DIRECTIONALITY DETECTION OF DELAMINATIONS BASING ON ANALYSIS OF CT SLICES USING WAVELET AND HOUGH TRANSFORMS-BASED ALGORITHM

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Summary

Growing demands for high reliability of constructions made of composite materials lead to a significant development of non-destructive testing methods of structural diagnostics. Among the most accurate and sensitive techniques used for analysis of internal defects, is the computed tomography (CT). However, since the results obtained from CT are highly precise, certain problems with their interpretation occur. The visual information about defects has isotropic character, thus it is not possible to evaluate directions of propagation of defects. The following study presents an investigation on a problem of identifying the directionality of delaminations evolution in layered composites. The tests were performed on specimens made of polymeric composites with delamination resulted from water-jet cutting. The images of cross sections of specimens were acquired by CT scanning. In the paper, the developed algorithm based on wavelet and Hough transforms as well as other methods of image processing and analysis is presented. The proposed method allows for automatic detection of directionality of delaminations and could be applied in quality control of composite components as well as non-destructive testing during their operation.

Keywords: directionality detection, delamination, computed tomography, image processing, wavelet transform, Hough transform

WYKRYWANIE KIERUNKOWOŚCI DELAMINACJI NA PODSTAWIE ANALIZY PRZEKROJÓW CT Z ZASTOSOWANIEM ALGORYTMU OPARTEGO NA TRANSFORMACJI FALKOWEJ I HOUGHA

Streszczenie

Rosnące wymagania dotyczące wysokiej niezawodności konstrukcji wykonanych z materiałów kompozytowych prowadzą do znaczącego rozwoju metod badań nieniszczących przy diagnostyce strukturalnej. Jedną z najbardziej dokładnych i wrażliwych technik stosowanych do analizy defektów wewnętrznych jest tomografia komputerowa. Jednak, poza wysoką dokładnością wyników otrzymywanych tą metodą, istnieją pewne problemy z ich interpretacją. Informacja wizyjna o defektach ma charakter izotropowy, dlatego nie jest możliwa ocena kierunków propagacji defektów. Niniejsze studium przedstawia badania dotyczące problemu identyfikacji kierunkowości propagacji delaminacje w kompozytach warstwowych. Badania przeprowadzono na próbkach wykonanych z kompozytów polimerowych z delaminacją wynikającą z cięcia próbek strumieniem wody. Obrazy przekrojów próbek uzyskano z wykorzystaniem tomografii komputerowej. W niniejszym artykule przedstawiono algorytm oparty na transformacjach falkowej i Hougha oraz innych metod przetwarzania i analizy obrazów. Zaproponowana metoda pozwala na automatyczne wykrywanie kierunkowości delaminacji i mogłaby być zastosowana przy kontroli jakości elementów kompozytowych, jak i badań nieniszczących podczas ich eksploatacji.

Słowa kluczowe: wykrywanie kierunkowości, delaminacja, tomografia komputerowa, przetwarzanie obrazów, transformacja falkowa, transformacja Hougha

1. INTRODUCTION

The development of applications of composite materials in engineering constructions is powered mainly due to a significant reduction of their mass and simultaneous maintaining very well strength properties. The other examples from many advantages are corrosion and fatigue resistance, a possibility of integration of a structure with control elements or actuators and a great flexibility in designing a form of a product. Ones of the industries for which application of composite materials is the most widespread are the automotive, marine, aircraft and aerospace ones, where high reliability and safety of constructions are extremely required. For this reason, structural diagnostics of composite materials and thus early detection of their possible defects is of a great importance both at the manufacturing stage as well as during their operation. A variety of non-destructive testing (NDT) methods of structural diagnostics has been developed to-date. The examples of them include a modal analysis together with advanced signal processing techniques, thermographic, interferometric, radiologic and ultrasound methods. A novel approach for diagnosis of composite structures is based on X-ray computed tomography (CT). First applications of CT were found in medical imaging and diagnosis (see e.g. [1-4]). Afterwards, the method turned out to be very useful also in structural diagnostics of engineering structures [5-7] as well as agricultural engineering [8-10]. Another examples of the use are found in the electric, electronic and food industries. More information about industrial application of CT can be found in [11]. The CT gives the possibilities that cannot be provided by any other method of structural diagnosis and is the most precise technique developed to-date. So far, this is the only method by which measurements of inner geometry is possible without destroying a tested object. The general principle of CT operation is to produce a set of slices (large number of 2D cross sections of a tested structure) during rotation of a scanning head around an object (or conversely) and passing an X-ray through the object. Subsequently, the 3D data array of the scanned object is being reconstructed from these single scans, what allows for precise analysis of an external as well as internal structure of the object. The spatial resolution that can be obtained by currently available CT technologies is even lower than 1 μm [12]. Since such a method is very sensitive and provides greatly precise results, certain problems in their proper interpretation appear. They are mainly caused by occurrence of a measurement noise and the so-called artefacts, which may result from various causes, e.g. inconsistency in a single measurement or errors in an individual detector calibration. Artefacts are therefore the differences between the obtained CT numbers and true coefficients of the object and usually appear in the form of streaking, shading, rings, distortion of the image, etc. Only some types of them are minimized by a scanner software provided with modern CT scans [13]. These artefacts could be misinterpreted as defects of tested elements. For above-mentioned reasons it is difficult to distinguish the physical nature of defects of composite structures (e.g. delaminations, air pockets, debonding, cracks of reinforcing fibres, interphase decohesion or others). Therefore, advanced image analysis is needed to remove undesirable artefacts from the obtained data and proper interpretation of technical condition of a tested structure. There have been many algorithms developed for structural condition analysis. In this paper, the authors have focused on the directionality detection of delaminations in composite materials. Delamination is one of the most critical damage process in laminated composites. Even a single plane defect may cause multiplane delamination growth [14]. Delamination typically grows along the direction of the fibres at a ply interface [15]. Since fibres orientation in laminated polymer composites is of great importance [16-19], it is necessary for structural diagnostics to analyse the directionality of a propagating damage.

Numerous studies on analysing fibres orientation have been done. In the paper [20], the authors used CT in order to measure the fibre length distribution and fibre orientation distribution in a polymer foam reinforced with short fibres. In this case, the internal fibre distribution could be analysed owing to virtual separation by concealing the cellular foam structure and thus leaving only the fibres visible in the image. Another example of fibre orientation detection in composite laminates is use of one-sided pitch-catch ultrasonic technique [21]. Other examples where analysis of fibres orientation using CT was considered are presented in [12,22]. As far as medical applications are concerned, authors of [23] proposed a two-step multiscale image decomposition method for measuring myofibre orientations from high-frequency ultrasound images. Other approaches of analysis of fibre orientation in medical images are described in [24-27]. Furthermore, numerous methods of streak detection in various images were reported, which might be useful in detecting the directionality, for instance [28-30].

The literature survey indicated that the undertaken problem has been investigated mostly for cases where a tested pattern has a certain texture and thus a directionality is usually well visible. Examples of analysis of damage development in similar to the considered open-hole composite specimens, where one can observe the physical nature of propagation of delamination, are presented in the following studies. In [31], the authors used solid finite element-based techniques to predict evolution of composite materials under fatigue loading and compared the results to the experimental data. In the two-step research [32,33], the authors performed numerical modelling and experimental investigation on a damage development and failure of open-hole tensile specimens. In the study [34], the authors monitored damage progression by various techniques (ultrasonic scanning, X-radiography, deply and microscopic examinations). From above cited studies follows that delaminations in laminated composites, taking into account a stacking sequence of layers, are expected to propagate with a direction of 0°, -45°, 45° or 90°.

In this paper, the authors focused on developing such a method by which the directionality of delaminations in composites could be automatically detected using a two-step approach of image analysis basing on wavelet and Hough transforms. The uniqueness of the proposed method is that the information about directionality is being extracted from isotropic images (which do not have a texture). Thus, directionality is possible to determine by taking into account the physical nature of a propagation of delaminations. First attempts on application of wavelet transform to the directionality analysis have been made in previous study [35], where the discrete wavelet transform was used. In the following study the better directional selectivity was reached due to application of dual-tree decomposition approach using 2D complex wavelet transform. The Hough transform was used for selection of the directions of delamination basing on results of wavelet analysis and finally the convex hull determination of the set of identified points was performed. Several tests of the developed algorithm were performed on real measurement data. The method is characterized by great effectiveness and can automate and support diagnostic process of structural laminated elements.

2. MATERIALS AND TESTING

2.1. Specimen

As a tested specimen, a multilayered composite plate with dimensions of 300×150×5mm (length×width×thickness) was selected. It was made of carbon fibres (CF) of the HTA type with a stacking sequence of layers ±45° and, as a matrix, the epoxy resin of Hexcel® Hexply® 6376 type was used.

The circular hole with a diameter of 30 mm was cut in the middle of the specimen by means of water-jet cutting on the Trumpf® Trumatic WS 2500 cutting system. The process of water jet cutting was performed using corundum particles with a nominal pressure of 300 MPa, a diameter of a jet in the range of 0.8-1 mm and a velocity of cutting equalled 1 m/min. For the purpose of reducing the risk of delamination occurrence in the plate during cutting, an initial pressure of a jet was set to 70 MPa. Furthermore, the cutting process was started in the middle of the contour area and a cutting head was moved following the spiral trajectory until the diameter of the hole was reached. Nevertheless, the obtained scans indicated the presence of significant delamination areas around the cut hole (see e.g. in Fig.1).

2.2. CT scanning

The CT scanning of the specimen was performed on the tomograph v|tome|x L 450 manufactured by GE® Sensing&Inspection Technologies GmbH, using the detector of a type DXR250 with an active area of 410×410 mm. The scanning parameters were as follows: current of 180 μA, accelerating voltage of 200 kV, Cu-filter with thickness of 0.5 mm. The RTG lamp of a microfocus type has the following parameters: maximal power of 500 W, maximal voltage of 300 kV, conic-type ray with an angle of 40°. More detailed information about testing procedures can be found in [35]. The CT scans were obtained in the form of the 3D array of data in the software myVGL (dedicated to the tomograph). The data were exported and further analysed using Matlab® environment. The structure of the specimen as well as its typical damage can be observed in exemplary 2D slices (see Fig. 1).

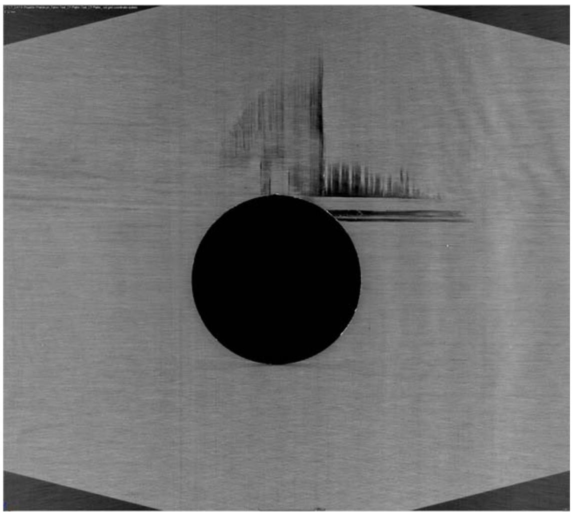

Fig. 1. Exemplary CT slice (cross section of the carbon fibre composite specimen)

3. THEORETICAL BACKGROUND AND ALGORITHM DESCRIPTION

3.1. Wavelet transform

The wavelet transform (WT) has found wide application in signal and image processing problems. This is due to its very high sensitivity to abrupt changes in an analysed signal. From the variety of various types of WTs the most appropriate one is the discrete wavelet transform (DWT), which is based on decomposition of the analysed signal into two sets of approximation and detail coefficients on each decomposition level. Generally, a set of approximation coefficients consists of elements of signal, which match a shape of applied wavelet and a set of detail coefficients consists of the rests. In case of analysis of images (or 2D signals) the generalized version of DWT should be applied, where, in the most simple case, a scaling function and three directional wavelet functions (horizontal, vertical and diagonal) can be obtained from the combination of tensor products of 1D scaling and wavelet functions. Obviously, it results in one set of approximation coefficients and three directional sets of detail coefficients. This approach was initially applied for distinguishing of directions in [35]. However, in such approach there are several problems with angular selectivity and lack of shift invariance, i.e. the resulted sets of detail coefficients have preferred directions (horizontal and vertical) and a diagonal set of detail coefficients, which have not straightforward interpretation [36].

In order to improve the previous approach one can apply complex wavelets, which ensure much better directional selectivity and near shift invariance. The application of complex wavelets was originated by Kingsbury in [36]. The transform becomes redundant with respect to DWT due to performing the dual-tree decomposition using complex wavelets, whose real and imaginary parts are the Hilbert transform pairs. This approach improves much the directional distinguishability of the directions of damage, thus it was chosen as an initial step in the proposed image processing algorithm.

3.2. Hough transform

The classical Hough transform (HT) is a method used for detecting straight lines in pictures named after Paul Hough and patented by him [37]. In general, this transform consist in dividing the viewed representation into small sectors (straight line segments). Each of straight line segments is detected and transformed into a slope and intercept data. One can describe the slope-intercept model of a straight line as:

$$y = mx + b\,, \tag{1}$$

where x and y are the Cartesian coordinates, m is the slope of the line and b is the intercept.

Duda and Hart [38] proposed a modification of classical HT, which consisted in using angle-radius instead of slope-intercept parameters. In this approach, the representation of a straight line is defined by an angle θ of its normal (angle between the x-axis and a vector perpendicular to the line) and its algebraic distance ρ from the origin:

$$x\cos\theta + y\sin\theta = \rho\,. \tag{2}$$

If we limit the interval of the distance $\theta \in [0,\pi)$, then each line in the plane (x, y) relates to a unique point in the plane (θ, ρ).

The Hough transform has found a huge interest among researchers. The classical and modified Hough transforms have been often applied in various studies as well as further developed. It was generalized for detecting shapes that are possible to be described analytically, for instance circles, ellipses, arcs. Ballard [39] generalized the Hough transform to detect arbitrary shapes. The authors of [40] proposed an improved HT method for detecting line segments in images of complex backgrounds by enhancing two-dimensional accumulator array. In [41] a method of orientation-based discrete HT for line detection is described. Another approach is presented in [42], where the authors generalized the Hough space to a 3D space by introduction of a third parameter.

This transform was selected as the next step of the processing algorithm due to the ability of detecting straight lines with joining their discontinued parts. HT was applied after performing WT-based decomposition in order to improve the detection of areas of damage in particular directions.

3.3. Algorithm

The proposed algorithm (see Fig.2) consists of two general steps with additional subprocedures.

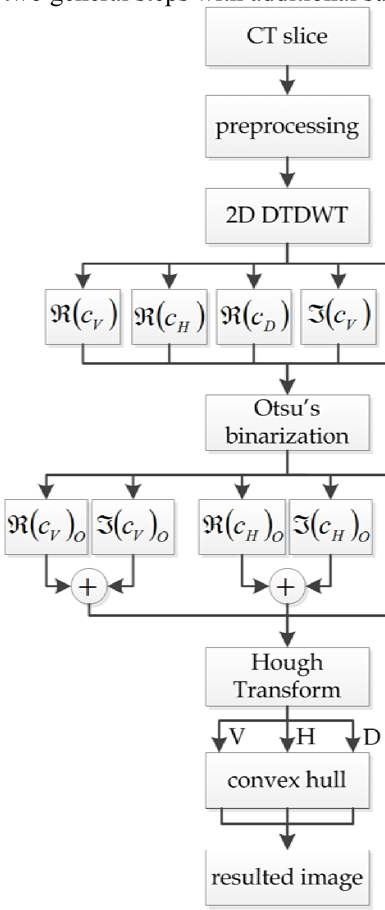

Fig. 2. Algorithm of directionality detection based on wavelet and Hough transforms

The initial images (slices of 3D array) obtained after the CT scanning were preprocessed using CT-dedicated software in order to emphasize the damaged areas. These areas have isotropic character. The exemplary initial and preprocessed images are presented in Fig. 1 and Fig. 3, respectively.

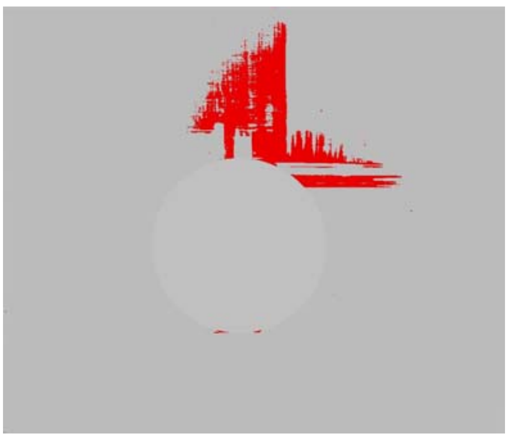

Fig. 3. Preprocessed image of CT slice using CT-dedicated software

Then, 2D dual-tree discrete wavelet transform (DTDWT) was performed on each preprocessed image. As a result, for each image we obtain six directionally sensitive sets of coefficients. Obtained sets were binarized using Otsu's method [43] and then the pairs of real and imaginary sets in specific directions were added up, which resulted in three sets. For each set HT was applied. Performing of HT allows obtaining three sets of structure arrays of detected lines, which consist of vectors of θ and ρ values (corresponding to the description in Section 3.2) and matrices of peaks (two end-points for each detected line segment) with corresponded row and column coordinates in an image. The coordinates of these end-points were used for construction of convex hulls of them, which determine the oriented areas of delaminations. Their directionality was automatically specified using the returned values of angles θ. The ranges of angles for each direction were defined basing on the possible directions of delamination propagation observed on raw CT images.

The resulted sets of data were merged with preprocessed images with indication of direction of delamination for each set. The directionality identification was distinguished by black arrows for vertical, blue arrows for horizontal and the green ones for diagonal delaminations. The example of the resulted image is presented in Fig. 4.

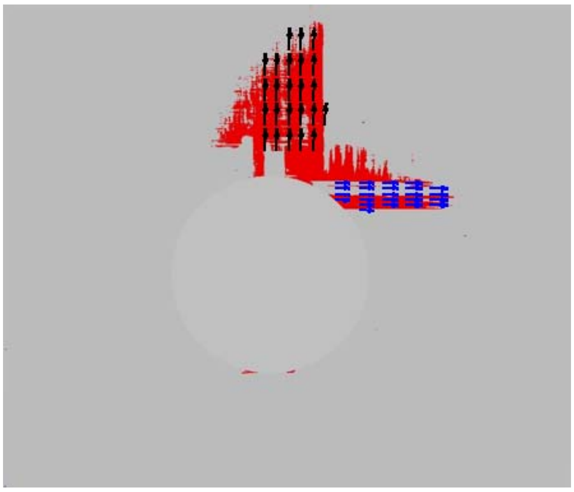

Fig. 4. An example of a resulted image

4. RESULTS OF THE DIRECTIONALITY OF DELAMINATION DETECTION

The directionality detection was performed on CT slices of the CF specimen with delaminations around the hole cut by water jet method, as described in Section 2.1. The data were obtained from CT scanning, according to the description in Section 2.2, and analysed following the algorithm presented in Section 3.3. The exemplary results of five different slices with delamination of various directionality are presented in Fig. 4 and Fig. 5. It can be observed that the directionality of delaminations in all cases was detected, localized and identified properly (Fig. 5a – horizontal and vertical, Fig. 5b – diagonal, Fig. 5c – diagonal and horizontal, Fig. 5d – vertical delamination).

The application of DTDWT allowed for detection of boundaries of delaminations and distinguishing their directionality from isotropic images. In several cases the boundaries were not detected as lines, what introduced additional noise from the point of view of application of. Usually, it is resulted by absence of delamination in particular direction. The addition of pairs of coefficients sets (as it was described in Section 3.3) allows for partial overcoming this problem. Then, HT was applied for detection of straight lines obtained from DTDWT in order to evaluate the delaminated areas.

However, certain small areas of delaminations were omitted what was caused by a necessity of limitation of the following two HT parameters. The first one is the number of pixels of a gap (or several gaps) between separated segments of a single line that are to be filled (thus these segments are connected and taken as one line). Due to the possible presence of noise in CT slices and loss of information after DTDWT, this parameter was used to merge interrupted segments of straight lines. However, the other parameter had to be additionally used in order to avoid detecting lines which would be formed as a result of merging the separate, neighbouring lines. To prevent the occurrence of such inconsistencies, the minimum length of lines that are acceptable to be merged was specified (ca. 7% of each dimension of an image). For this reason, the areas of delaminations which are shorter than this dimension were discarded.

Nevertheless, the proposed approach is suitable for automatic extraction of information about directionality of delaminations together with localizing their largest areas.

5. CONCLUSIONS

In this paper, the directionality of delaminations in a multilayered composite plate was analysed using wavelet and Hough transforms-based algorithm. The tests were performed on a carbon fibre specimen with delaminations around the cut hole. The 3D scan of the specimen was obtained using X-ray computed tomography and then divided into 2D slices (cross sections of the tested plate). The proposed approach allowed for detection, localization and identification of the directionality of delaminations. The analysis procedure was based on two general steps: 2D dual-tree discrete wavelet transform, used to obtain six directionally sensitive sets of coefficients, and Hough transform, applied for detecting straight lines in images and identifying their directions. To localize the areas of the delaminations directionality, the convex hulls of sets of end-points of the detected lines were determined. It was indicated that using the algorithm allows acquiring the relevant information about delaminations presence, its location and orientation in arbitrary direction.

The presented work is a part of on-going research. The improvement of detection accuracy is planned in further studies. The method could be applied in quality control problems of composite components as well as in non-destructive testing during their operation.

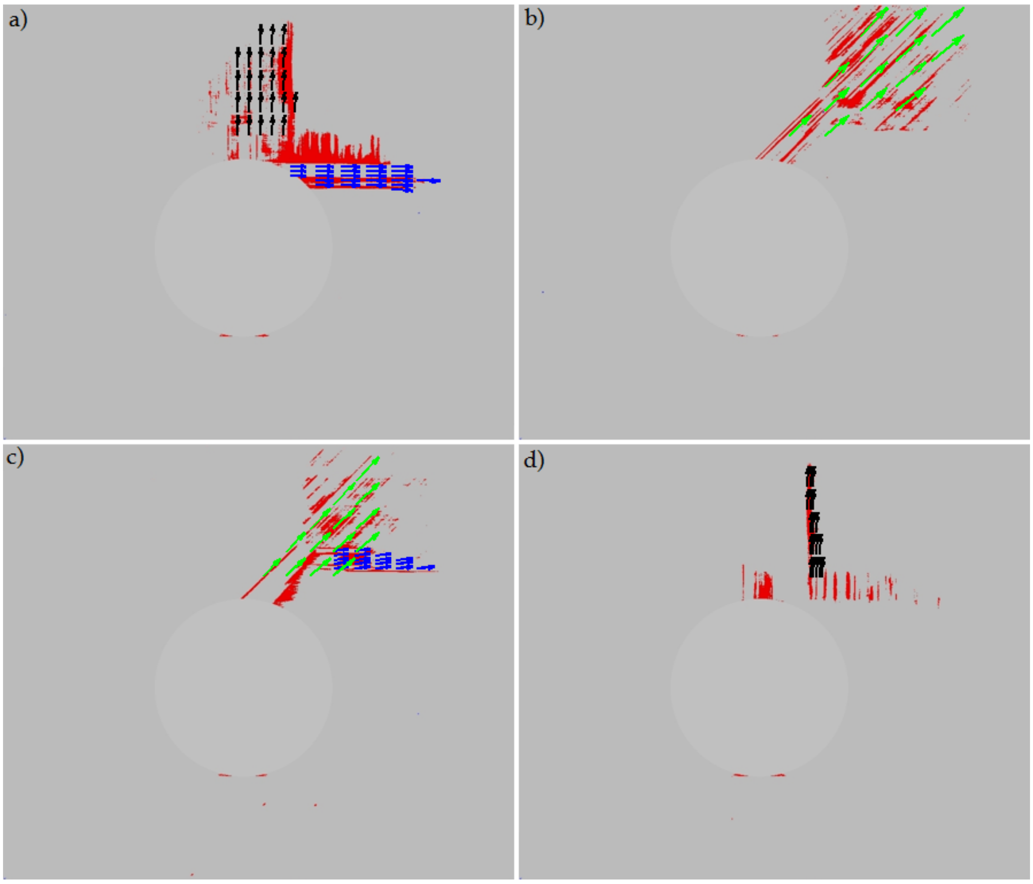

Fig. 5. Results of four different CT slices – detection of vertical, horizontal and diagonal directionality of delamination

ACKNOWLEDGEMENTS

The presented research was financed by the National Science Centre (Poland) granted according the decision no. DEC-2011/03/N/ST8/06205.

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