the beam current was 300 μA. A short detector exposure time of 250 ms allowed for scan times as little as 18 minutes.

As both cross sections show the same plane in the sample, the degradation from 71 to 112 MPa is clearly visible (Fig. 8). The cracks formed at the matrix-fibre interface and also at the surface of the specimen. With the help of the in situ CT, the crack propagation over the course of the experiment can be visualised and analysed and damage models can be validated which will lead to a better prediction of damages and durabilities of components made of carbon fibre-reinforced polymers.

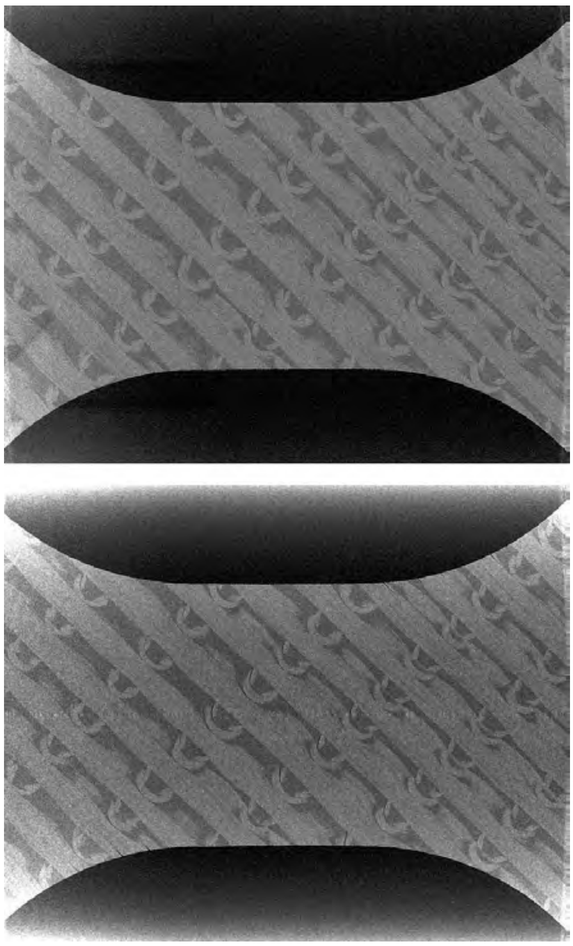

Fig. 8. Degradation of carbon fibre-reinforced polymers from 71 MPa (top) to 112 MPa (bottom) load during in situ testing

Rys. 8. Różne zjawiska uszkodzenia polimerów wzmocnionych włóknem węglowych podczas badań in situ obciążonych odpowiednio 71 MPa (na górze) do 112 MPa (na dole)

CONCLUSION AND OUTLOOK

As seen in this article, x-ray computer tomography presents a very useful tool for qualifying and quantifying damages and failures in composite components. Because of its high resolution and broad spectrum of applications, it is used more frequently in quality assurance and the research of polymer composites.

In comparison to other NDT methods like ultrasonic testing and thermography, this technique proves to be especially beneficial when it comes to small features and extracting CAD or FE models for further understanding and simulation of degradation mechanisms. It is uniquely qualified for reverse engineering and a very helpful tool to develop and further improve manufacturing processes.

Although promising results concerning initial and spreading cracking of fibre reinforced composite specimens were obtained, it is expected to even deepen the understanding in composite engineering by installing a more powerful in situ CT system in the near future.

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