Improvements to image processing algorithms used for delamination damage extraction and modeling

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Abstract. Assessment and identification of delamination damage in composite materials is necessary for safe operation of modern composite-based aircraft components. Nowadays, numerical simulations provide increasingly reliable predictions of delamination damage growth. However, these simulations often incorporate simplified or idealized models of the initial damage. Authors created a software-based method of extraction of the actual damage and of mapping of the damage to a finite element model. The software utilizes ultrasonic C-Scan images for the mapping process.
In the paper, an improvement to the image processing algorithm used in the method is presented. In essence, a metric for the quality of processing has been introduced – this metric will be used for optimal selection of processing parameters in future versions of the software.
Simple, impact tested composite coupons were used as an input for the method. Results of the processing, including calculation of the quality metric are presented in the paper.

1. Introduction

1.1 Introduction and motivation

Monitoring of the integrity of military aircraft composite components is an essential step in assuring the safety of flights. One of the most problematic modes of composite damage is the delamination of composite skin panels which may lead to an immediate, unstable catastrophic failure of a structural element [1].

The composite elements of aircraft are routinely monitored at the Air Force Institute of Technology, Poland (AFIT) by using ultrasonic testing, performed with the Boeing's MAUS V automated scanner. In addition to the routine ultrasonic inspections, AFIT is currently involved in a program of a composite vertical stabilizer repair for a military fighter aircraft. In the program a numerical, finite element based structural integrity assessment framework is being implemented. To fully and reliably assess durability of a composite structure in such a framework, a method of quantification of delamination defects needs to be devised. The method will be based on defect feature extraction and a transfer of these features into a finite element structural model.

Initial approach to the problem of delamination damage feature extraction was presented in [1]. In the present paper authors present a methodology that will enable the development of a robust method for delamination defect mapping. The methodology is based on study of experimental data taken from impact tests performed on simple composite specimens. An improved, novel approach to image processing of ultrasonic C-Scan images is presented, along with the outline of underlying algorithms.

1.2 Similar applications

Extraction of damage or microstructural features from images is a common practice. For instance, example of defect feature extraction can be found in [2], where edge detection algorithms were used to model simply shaped delamination, and mapping into Finite Element models took place (DSPI was the source of the image data). Image analysis has also been used in [3] to analyze non-destructive test results (i.e. thermography). Image processing based composite feature extraction was shown in [4] – were geometrically simple composite disbonds were analyzed. Ultrasonic scan based composite characterization (i.e. waviness extraction) was done in [5]. Important image processing and composite feature extraction work has been done by R.A. Smith and his team [6 - 9]; a feature extraction research that resulted in a FE model of the composite structure was shown in [10]. Automated defect extraction from ultrasound data was also presented in [11, 12] where the method was tested on specimens with artificial defects. In [13] the delamination feature extraction was performed on data provided by AFIT – however in this case the segmentation was based on processing of the time-of-flight (depth) C-Scan images, with the use of multilevel intensity threshold.

2. Method outline

2.1 General approach

In the paper a preliminary approach for initial extraction of delamination defect from typical inspection ultrasonic (UT) C-scan measurement data is presented. Such extraction method is needed because ultrasonic scans of large areas of aircraft are routinely performed by ITWL personnel.

An attempt to verify and validate the results of C-scan processing has been made. To create the quality assessment, a new processing method should be compared with a (more reliable) reference. In the present research, three-dimensional X-ray computed microtomography (CT) data were used as the reference.

As has been discussed, typical approach to defect extraction from C-scan images involves delamination patch extraction from the time-of-flight C-scan images. In essence, the intensity image related to the depth of the defect (discontinuity) undergoes segmentation. In this paper, authors have observed that for determining outlines of individual delamination patches, the amplitude image also can be used. This is in contrast with the usual approach of depth-image processing. By overlaying (masking) the amplitude-extracted contours on the time-of-flight data, extraction of individual delamination patches is possible.

2.2 Comparison with microtomography as a method of validation

In the present research, X-ray computed tomography (CT) data taken from measuring impacted composite plate specimens, was used to generate the reference defect model. Authors applied simple image processing methods to extract the discontinuity regions from CT. The raw CT data was processed slice by slice and the extraction results were mapped into a binary 3D voxel set, resulting in a 3D volumetric representation of the defect.

Processing results are represented in a form of a binary voxel set – morphological and connected component operations are therefore easily applicable. Creation of the voxel set is not the final processing step, however. To create a fully quantifiable comparison of CT and UT extraction results, for both measurement methods the data has to be mapped to a common feature space. To do that, the planar discontinuities (delaminations) are separated into patches and for each patch, a set of two data types is extracted – planar outline (point set) and uniform depth (scalar). The depth scalar is the median depth pixel value in the respective patch area. The CT generated patches are then superimposed, and the patch regions not visible in a top-down projection are removed. This enables a simulation of the ultrasonic C-scan conditions (in which top patches obstruct the lower patches).

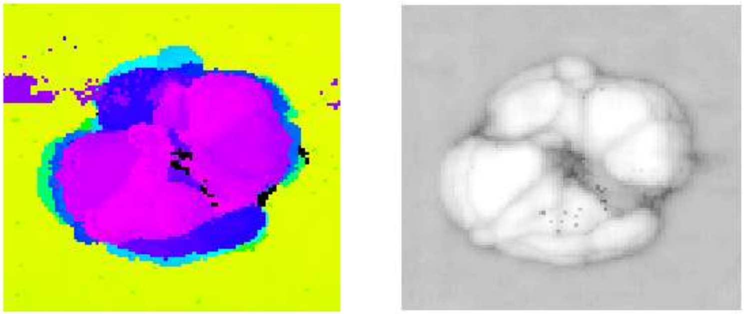

Fig. 1. Ultrasonic C-scan of a delamination used in the present study – time of flight (depth), amplitude .

UT data processing results have an identical data structure (contour-depth pairs). This makes direct, quantitative comparison possible. Authors propose a simple, area based metric that enables assessment of the processing quality.

Simple, impact damaged rectangular specimens, produced for another study [14] were used as the source of example data for development of the processing method. Ply stack consisted of 32 plies of overall 4 mm thickness. The planar dimensions were 100x150 mm. The impact tests have been performed by means of a drop test apparatus, with the specimen fixed in a dedicated frame. Several specimens were impacted. However, in the present study a single, 3.5 cm diameter defect was used as an example. The example defect was a result of a 16 J impact [14]. The defect images (ultrasonic C-scan) used for subsequent processing in the paper are shown in figure 1. The CT scan planar resolution was 0.05 mm/pixel, while the UT C-Scan image resolution was 0.2 mm/pixel.

3. Microtomography data extraction – creation of reference defect

3.1 CT processing algorithm

Authors decided to extract discontinuity voxels (corresponding to delaminated areas) by processing each planar slice separately. The processing was performed in orthogonal directions. The final voxel set was a weighted sum of voxels sets obtained from different directions.

For the processing in the transverse direction, simple thresholding segmentation was the main method for feature extraction (see algorithm on figure 2). The raw image was subjected to Difference of Gaussian [15,16] filter to remove the non-uniform intensity (which is a result of measurement conditions). Main segmentation was done with the use of an adaptive intensity threshold. Morphology operations were then performed on the thresholded binary image, mainly to bridge the longitudinal components (representing the planar delaminations). The algorithm schematics are presented in fig. 2. Intermediate example results for the processing are presented in fig 3.

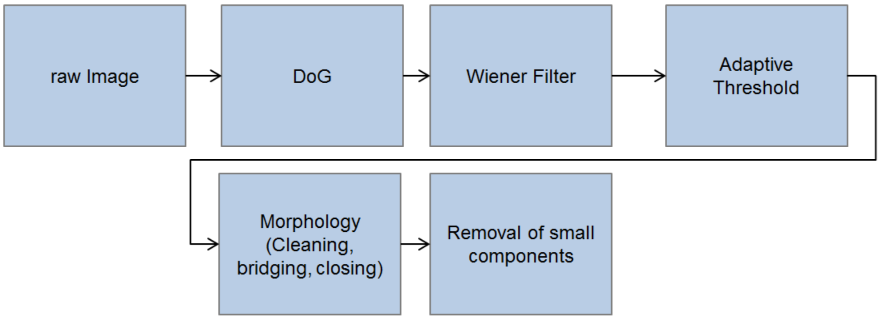

Fig. 2. Defect extraction from CT data – image processing algorithm.

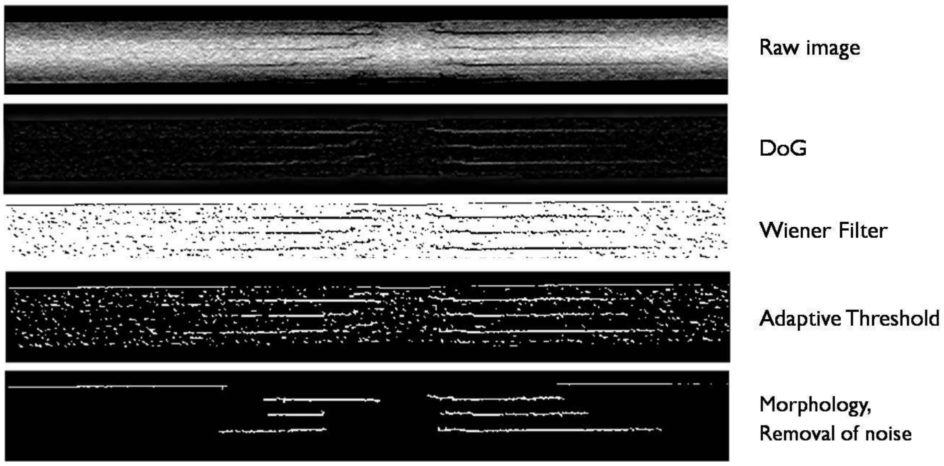

Fig. 3. Defect extraction from CT data – interim steps.

Processing in the transverse direction gives better representation of the diagonal portions of the delamination (matrix cracking). Top-down direction processing results in a less noisy contour extraction for the patches.

3.2 CT data processing – voxel results

Results of the processing are presented below. The 3D voxels sets are shown in the figures. The mapped color represents the thickness coordinate value, for ease of interpretation. The initial voxel set still contained some processing artifacts, which were removed with use of morphological operations and some manual cleaning.

Example of a resultant voxel set (after manual cleaning) is shown in fig. 4 (different viewpoints are shown). In figure 5 – a top-down projection generated from the CT data is presented. The top-down projection is an analog to the delamination representation obtained in a ultrasonic C-Scan. In the particular discussed example, the delamination had the form of a set of concentric, radially distributed planar patches. The planar patches are connected by diagonal regions of matrix cracking. To further facilitate mapping, however, the planar patches have to be separated – the matrix cracking regions have to be removed. This was done by removing diagonal elements in each two-dimensional slice of the voxel set. Removal has been done by applying a binary hit-miss transform [17], using a simple 9-pixel line structural element and subtracting the results from input image.

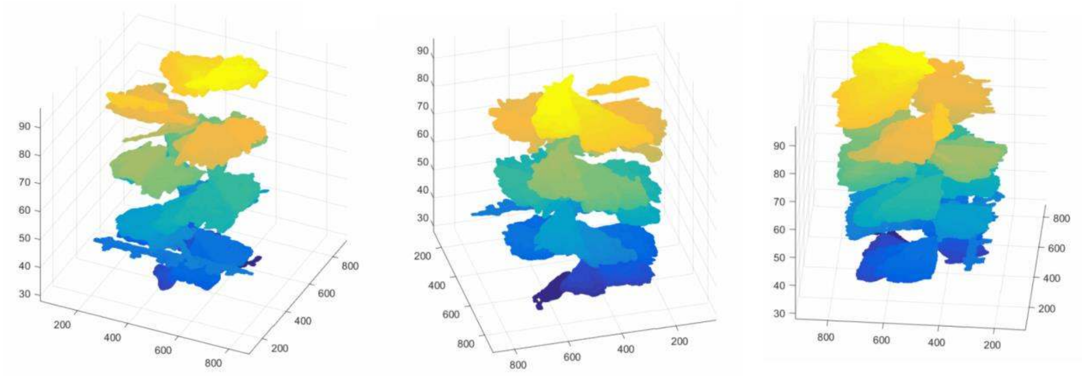

Fig. 4. Resultant delamination – voxel set obtained from CT data processing.

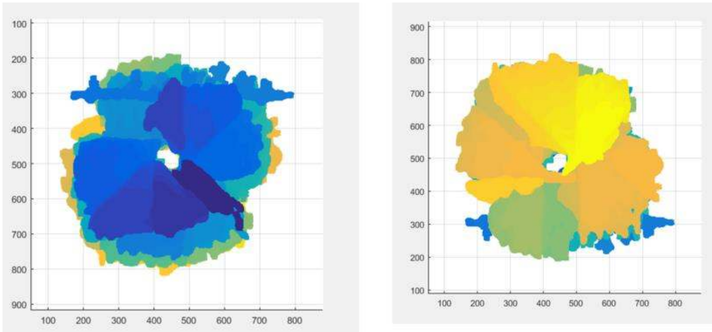

Fig. 5. Resultant delamination – top projection, analog to ultrasonic C-Scan.

3.3 CT data processing – feature extraction

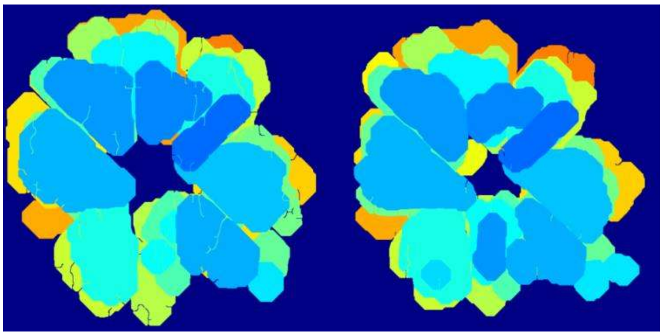

Fig. 6. Feature extraction result for different processing parameters.

Removal of matrix cracking regions enabled the separation of delaminated (in-plane) patches. This enabled generation of contour-depth pairs. The resulting feature set examples are shown in figure 6 – color on the image represents the median depth value for each patch.

4. Ultrasonic C-Scan feature extraction

As mentioned, to facilitate the extraction of individual delamination patches, contours of the amplitude image have to be extracted and superimposed with the depth data. The main amplitude contour extraction relies on the combination of Laplacian of Gaussian filter (LoG – done for edge emphasis) and of a simple Otsu-based [18] intensity thresholding. Morphology operations are then applied to clean up and smooth the contour edges. The full algorithm schematics are presented in figure 7.

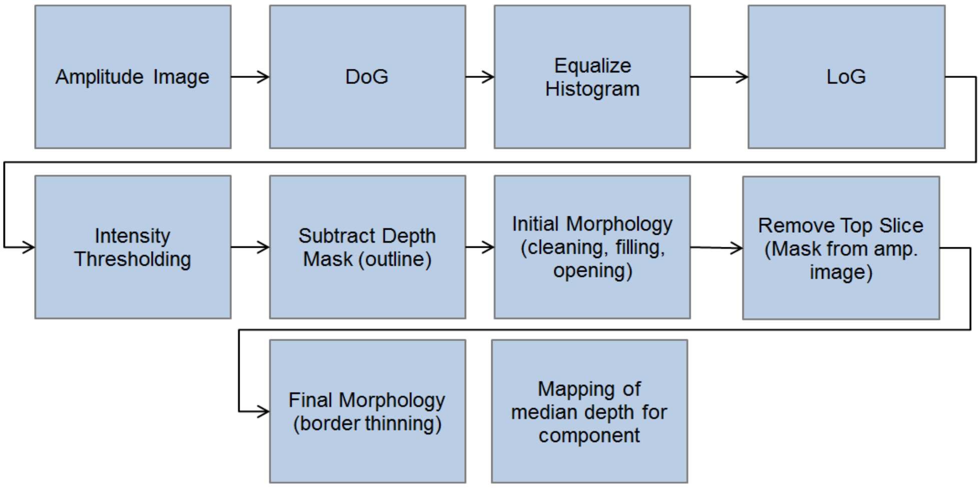

Fig. 7. Image processing of ultrasonic C-Scan data.

Example of ultrasonic scan processing, including interim results, is shown in figure 8. Once again Difference of Gaussians (DoG) filter is used to remove global gradients and intensity non-uniformity. Histogram equalization and Laplacian of Gaussian (LoG) edge emphasis are the most important edge extraction methods used. The top patch (lowest depth) required some additional processing. After final component separation and extraction, the median depth is extracted for each patch (component) – therefore resulting in a set of depth-contour pairs needed for further quantification.

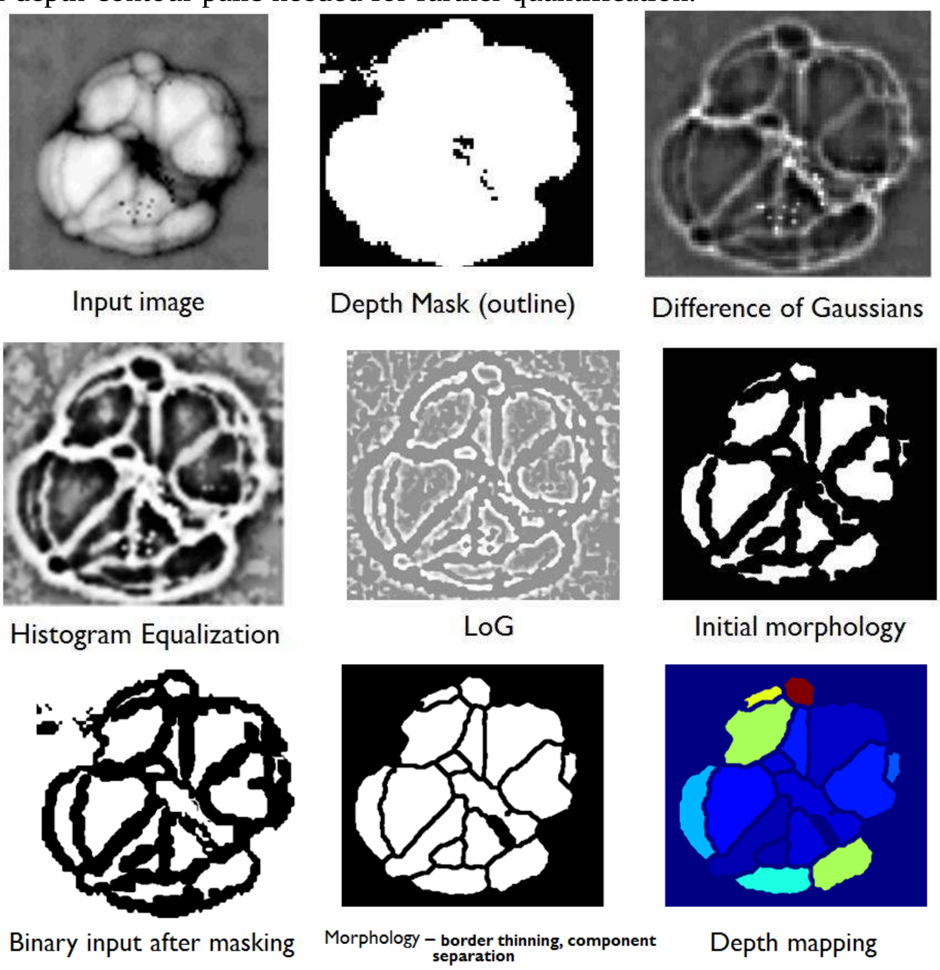

Fig. 8. Image processing of ultrasonic C-Scan data – interim steps.

5. Comparison of measurement types, initial quality assessment

Results of qualitative comparison are presented side by side on the image below (figure 9). Depth extraction was not perfect – this can mainly be attributed to the measurement system parameters and inaccuracies. To enable assessment of the processing quality, as well as fine tuning and (automated) optimization of the processing parameters a simple scalar quality score is needed.

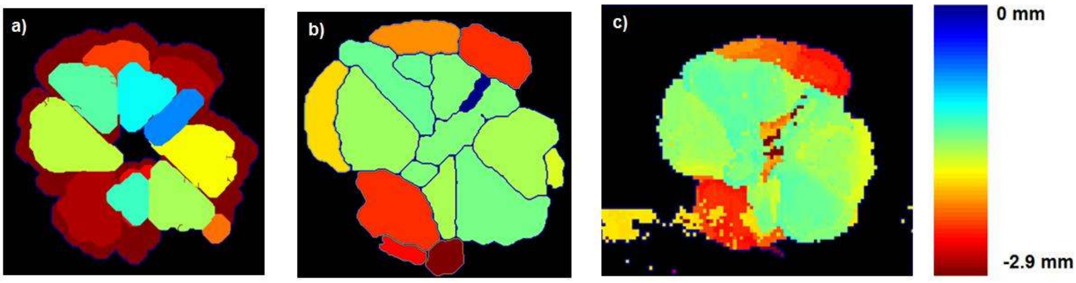

Fig. 9. Qualitative comparison a) features extracted from CT, b) features extracted from UT, c) raw UT data (time-of-flight).

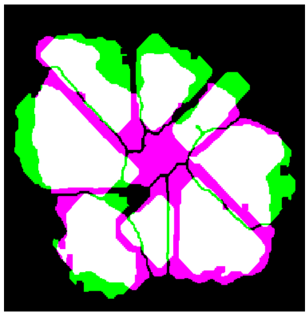

Fig. 10. CT and ultrasonic C-scan – extracted patches overlay

Currently, authors propose a simple area-based metric. The metric compares the areas of the corresponding patches of the reference CT mapping result (reference) and the assessed UT result. On figure 10 the two results are superimposed.

The proposed metric M (eq. 1-2) enables only assessment of contour extraction reliability, and higher order features (such as orientation, symmetry, aspect ratio) are not taken into account. Depth data is also not included in the metric – this will be addressed in further work. The metric M can have values in the range of <0,1> - ‘0’ symbolizing a completely erroneous mapping and ‘1’ being an ideal mapping.

$$m_i = \max\left(\left\{\frac{2\Delta_i}{CT_i + CS_i}, 0\right\}\right) \tag{1}$$

$$M = \frac{\sum m_i CT_i}{\sum CT_i} \tag{2}$$

Where: CT_i – ith CT-extracted patch area, CS_i – ith C scan-extracted patch area, m_i - ith individual patch metric, $\Delta_i = |CT_i - CS_i|$

6. Conclusions and further work

Analysis of x-ray tomography data is necessary to create a reference for the feature extraction process, because of the inherent artifacts and flaws in an industrial C-Scan inspection result. However in the current framework, the CT data cannot serve as an ideal reference. Nevertheless authors have shown that some correlation between defect models extracted from UT and CT can be achieved – comparison of defect sub-component areas yields promising results.

Comparison of CT and ultrasonic mapping results suggest that amplitude C-Scan image contains important information about defect topology for the class of industrial measurement systems used routinely for inspection.

In further studies, measurement conditions and parameters for both ultrasonic and CT measurements will be improved, so that a more reliable mapping may be achieved. Creation of a more complex scoring metric is necessary – this will enable minimalization of parameter number as well optimization of the parameter vector, by means of automated finding of a global processing parameter optimum.

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