PLY WAVINESS DETECTION AND MESH GENERATION FOR COMPOSITES BASED ON X-RAY COMPUTED TOMOGRAPHY

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1 Introduction

Thick-section composites are commonly used in fixed-wing and rotary-wing fatigue-critical, flight-critical components and structure. Manufacturing imperfections in thick composite structures, such as fiber waviness and porosity/voids, remain a serious problem that leads to significant component scrap rates in production. Such defects usually result in degraded strength and fatigue performance [1]. Accurate assessment of composite part capability and useful life should be based on advanced structural analysis methods that account for manufacturing defects.

The main objective of this work is to determine the feasibility of fiber waviness detection by X-Ray Computed Micro-Tomography (CT) and using it in mesh generation for structural analysis of composite specimens with ply waviness. Accurate measurements of fiber waviness are essential to establish the part structural condition. Such measurements must also be converted to finite element (FE) models for assessment of the effects of defects [2].

Due to advances in computer hardware and 3D reconstruction software Computer Tomography has become a practical tool for non-destructive evaluation of composite structures. The potential of the technique in reconstruction of the fibers in composite materials was established in [3]. The authors of this work have recently investigated the feasibility of using CT imaging for detection of waviness and porosity in thick composite structures used in helicopter applications [4].

Numerical analysis methods are essential for the assessment of strength reduction of unidirectional composites and laminates with ply waviness defects. FE analysis of waviness defects using meshes obtained from cross-sectional micrographs was presented in [2]; and the authors of this work used FE analysis of meshes generated from surface photographs and mixed-mode failure criteria to predict tensile failure of wavy laminates [5].

Unique features of presented methodology include combination of accurate qualification of an individual part condition, and structural modeling and analysis based on the nondestructive sub-surface measurements of the part features such as manufacturing defects. The methodology includes the ability to detect and measure the defects in three dimensions and the automated interpretation of the defect measurement; and the structural methods able to utilize the results of NDE in a failure prognosis that captures multiple failure modes in a composite structure.

An automatic algorithm of mesh generation is presented for the objective scan interpretation. The contrast between material phases in unidirectional composites (especially carbon/epoxy composites) found in typical CT images is such that fiber orientations cannot be detected everywhere. This work proposes a computational procedure for automated generation of quadrilateral finite element mesh based on CT scan images of composite specimens. The procedure’s performance is demonstrated by the two- and three-dimensional finite element meshes generated by the detection algorithm for composite specimens of different geometry and size of waviness defects.
2 Techniques for Waviness Detection

This section describes the CT techniques of non-destructive evaluation with the emphasis on waviness detection. The X-ray tube produces a beam of high-energy photons that penetrate the specimen, and the detector panel records the attenuation of the beam in the digital radiograph image. The specimen is placed on a rotational table and 2D radiographs are acquired for the 360 degree-rotation. Scans accomplished in this work captured 4 digital images, 10 megapixel in size, per one angular degree resulting in 1440 images total. The reconstruction software generates three-dimensional volumetric data from the 2D images that can be inspected in the volume-based viewer. This work utilized X5000 industrial CT system with 225 KV micro-focus X-ray tube and Varian 4030E series flat panel detector manufactured by North Star Imaging; and its efX-CT software was used for reconstruction.

Recent advances in computer hardware reduced processing required for reconstruction to only a few minutes. Typical inspection of volumetric data consists of slicing the volume in the directions that identify the sub-surface features of interest. Images of the volume sections can be used for automatic feature analysis and mesh generation as shown in the following sections. However, detection of fiber waviness is a challenging task due to lack of data quality in the slice images.

The analysis method presented in this work uses the slice images that represent virtual sections parallel to the nominal fiber direction. These sections typically show contrast variations between the areas of different fiber content that allow visual identification of fiber bundles. Fiber bundles are seen as smooth curves with relatively small thickness and curvature that varies throughout the specimen (see Fig. 1). The scanning technique optimized for fiber waviness detection needs to maximize the contrast between very similar material densities in the specimen. The scan images should also have enough resolution and focus to discern the variations at less than 50 micron-scale.

Fig. 1. Example of a cross-sectional slice from the CT scan of a curved-beam composite specimen.

The following techniques can be employed to increase contrast-to-noise ratio in the images produced by CT:

1. Increasing the X-ray tube target current;
2. Averaging over group of pixels (i.e. bucketing);
3. Averaging more frames per each CT scan rotation angle.

Increase in X-ray tube current is limited by defocusing of the tube that is proportional to the electron-beam generating power – a product of the voltage and current. To obtain necessary resolution, focus and minimize noise in the CT scan images, the following techniques must be utilized, respectively:

1. Pixel resolution of the scan should not exceed 10-20 microns. The detector used in this work had a pixel pitch of 127 micron, which required geometric magnification of at least 6X.
2. Minimum X-ray tube voltage necessary for the adequate penetration of the specimen (lack of penetration results in increased noise) should be used to keep tube focus below 10 microns.
3. Using tube filter (which hardens the beam and typically recommended for reducing photon scattering noise and reconstruction artifacts) is discouraged for waviness detection as it requires increasing tube voltage to values that lead to defocusing.

Finding scan parameters that lead to optimal waviness detection requires careful balancing of the parameters above.
3 Mesh Generation for Waviness Analysis

3.1 Summary of Mesh Generation Algorithm

We assume that fiber bundles follow the smooth curves which are not too far from straight lines and that they have a predominant orientation such as hoop direction in Fig. 1. Major problem in creating the finite element mesh is due to fiber curves being not visible and discoverable enough in all regions of a CT scan section image.

The structural analysis that uses generated meshes requires that element edges in finite element mesh follow the local orientation of the fibers. The proposed algorithm of mesh generation from a CT scan section image consists of the following steps.

1. Determine the analysis domain in each cross-sectional slice of the specimen by automatic shape detection, subdivide the analysis area in superelements with curved edges and map the domain to a rectangular image.
2. Detect reliable fiber curve fragments using an edge detection technique, filter and approximate them as splines and compute the fiber slopes.
3. Create a discrete field of fiber slopes at the rectangular grid by interpolating the slope values. Perform smoothing of the slope field at rectangular grid using mesh denoising method.
4. Create nodes of the finite element mesh by integration of two ordinary differential equations for the slopes in two orthogonal directions.

The algorithm of mesh generation is implemented in Python programming language. Edge detection in CT scan images uses algorithms available in the literature as referred in section 3.3. Smoothing of fiber slope field is done with external software available from the authors of the mesh denoising method, see section 3.4. The following sections present selected algorithm steps and aspects of their computational implementation.

3.2 Mapping of the Analysis Domain

Composite specimens are not limited to rectangular shapes; however, their shapes have simple topology. Since image processing operations can be conveniently done on rectangular images, we propose to perform parametric mapping of a non-rectangular image domain onto a rectangular image. The first step is to appropriately define a non-rectangular domain used for mapping on the source images. Since CT scans often include more than a thousand slices, an automatic method is required. The second step is selection of a transform that aligns the fibers in the slice with the principal axis in the rectangular image.

An algorithm to detect specimen shape in a slice is presented below.

1. Apply binary threshold transformation. We recommend selecting threshold at an average of the air and material gray values in each CT scan.
2. Apply sequence of binary opening and closing transforms to remove cracks, voids and surface artifacts from the binary image of the slice. Typically it is sufficient to apply one binary closing transform with \( C_x \) iterations where \( C_x \) is the size of the largest void in pixels. When other unwanted features are present (such as fixturing tape on the surface or cracks near the surface), it may be required to apply more opening and closing transforms.
3. Scan the image in the appropriate direction to determine locations of entering material (pixel switch from zero to one) and exiting material. For majority of CT scans, only as many scan lines are necessary as the number of subdivision nodes. When high levels of noise are present, one may need to detect larger number of nodes, smooth the resulting border lines and then select border nodes.

Detection of shape allows precise alignment of the coordinate systems of all slices in order to correct image shifts due to mismatch in section plane orientation. The second step is the selection of border nodes for coordinate transformation. For composites the border nodes are selected to define transformation from image coordinate system to the coordinate system aligned with the material axes of the specimen. For example, the opposite border points for the curved-beam example (section 4.2) are selected at the same hoop angle, which transforms image coordinates to polar coordinates of the specimen center part.

The coordinate system transformation is an interpolation of nodal coordinates with coefficients defined as quadratic function of local coordinates. This transformation that is based on shape functions of quadratic 8-noded elements is widely used in

3.3 Detection of Fiber Slopes

Fibers in composites are typically too small to be separated in cross-sectional images generated by CT scan. The images contain contrast variations that indicate orientation of fibers. Based on the application of analysis domain mapping we assume that fibers are approximately parallel to the image edges, except for some areas where fiber slopes are of moderate magnitudes.

First step in the detection of fiber lines is applying the median filter in the direction that is approximately tangent to the fiber lines. This step aims to suppress the noise between mostly horizontal fiber bundle lines and improving their identification.

Second step is image-based edge detection accomplished by the Canny method [7]. The Canny method is a multiple step edge detection procedure aimed at detection of image edges with simultaneous noise suppression. The method includes the following steps:

1. Apply a Gaussian smoothing filter (width of $\sigma$) to reduce image noise.
2. Determine the magnitude and direction of the image gradient using edge detectors.
3. Perform non-maxima suppression with the purpose of edge thinning.
4. Perform a hysteresis thresholding using two different thresholds.

Typical quality of the scan data for composite materials is such that the direct computation of gradients by a differential operator (for example, the Sobel operator used in the Canny method) leads to considerable oscillations in gradient values.

The following algorithm of improving reliability of gradient estimation is used:

1. Scan lines in the image with detected edges and find chains of connected pixels with length larger than minimal specified length.
2. In each pixel chain, select pixels using the specified step along x direction.
3. Approximate selected pixels by spline function $y_n = y_n(x)$.
4. Find slopes at selected pixels as a derivative $dy_n/dx$ of the spline approximation.

These steps perform B-spline approximation of selected pixels at each chain and estimation of derivative values $dy_n/dx$. Gradient values at both ends of the pixel chain are discarded to avoid excessive errors. In addition to estimated gradient values at the selected internal pixels, zero gradient values are specified at the image border; same step as for the internal pixel selection is used.

3.4 Interpolation of the Gradient Field

Fiber line gradients $g(x, y) = dy_n/dx$ are determined at arbitrary locations defined by the algorithm in section 3.3. To determine the gradients at the nodes of a rectangular mesh, the interpolation of scattered data is required for further smoothing and improving performance of the interpolation. Radial basis function (RBF) interpolation is suitable for such kind of data [8].

RBF interpolation is based on the solution of a linear system of equations of the order equal to the number of data points. The whole set of gradient data contains too many points; the subset of data points in the neighborhood of the point selected for interpolation. In this work, we use the multiquadric radial basis function for gradient interpolation such that the radius is scaled by the average distance between data points. The radius of interpolation region $R$ is estimated on the basis of average density of the gradient points in the whole image. See Ref. [6] for the particular details of RBF interpolation.

Values of fiber line gradients $g(x, y)$ determined at the nodes of the polygonal mesh have significant noise levels due to uncertainty in detected image edges and errors in their approximation and differentiation. To smooth the gradient field, the following mesh denoising method is used [9]. During the first stage of the method, polygon face normals are filtered iteratively by weighted averaging of adjacent face normals. In the second stage, node heights (gradient values) are iteratively updated to be in agreement with the denoised face normals. Regular grid of triangles with specified size is generated for the rectangular image. The triangular mesh used by the mesh-denosing step is obtained from a regular rectangular mesh by dividing each quadrilateral into two triangles. Finally, the gradient values are computed at the grid nodes by the RBF interpolation.
3.5 Mesh Generation

We intend to generate a topologically regular mesh of quadrilateral elements with “horizontal” edges along the fiber lines. “Vertical” element edges should follow curves that are normal to the fiber lines. Nodes of the finite element mesh are generated by integrating the ordinary differential equation for the fiber line slopes. The algorithm uses the specified number of elements in horizontal $x$ and vertical $y$ directions of the cross-sectional region.

The horizontal element boundary lines are obtained from the solution of the ordinary differential equation $dy/dx=g(x, y)$, where $g(x, y)$ is the gradient value at $(x, y)$ point estimated by the bilinear interpolation of the smoothed gradients at the nodes of the polygonal mesh. Integration of this differential equation is performed using the fourth order Runge-Kutta method. The element size is divided in sub-increments to increase the precision of numerical integration. The integration of the $i$th row of nodes starts at the mid-point location $(0.5n_x, i\Delta y)$ and proceeds in both directions from the starting point.

If the transformation that maps analysis domain (section 3.2) from the coordinate system $(x, y)$ to the coordinate system $(X, Y)$ preserves angles between lines then the vertical element boundary lines (normal to fiber lines) can be determined by integrating the same gradient field rotated by 90 degrees. Similarly, the integration proceeds from the central point $(i\Delta x, 0.5n_y)$ in the upper and lower directions.

When local coordinate system lines $\xi=\text{const}$ and $\eta=\text{const}$ are not perpendicular in the global coordinate system $(X, Y)$, the integration should be done in a coordinate system rotated by angle $(90^\circ-\alpha)$. Here $\alpha$ is an angle between lines $\xi=\text{const}$ and $\eta=\text{const}$. Since angle $\alpha$ changes from point to point the integration coordinate system should be determined at each integration step to ensure that the element edges are orthogonal.

Nodes of the finite element mesh are found as intersections of the horizontal and vertical element boundary lines in the coordinate system $(x, y)$. Finally, mesh nodes are transformed to the coordinate system $(X, Y)$ using the inverse of a transformation defined in section 3.2.

3.6 Example of Mesh Generation

An example of mesh generation for glass/epoxy composite wedge specimen (trapezoidal cross-section) is presented below. The example demonstrates the algorithm steps from the scanned specimen cross-sectional image to the generated 2D mesh, and shows that the proposed algorithm allows automatic creation of FE mesh from the CT scan.

Typical CT scan image of glass/epoxy composite wedge specimen cross-section is presented in Fig. 2a. The cross-section is oriented such that the fiber direction is along the length of the specimen and parallel to the section. The image size is 1200x566 pixels; specimen thickness varies from 0.71 to 1.56 inches (18.1 to 39.6 mm). The central trapezoidal part of the specimen is represented with one subdomain and transformed into a rectangular image, 933x288 pixels in size. The CT scans of glass/epoxy composites result in higher contrast-to-noise ratio as compared to carbon/epoxy composites; however larger specimen size that leads to smaller geometric magnification of the scan presents additional challenges to the algorithm due to lower resolution of the fiber lines.

After convolving the image with the median filter of 8 pixels along the fiber direction, the Canny method with $\sigma = 3$, thresholds 0.3 and 0.6 was used to detect edges. Detected edges along fiber lines are presented in Fig. 2b. The figure shows significant amount of shorter edges with random orientations that need to be discarded for the robust gradient calculation. Minimum length of acceptable edges was set at 32 pixels and maximum acceptable slope was set to 0.5 radian. Fig. 2c shows points of fiber waviness field gradient calculation – a total of 3944 points. The RBF interpolation is able to infer enough waviness data to generate a mesh with good quality. A polygonal mesh of 5208 triangles with $z$-coordinates equal to fiber waviness field gradients at mesh nodes is created and smoothed by the mesh-denoising method with threshold of 0.3. Runge-Kutta integration (integration step: 6 pixels) of filtered fiber gradients in horizontal and vertical directions generated rectangular mesh of 60x24 quadrilateral elements. Nodal locations in the rectangular image are shown in Figure 2d.
3.7 Three-dimensional Mesh Generation

FE analysis of complex structures motivates extension of the method to three dimensions. Three-dimensional meshes can be generated by combining planar meshes for cross-sections of the specimen. While the two-dimensional meshes are created separately for each cross-section, the RBF interpolation of fiber slopes is done in three dimensions using the gradient data within the sphere of the radius calculated by the RBF interpolation algorithm. The final three-dimensional mesh is obtained by joining the nodes of the cross-sectional meshes and generating indices for 3D solid elements.

Care must be exercised when defining a fiber-oriented coordinate system from the specimen shapes as errors in boundary detection may lead to abrupt changes in nodal coordinates. In the examples below, the least-squares fit of the coordinate system parameters was obtained for all cross-sectional slices and the resulting averaged coordinate system transformation was used. Fig. 3 presents the example of three-dimensional mesh built for the wedge specimen.

4 Analysis of Curved-Beam Specimen with Waviness Defects

The curved-beam test is used by the composites community for measurement of the interlaminar tensile strength. Fig. 4 shows curved-beam test setup. The failure mode is tensile delamination which normally starts in the beam radius area at about 60% of the thickness corresponding to the maximum interlaminar tensile stress location, and quickly propagates through the beam flanges.
Fig. 4. A curved-beam test setup showing the area of CT scan.

The CT scans were accomplished at 40 kV tube voltage and 600 μA target current at 0.6 frames per second. 15.5X magnification was used to maximize scan resolution for the curved part of the specimen. This magnification resulted in the effective pixel pitch of 0.3×10⁻³ in (8 μm). The image size of the cross-sectional slices used for the analysis was 1225x631 pixels. In addition to low contrast-to-noise ratio and lower magnification of the CT scan, the curvilinear shape of the specimen presents additional challenge due to increasingly three-dimensional nature of waviness defects. Sample cross-section of the specimen is shown in Fig. 1.

The analysis area is represented with four subdomains. Fig. 5 illustrates the steps of the algorithm. Fig. 5a shows rectangular image obtained by mapping of the four subdomains using quadratic interpolation. Fig. 5b shows points of fiber waviness field gradient calculation in the rectangular image. The same edge detection method and parameters as in section 3.2 are used. The figure shows detected edges of mostly average length; the areas of smaller waviness have the best quality while the areas of larger waviness lack continuity of edge detection. Again, shorter edges with random orientations were discarded for gradient calculation. Although more points are used for gradient calculation than in section 3.3, they tend to have more noise due to smaller waviness and lower data-to-noise ratio. A 40x20 element mesh in the rectangular domain is shown in Fig. 5c. The three-dimensional mesh obtained by combining the 2D meshes for through-the-width slices and transformed to the initial coordinate system is presented in Fig. 5d.

Fig. 5a. Transformed CT scan image of the curved-beam specimen cross-section.

Fig. 5b. Filtered points of gradient calculation.

Fig. 5c. Nodes generated by gradient integration.

Fig. 5d. Resulting three-dimensional FE mesh of the curved-beam specimen.

The generated mesh of the curved-beam specimen shows good approximation of the fiber directions in the regions of sufficient scan quality; and the tendency to approximate fiber waviness in the regions of poor contrast. The mesh also shows that noise in gradients can accumulate to produce undesirable mesh concentration at the border of the analyzed area.
5 Conclusions and Future Work

Non-destructive measurement of manufacturing defects is becoming an important tool for assessment of the actual part condition and allows avoiding assumptions of the worst-case scenario in structural disposition. Accurate three-dimensional measurements of fiber waviness are necessary to determine the effects of defects in composite parts. Automatic conversion of measurement to finite element models is required to process the large data sets obtained by CT scans.

A novel algorithm and computational procedure for finite element mesh generation from X-Ray Computed Micro-Tomography images have been developed for composites with fiber waviness. The CT scans of composite specimens with waviness imperfections show wavy patterns due to the contrast between areas of different fiber content. These patterns correspond to local orientations of fibers, and their accurate identification is critical for strength and durability predictions by composite specimen structural analysis.

The presented algorithm was able to generate finite element meshes with high quality of waviness approximation for the scans with low contrast (carbon/epoxy composites) and low magnification. The CT scans with low contrast, lower magnification and curvilinear geometry provided special challenge for the algorithm. Overall, the algorithm has demonstrated robust and accurate results for the scans that allow good identification of fiber waviness by visual inspection and produced viable solutions for the scans of lesser quality.

The algorithm can be readily extended to handle mesh generation for practical structures that have more complex cross-sections. The potential benefits of the ability to accurately measure material structure and transfer non-destructive measurements into structural failure models can lead to a fundamental shift from the statistics-based to condition-based structural substantiation.

In this work, three-dimensional FE meshes are generated by combining planar meshes generated from the specimen sections. Availability of 3D mesh is important for computational structural analysis methods that predict interlaminar failure of the composites. Additional efforts are required to substantiate the relationship of manufacturing procedure, CT scan parameters and quality of structural predictions. Computational models that use generated meshes will be implemented in the ABAQUS finite element software [10], and failure analysis will be based on methods previously developed by authors [5] that use modified LaRC04 failure criterion [11-12]. Tests of curved-beam specimens with waviness defects demonstrated failure loads from 1.47 to 2.02 kN (330 to 454 lbs). Critical voids and failure loads will be determined and compared with test results.

References
