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Damage detection and classification in composite structure after water-jet cutting using computed tomography and wavelet analysis

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ABSTRACT: The proposed method of processing of X-ray Computed Tomography (CT) data is based on its three-dimensional (3D) wavelet analysis, which allows for detection and localization of sudden changes in voxels of CT data array. The applied wavelet transform can be considered as filtering using sets of low-pass and high-pass filters over directions of a domain. The internal damage, which initially has different spectrum than the healthy regions of a structure, are emphasized after the wavelet analysis and depending on its intensity in the CT data array the wavelet coefficients become different for them. The tests were performed on the carbon fibre reinforced composite plate. The water-jet method was used for cutting of a circular hole inside. During the cutting process several delaminations in various layers occurred. Moreover, during the manufacturing process several air pockets in the matrix appeared. Application of the proposed processing algorithm allows not only for detection and localization of internal damage but also its classification by a type. It is possible due to analysing the magnitude of wavelet coefficients after wavelet-based decomposition and characteristic shape and dimensions of various types of damage. This allows for automation of the examination process.

1 INTRODUCTION

The problem of Non-Destructive Testing (NDT) of composite structures becomes more and more important in modern examination studies, since nowadays composite materials are very often applied for manufacturing of structural parts in aircraft, aerospace, automotive, naval industries and many others. From a great variety of NDT methods applied for structural damage assessment one of the most precise is the computed tomography, which allows for identification of even micro—and nanoscale damage in a tested structure. In spite of a great resolution and detection performance of this testing method several problems may occur during interpretation of results and it is difficult to process the output data due to its great capacity.

One of the main problems with CT data handling is the isotropy of detected and localized damage, i.e. damaged regions usually have different colours in comparison with healthy regions due to different absorption of radiation and such a difference is the only information concerned with detected and localized damage. Thus, the identification and classification of damage observed in reconstructed CT scans is not obvious and additional signal processing techniques should be applied in order to identify a type of damage and make it distinguishable. Additional difficulties appear due to presence of measurement noise as well as reconstruction noise, which might be improperly classified as a structural damage.

Several studies on extraction and classification of damage features from 3D arrays of reconstructed CT scans have been performed. The earliest studies (Chu & Lee 2004, Chu et al. 2004) were based on a thresholding performed using Otsu's method extended to the 3D space. This technique solves a problem partially—the data still contain a lot of measurement noise and reconstruction artefacts. Other, more advanced algorithms of feature extraction described e.g. by Lontoc-Roy et al. (2006), are based on 3D neighbourhood analysis, however the procedure was performed on binarized input data, which results in loss of information. The post-processing algorithm presented by Perret et al. (2007) is based on selection of upper and lower thresholds by the trial-and-error method. The more advanced noise reduction algorithm with use of anisotropic diffusion filter was proposed in (Heinzl et al. 2007), while in (Huang et al. 2003) the authors used 3D Gaussian filter for noise reduction. Another feature extraction algorithm was presented in (Kaestner et al. 2006), where the authors used non-linear diffusion filter to enhance the contrast and then the adaptive thresholding procedure for overall enhancement of measurement data and availability of features extraction from them. Several studies of feature extraction from CT scans were performed using wavelet analysis. The authors of (Roeding &

Westenberg 1998) were probably the first who described the advantages of application of 3D wavelet transform (WT) to CT data. An algorithm, which was based on 3D discrete wavelet transform (DWT), was successfully applied to 3D data from CT scans by Chen & Ning (2004) for denoising and feature extraction. Another approach was proposed by Moss et al. (2005). Considering effectiveness of wavelet-based filtering and denoising it was decided to use 3D DWT for a construction of novel algorithm for identification and classification of internal damage in composite structures.

The proposed algorithm is based on 3D DWT and thresholding of wavelet coefficients and allows for extraction of damage features from reconstructed CT scans. The algorithm was tested on a composite plate, in which a circular hole was cut using a water-jet method. The cutting procedure caused delamination around a hole with various directions of propagation. The tested plate was subjected to X-ray CT scanning and obtained reconstructed 3D data array was used as an input in the proposed algorithm. By application of 3D DWT it was possible to identify the defects in the structure and filter out the most of measurement noise. The application of classification algorithm, which is based on evaluation of characteristic dimensions of extracted volumetric features and values of wavelet coefficients, allows classifying the defects into three classes: delamination, air pockets and measurement noise. The CT scanning together with a proposed algorithm allows for automation of identification and classification of defects in composite plates and could be useful in a quality control of composite elements as well as in NDT of structures being in operation.

2 MATERIALS AND TESTING

2.1 *Tested structure*

The tested structure was prepared in the form of an epoxy-based laminate with a stacking sequence of $[\pm 45]_S$ reinforced by carbon fibre with dimensions of $300 \times 150 \times 5$ mm. A circular hole in this structure was cut using water-jet method on the Trumpf® Trumatic WS 2500 cutting system. The cutting process was performed using a water jet with corundum particles with a nominal pressure of 300 MPa. The diameter of a jet was in the range of 0.8÷1 mm and the velocity of cutting was 1 m/min. In order to prevent an initiation of delaminations in plates during cutting an initial pressure of a jet was set to 70 MPa. Moreover, the cutting process was initiated in the middle of a cut contour and the cutting head was moved following the circular trajectory. A picture of a tested structure with a hole is presented in Figure 1.

2.2 *Ultrasonic scanning*

Despite a composite-optimised process parameters and cutting trajectories, the ultrasonic scanning of these plates indicated the presence of significant delaminations area around cut hole observable in Figure 1.

The Ultrasonic Testing (UT) was performed on the air-coupled ultrasonic transducers system HFUS 2400 AirTech manufactured by the Ingenieurbüro Dr. Hillger. The focusing distance between 250 kHz emitter AirTech 4412 and receiver AirTech 4422 probes was set to 50 mm. The attenuation range was defined from -31 dB to 0 dB with 16 levels in between. The wave running time was set to 250 μs, which ensures the acceptable quality of the obtained C-scan (Figure 2).

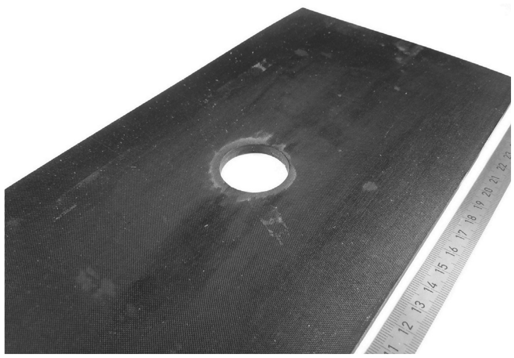

Figure 1. The tested structure.

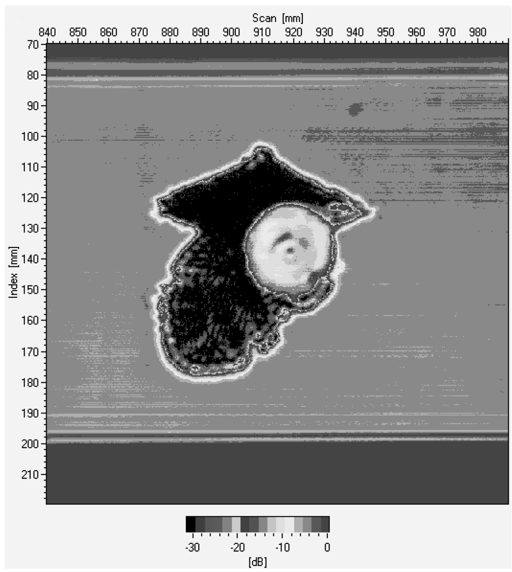

Figure 2. The C-scan of the tested structure.

The delamination, resulted from the water-jet cutting, is clearly detectable in C-scan, however this technique allows for damage detection and localization in two dimensions, which results in loss of information of damage location in the normal direction to the surface of the tested structure. Moreover, it is still impossible to determine a type of a damage. The next step of damage localization was performed using CT.

2.3 *CT scanning*

The CT scanning procedure was performed on the X-ray tomograph v|tome|x L 450 manufactured by GE® Sensing & Inspection Technologies GmbH. The GE® detector of type DXR250 with 410×410 mm active area was used during the scanning process. The parameters of scanning were as follows: accelerating voltage of 200 kV, current of 180 μA, Cu-filter with thickness of 0.5 mm. The RTG lamp of a microfocus type (which allows obtaining the tomography resolution up to 5 μm) has the following parameters: maximal voltage of 300 kV, maximal power of 500 W, conic-type ray with an angle of 40°. The scanning was performed on the area of 100.7×90 mm of the tested plate centered on the hole with a resolution of 50 μm.

The CT scans were reconstructed to a 3D data array and exported to the tomograph-dedicated software myVGL by Volume Graphics. Examples of virtual 2D slices of the tested structure are shown in Figure 3.

The damaged regions are clearly detectable in the virtual slices presented in Figure 3 but are still of isotropic character. The damage is represented now by three spatial dimensions, which allows performing the classification procedure. Obtained 3D data array with dimensions of $452 \times 504 \times 83$ voxels was exported to Matlab® environment for further processing.

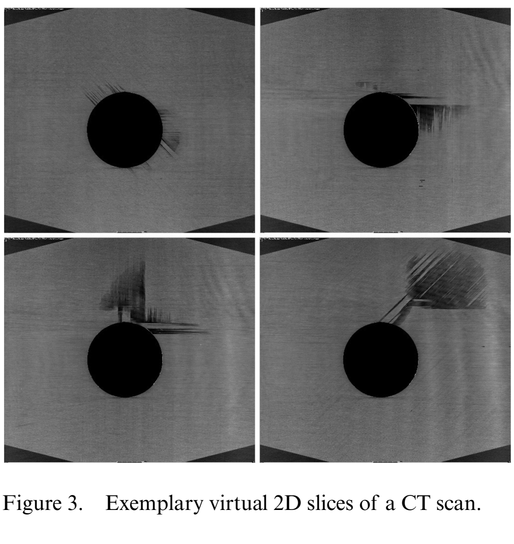

Figure 3. Exemplary virtual 2D slices of a CT scan.

3 DAMAGE IDENTIFICATION AND CLASSIFICATION

3.1 *Description of damage extraction algorithm*

The exported array was subjected to 3D DWT using the B-spline wavelet of order 4. This wavelet was selected basing on previous analyses (Katunin 2011). As a result, eight sets of coefficients (one set of approximation a and seven sets of directional detail $d_{1,\dots,7}$ coefficients) were obtained. Since the measured data was highly biased by the measurement noise and artefacts it was necessary to apply the pre-filtering procedure. It was realized by hard thresholding of the data with a threshold level of 25% from the maximal value of every set of detail coefficients. Such a procedure allows filtering out most of low-magnitude noise and the blurring surroundings, resulted by application of decomposition algorithm, of detected defects. After thresholding the labels on the CT images were removed and the boundary effect was reduced using the zero-padding method. After these operations the resulted arrays of detail coefficients (without the array of approximation coefficients) were reconstructed using 3D Inverse DWT (IDWT) algorithm. Each of the sets of detail coefficients was reconstructed separately and then their absolute values were added up, which formed single 3D arrays—the sets of D-coefficients. The scheme of this algorithm is presented in Figure 4.

The results of damage extraction is presented in the form of a 3D plot in Figure 5. In order to increase the visibility of particular features on a 3D plot the transparency property, depending on the magnitude of the D-coefficients, was used.

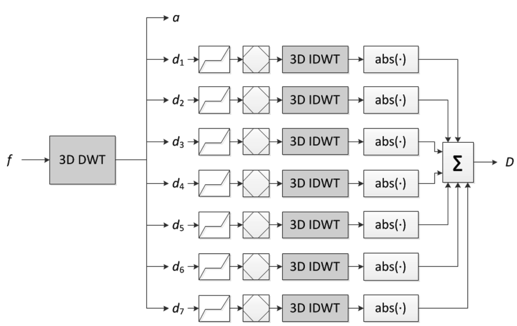

Figure 4. A scheme of wavelet-based processing algorithm.

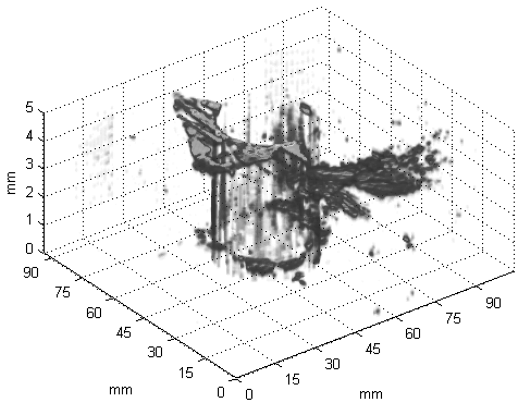

Figure 5. Results of damage extraction using proposed algorithm.

3.2 *Description of damage classification algorithm and classification results*

In order to classify the defects in the tested structure the set of *D*-coefficients was thresholded with an empirically determined threshold level of 2.7%. Such thresholding allows for filtering out low-magnitude *D*-coefficients, which have no dominant influence on the defects identification, and preparing the data for classification. The thresholding procedure is based on the wavelet-based hard-thresholding approach applied for obtained *D*-coefficients, which extracts the significant components of a signal (i.e. useful diagnostic information) based on the magnitudes of *D*-coefficients. The hard-thresholding approach was chosen due to better preservation of boundaries of locally increased magnitudes of *D*-coefficients with respect to soft one. In this approach the analysed *D*-coefficients below the threshold value λ were set to zero.

The next step of preparing the data for classification was a 3D boundary tracking. During this operation the sets of non-zero voxels, which represent various types of defects, were identified and classified to several clusters. The classification procedure was based on the geometric properties of the resulted 3D array as well as on the magnitudes of *D*-coefficients after thresholding. It should be considered that during decomposition/reconstruction procedures the highest magnitudes of *D*-coefficients were obtained for the greatest singularities in the analysed array and thus the defects locations. Following this, the geometrical criteria were applied in order to classify three types of defects:

- delamination, which is characterized by the great spatial dimensions of the sets of non-zero voxels in the tangent plane to the surface of the plate and low dimensions of non-zero voxels in the normal direction to the surface of a structure, it was also assumed that the *D*-coefficients are high for this case of defects,
- air pockets (appeared during manufacturing of a structure), which have near-spherical geometry and the number of voxels with high-magnitude *D*-coefficients is higher than 20 close-located voxels,
- noise (resulted from CT scanning as well as processing procedures), which is characterized by low-magnitude *D*-coefficients with a small number of non-zero voxels.

Using the above-discussed measures three types of defects were effectively classified. The results of classification are presented in Figures 6–8.

In order to compare the effectiveness of the proposed method of extraction of damaged regions from CT scans the quantitative analysis of the area of the delamination was performed. Firstly, the surface area of delamination was determined from the C-scan of the tested structure (see Figure 2). Since the obtained result after processing of the

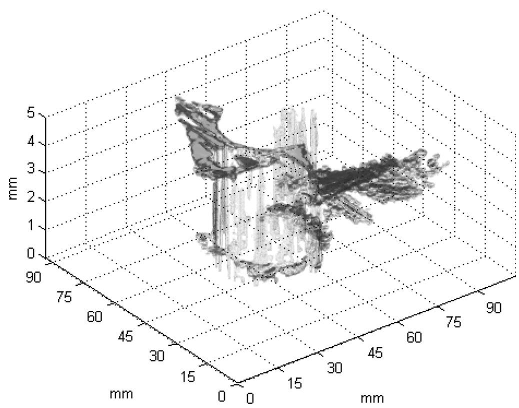

Figure 6. Classified set of delaminated regions.

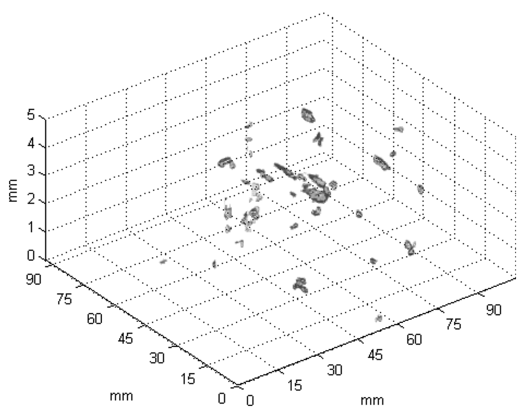

Figure 7. Classified set of air pockets.

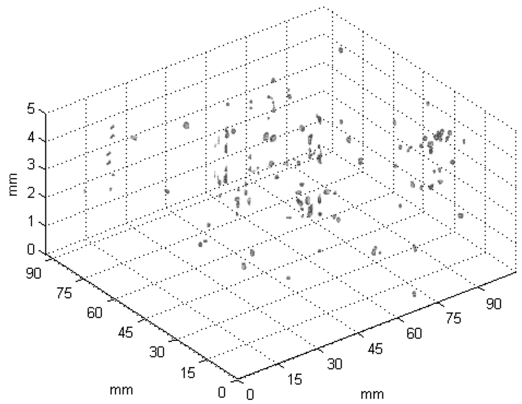

Figure 8. Classified set of noise.

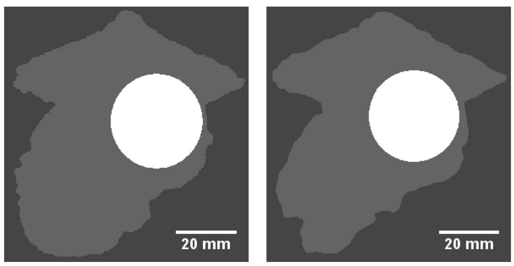

Figure 9. Delaminated region: left—UT, right—CT.

CT scan is the 3D dataset (see Figure 5) the top projection was considered during determination of an area for comparability purpose. Using binarization and some logical operations on the analysed images the boundaries of delamination were determined in both cases (see Figure 9).

At it can be noticed the area of delamination determined using UT and CT differs and equals 3024 mm^2 and 2892 mm^2, respectively. The difference between calculated amounts of delamination area equals 4.36%. This difference results from different resolutions of applied testing techniques as well as wavelet-based filtering operations, which filtered out some low-magnitude regions in the analysed dataset.

4 CONCLUSIONS

The study presented a novel approach of damage identification and classification based on wavelet analysis of the CT scan of the tested structure. The proposed algorithm effectively classified defined types of damage (delamination, air pockets and noise) basing on the values of *D*-coefficients obtained from isotropic 3D DWT decomposition/reconstruction procedures and geometric properties of specific types of damage. By appropriate configuring the parameters of the proposed algorithm the classification procedure can be automated.

Further studies in this area will be concentrated on development of the processing algorithms as well as development of new and more effective classification procedures with use of soft computing and artificial intelligence methods.

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