MICRO-COMPUTED TOMOGRAPHY IMAGE CONTRAST ENHANCEMENT FOR DIGITAL VOLUME CORRELATION OF TUBULAR BRAIDED COMPOSITES

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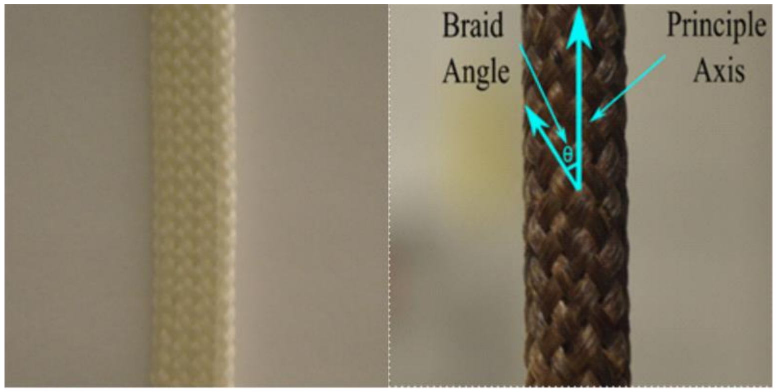
ABSTRACT

Tubular braided composite materials are made from woven fibers impregnated within a matrix. Currently, the mechanics of braided composites are limited to understanding the external behavior using techniques such as strain gages, extensometers, and digital image correlation (DIC). To resolve the internal strains, a technique known as Digital Volume Correlation (DVC) can be implemented using images from X-ray based micro-computed tomography. To achieve a proper correlation from image tomographs a contrast pattern is required. This is attainable by impregnating the braid matrix with high density micro-particles to track deformation using DVC software. The focus of this study is to analyze the effectiveness of these micro-particles seeded within an epoxy matrix for DVC analysis. This work will lead to the analysis of braided structures impregnated with micro-particle seeded epoxy and will allow for accurate characterization of the internal deformation and strain of TBC structures.

KEYWORDS: Braided Composites, Digital Volume Correlation, Micro-computed Tomography

INTRODUCTION

Tubular braided composites are formed using a Maypole braider through the interweaving of yarns into a braid preform and then impregnated with a matrix material [1]. The yarns are composed of continuous light-weight and high strength fibres. These yarns are braided into one of three commonly used patterns: Diamond, Regular, and Hercules [1]. The braid angle, shown in Figure 1, is one of the most important features for controlling braid mechanical properties [1]. The mechanical properties of a braided composite are dependent on the braid angle and thus as the angle changes so to do the composites properties [1]. This factor makes the effects of loading on a braid difficult to predict using conventional measurement techniques such as strain gauges and extensometers. To obtain full field displacement and strain measurements two dimensional (2D) and three dimensional (3D) digital image correlation (DIC) have become common use from researchers [2]–[6]. However, these measurements only provide the information along the surface of the material [3].



(a) (b)

Figure 1: Example of a Diamond configuration braid (a) braid preform prior to epoxy impregnation (b) fully manufactured braid where the angle of the yarns is indicated

Micro-computed tomography (μ-CT) is a radiographic imaging technique that allows for the non-destructive analysis of materials [7]. μ-CT operates by emitting x-rays through a material to capture a full volumetric view of the sample [7]. As the x-ray passes through a sample the beam attenuates in relation to the density of the material [7]. By measuring the ratio of the attenuated beam to the original beam a shadow projection is formed which can be reconstructed into cross-sections of the sample internal micro-structure [7]. μ-CT has proven itself a very powerful tool for the analysis of the geometry of textile composite materials [8],[9]. Additionally, its ability to resolve internal features on the microscale has proven useful for the identification of voids and irregularities within braided structures [8].

Digital volume correlation (DVC) is the three-dimensional (3D) volumetric counterpart to digital image correlation (DIC). DIC is commonly utilized for measuring displacement and strains of TBC [2], [4]. However, DVC has a distinct advantage over DIC since it is a volumetric technique rather than a surface measurement technique, thus allowing for full internal 3D volumetric strain fields to be visualized. The principles of DVC were first described by Bay *et al.* [10]. DVC extends surface measurements to a full field volumetric view of the displacement and strain behaviour which is useful for studying multiphase heterogenous such as braided composite materials [11]. DVC operates by first discretizing a reference and deformed 3D datasets into a series of nodes [10]. By defining a subset size which is centred around each node, an objective function is used to map the deformed dataset to the reference [10]. For a successful correlation it is important that there is variation in greyscale intensity throughout the micro-structure [10].

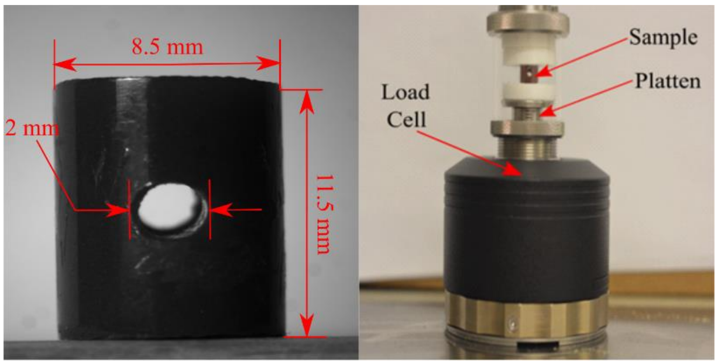
The usage of DVC in its early stages had primarily been focused for obtaining strain field of trabecular bone [12], [13]. As the technique further developed researcher began to utilize this for more typical engineering material such as wood and metals [14], [15]. More recent studies have looked at utilizing this technique for strain field analysis of composite structures, such as composite laminates and textiles [16]–[21]. However, DVC measurements are still and emerging area. As a result, limited studies have been performed for composites or braided composite structures.

This paper will outline the usage of μ-CT for obtaining high quality tomographs for DVC studies of braided composite materials. This work will focus on optimizing the x-ray scan settings, sample preparation, and optimization of the DVC analysis procedure. As a first step towards understanding the volumetric behaviour of braided composites, a resin material was investigated. Resin was utilized in this work as a test case to optimize μ-CT scan parameters and DVC correlation parameters. For a proper correlation it is necessary for a contrast pattern to exist within a sample. This contrast pattern could be natural or can be artificially produced. To this end, 5 μm copper particles have been distributed into the resin before curing to enhance sample contrast patterns. A hole was introduced in the test sample to create a stress concentration and to allow for analysis of the resulting volumetric strain fields. The test sample was subjected to compressive loading and a reference and deformed dataset was collected. Volumetric displacement and strain measurements were obtained via an open source DVC software package. The methods utilized in this work will be adapted for the analysis of strain fields within braided composite structures.

METHODOLOGY

3.1 SAMPLE PREPARATION

The test sample was prepared from a two-part epoxy: resin (#2000 epoxy resin, Fibre Glast, Brookville, OH), and hardener (#2020 epoxy hardener, Fibre Glast, Brookville, OH). The resin and hardener were mixed at a ratio of 100:27 wt%. Within these samples 5 µm copper particles (5 micron purity 99.8%, Copper powder, Sigma Aldrich, Canada) were embedded into the mixed epoxy. The difference in density between the epoxy (1134.89 kg/m^3) and copper particles (8960 kg/m^3) will result in two distinct phases appearing in the CT tomographs. These particles were manually mixed into the epoxy mixture at a 5 wt%. The test sample was cured in a vacuum oven (5851 vacuum oven, Napco, Winchester, VA) at 66 ºC (150 ºF) for 6 hrs. The manufactured epoxy sample is shown in Figure 2 (a). The sample was cured in a cylindrical Pyrex test tube with a 10mm OD and 8.5 mm ID. The cured sample was a 8.5 mm diameter cylinder that was 11.5 mm in length. For the loading test a 2 mm hole was drilled through the centre of the sample to introduce a stress concentration. The epoxy test sample and material testing stage used in this study is shown in Figure 2 (b). The material test stage is placed within the µ-CT scanner to perform in-situ strain measurement.



(a) (b)

Figure 2: Test epoxy sample for DVC analysis (a) Final cured sample of the epoxy-copper sample (b) Epoxy sample within material test stage. The material test stage is placed within the µ-CT scanner for in-situ mechanical testing

3.2 COMPUTED TOMORGRAPHY

Sample x-ray imaging was performed using a desktop µ-CT (Skyscan 1272 µ-CT scanner, Bruker, Belgium) to obtain 3D datasets. Two datasets were collected, a reference and deformed dataset, in order to perform the DVC measurement. For the epoxy samples an x-ray with a source voltage of 70 kV and source current of 142 µA was used. As recommended by the µ-CT manufacturer a 0.5 mm aluminium filter was also utilized to improve image results and minimize x-ray artefacts. The resolution of the scan was set to 4904 px by 3280 px with a pixel size of 3.5 µm/px. This allowed for the entire sample diameter of the sample (8.5 mm) to be in the image field of view while being able to image the smallest copper particles (5µm) within the epoxy sample. A rotation step of 0.1 degrees was used resulting in 1920 shadow projections.

A compressive load was applied for DVC analysis by utilizing the µ-CT's integrated material test stage (MTS) (440 N integrated test stage, Bruker Belgium). A custom platen was 3D printed to ensure sample alignment in MTS during compression. Figure 2 shows an image of the sample and MTS. Scans were performed on the 5 µm sample at two different load steps: 1) 100 N, and 3) 300 N. Between each load step the sample was let to stabilize at each force for 5 minutes before scanning.

3.3 RECONSTRUCTION

After scanning at each load step the image shadow projection were reconstructed into a series of 2D perpendicular cross-sectional images that span the volume of the scanned sample. Reconstruction was performed utilizing a reconstruction software package (NRecon version 1.7.1.0, Bruker, Belgium) and reconstruction engine (InstaRecon version 2.3.0.7, Bruker, Belgium). For reconstruction a threshold of greyscale values must be selected that fully capture all features of the image microstructure. It is recommended by the reconstruction software manufacturers that the lower limited be set to an attenuation of 0 (-1000 HU) and the upper limit be set to a 10-20% greater than the maximum variation in greyscale. For both load steps the sample an attenuation range was set to 0 to 0.7 (-1000 HU to 44874.5 HU) [22]. A single shadow projection of the epoxy sample is shown in Figure 3 (a). A reconstructed cross-section along A-A plane of the particle impregnated epoxy is shown in Figure 3 (b). In this figure the epoxy and particles can be seen. The epoxy and copper particles are identified from one another due to their different greyscale values associated to their density. This can be seen in Figure 3 (b). The resulting reconstruction process lead to 2940 images with a resolution of 4904 px by 4904 px.

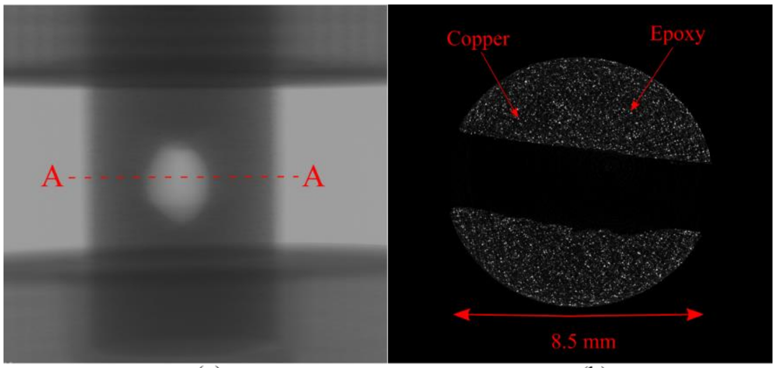


Figure 3: Example images from CT scan of copper impregnated epoxy sample a) x-ray shadow projection showing the sample with central hole b) reconstructed cross-section across the A-A plane (contrast enhanced) where the copper particles and epoxy can be seen.

3.4 PRE-PROCESSING FOR DIGITAL VOLUME CORRELATION

Due to the computational load that is required to perform a DVC measurement the images were rescaled and cropped to lessen the computation burden. Utilizing an image segmentation and visualization software package (CTAn, 1.16.90, Bruker, Belgium) the image stack was resized by a third. The new image stack consisted of 980 images with a resolution of 1165 px by 1162 px. As seen in Figure 3 (b) there is a substantial amount of blank space which is associated with air. Additionally, within the epoxy a network of grey speckles associated with the copper can be identified. To save correlation time this space was cropped out of the final image utilizing MATLAB (MATLAB R2018B, The MathWorks, Natick, Mass). The final cross-sectional image size was 960 px by 923 px.

3.4 DIGITAL VOLUME CORRELATION

A MATLAB based DVC software package (FIDVC, version 1.2.4) was utilized to calculate the in-situ 3D displacement [23]. Full-field Lagrangian strain measurements were then calculated from the displacement fields using a software extension (LD-3D-TFM, version 1.1) [24]. FIDVC utilizes a Fast Fourier Transform (FFT) approach to perform the cross correlation and track the movement of the imbedded copper particles from the reference and displaced subset. In conjunction with the cross-correlation and iterative deformation method is used to improve the accuracy of the displacement.

To perform the DVC measurement, the image stacks were saved as a 3D matrix with the MAT file extension. Displacements were than calculated using a 128x128x128 px search window with a 30 px step size. The search window size was chosen based on the largest size available, since each pass will reduce the subset size and thus this will provide the best resolution on displacement and strain. The discretization process resultedt in a grid of 33x33x35 nodes where displacement and strain measurement were calculated. Four displacement fields are calculated: displacement in x, y, z, and the displacement magnitude. Displacement fields were than uploaded into the strain software package to calculate the 3D strain fields. Six unique values of strain are measured from this procedure: three normal strain and three shear strain according the 3D strain matrix seen in equation (1). To find the equivalent strain values the field are converted into equivalent Von-Mises strain according to equation (2) [25]. The reason for utilizing the Von-Mises strain is that the value is completely independent of the coordinate system. Displacement and strain were calculated through the volume of the material and then displaced in three planes according to Figure 4. Computation was performed on a computer (Precision T5600, Dell, Round Rock, Texas) equipped with 128 gigabytes of ram. Results were visualized utilizing an open source MATLAB 3D array plotter (PATCH_3Darray) [26]. Using this configuration processing time for the sample was approximately 5.0 hrs.

$$\varepsilon = \begin{bmatrix} \varepsilon_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \varepsilon_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \varepsilon_{zz} \end{bmatrix} \tag{1}$$

$$\varepsilon_{eq} = \frac{2}{3}\sqrt{\frac{3(\varepsilon_{xx}^2+\varepsilon_{yy}^2+\varepsilon_{zz}^2)}{2} + \frac{3(\tau_{xy}^2+\tau_{yz}^2+\tau_{zx}^2)}{4}} \tag{2}$$

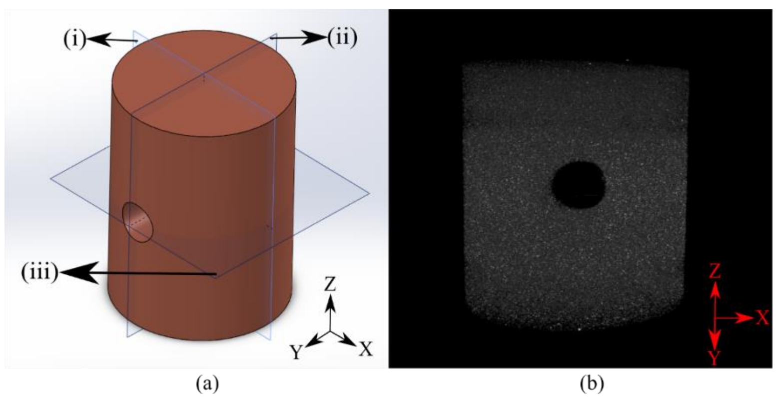
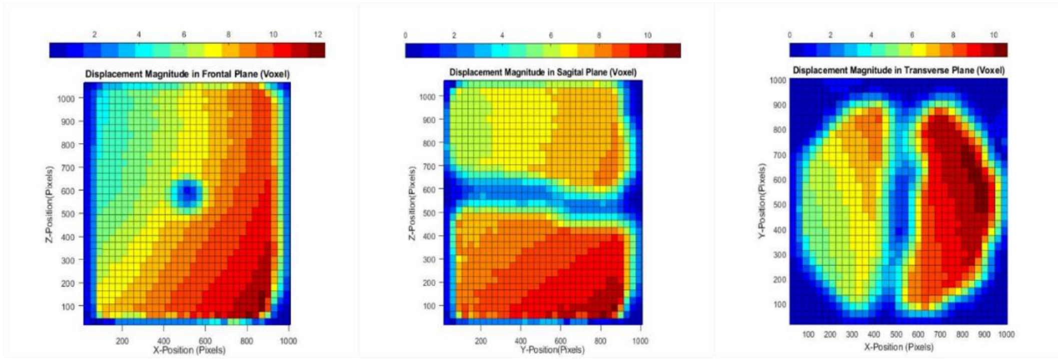


Figure 4: 3D Model of the copper impregnated sample: a) Geometrical solid model showing the 3 main planes : i) frontal plane, ii) sagittal plane, & iii) transverse plane. b) 3D reconstruction of the sample geometry from µ-CT tomographs.

RESULTS

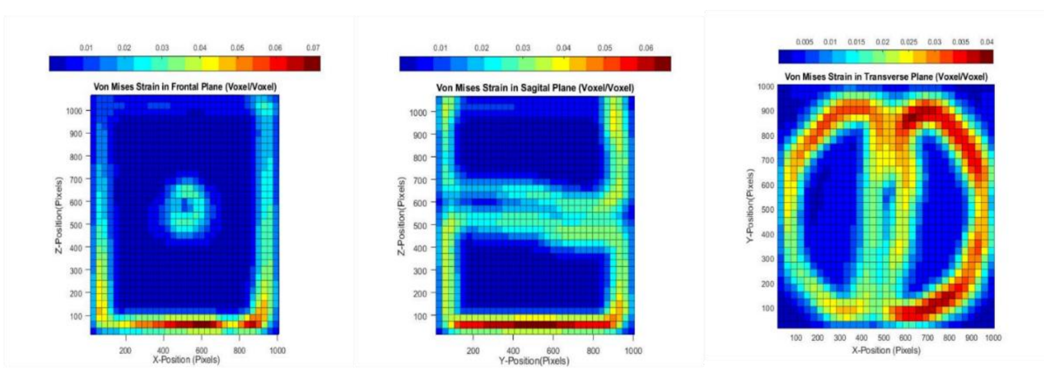
The DVC measurement technique provided full field measurements of the displacement and strain development from the compressive load applied in this study. The magnitude of displacement measured in pixels is shown in the sagittal, coronal, and transverse plan are shown in Figure 5. It can be seen from Figure 5 the displacements that along the 2 mm hole there is no displacement. From this point the displacement radiates outward from the hole. Two distinct band of displacement seem to form along the center of the plane of the sample. One band of displacement has a displacement between 5 pixels-8 pixels (52.5µm-84µm). The other band has a slightly larger displacement between 8.5-10.5 pixels (89.25µm-110.25µm). Although the sample was placed under uniaxial compression the difference in displacements is likely due to the surface of the sample being uneven while the sample was placed under load. This resulted in bulk translation of the test specimen. The results shown in Figure 5 demonstrate that the bulk translation of the test sample can be measured using the DVC analysis technique. Additionally, the particle seeding technique has proven effective at detecting sub-millimetre levels of displacement from the applied loading.



(a) (b) (c)

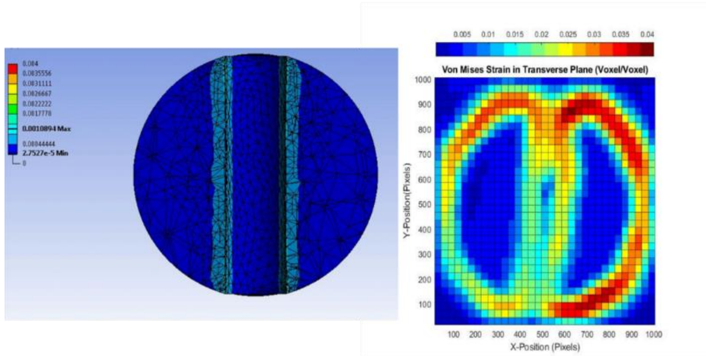
Figure 5: DVC displacement magnitude for the epoxy sample under compressive loading: a) Frontal plane b) sagittal plane & c) transverse plane

Along with the displacements, the equivalent Von Mises strain calculated using equation (2) for the full geometry of the epoxy resin is shown Figure 6. Figure 6 shows the Von Mises strain in three planes (Frontal, sagittal and transverse). From the transverse plane shown in Figure 6 (c) the development of strain through the resin can be seen to from at the edge of the 2 mm hole. At the edge of the hole it is expected that the strain be at its maximum. The DVC measurement shows that the two symmetric about the centre bands strain of develop where the strain is in the range of 0.015 px/px to 0.02 px/px. This is slightly higher than the bulk of the material which has a range an equivalent strain slightly less than 0.005 px/px. Of note is a band of high strain developed around the circumference of the epoxy. At this point potential causes of this could be an uneven distribution of force on the sample or the existent of fewer particles within the subsets along edges. For comparison, a finite element analysis (FEA) model was created using a commercial software (ANSYS Workbench, Academic, R19, Canonsburg, PA) to show the development of the strain gradient which is seen in Figure 7. The model was made from 6.4266E-4 m (ANSYS default mesh size) tetrahedron elements with a quadratic element order. To properly capture the behaviour around the stress concentration a mesh refinement was conducted around the nodes. The element system count after refinement resulted in 16834 elements. Comparing the gradient, it behaves similarly between both the finite element model and DVC model which shows an outward expansion from the compressive force. Strain development is similar between the FEA and DVC model everywhere except the outer perimeter where the DVC model predicts a significantly larger amount of strain then the rest of the sample. Further investigation of experimental and model parameters will allow for better matching of FEA and DVC results. Figure 7 shows this key advantage of the DVC technique as results are directly comparable to FEA models.



(a) (b) (c)

Figure 6: Equivalent Von Mises strain for the epoxy sample subjected to compressive loading a) frontal plane b) sagittal plane & c) transverse plane



(a) (b)

Figure 7: Comparison of Von Mises strain across the transverse plane for the epoxy sample a) finite element model and b) DVC model

CONCLUSION AND FUTURE WORK

In this study, a particle seeding technique was utilized to improve image contrast of tomographic images for DVC measurements. An epoxy resin was seeded with 5 µm copper particles at a 5 wt% ratio. A three-dimensional image stack was obtained via µ-CT. For the DVC measurement a reference and deformed state a needed for displacement and strain correlation. An integrated testing stage within the µ-CT performed in-situ loading with forces of 100 N and 300 N. Resultant displacement and strain fields for the test sample were demonstrated. Displacement and strain were computed using an open-source DVC software package.

Observations of the cross-sectional images show a dispersed network of particles throughout the sample. A proper dispersion of particles is necessary to allow for correlation of the displacement and strain measurements. The measurement technique allowed for the volumetric visualization of both the bulk movement of the epoxy and the equivalent strain. Displacements showed to be uneven throughout the sample rather than a uniform shift. This is due to translation of the sample during testing. The equivalent volumetric strain has a gradient that that is largest around the hole and gradually reduces until it reaches the edge of the sample where there is a large increase in strain. The strain behaviour around the hole and in the bulk shows a similar loading behaviour to similar finite element model except around the edges.

The particle seeding method used in this work was demonstrated to be an effective technique for enhancing the image contrast for DVC results. This is a critical first step towards the measurement and investigation of volumetric deformation and strain of braided structures. To extend this research towards the DVC measurement of braided structures there are two important parameters which need to be investigated. First, the relationship between particle size and scan resolution must be examined as in this work only one particle size was explored. The effects of particle size and particle type also require investigation. Additionally, a sensitivity analysis on the effects of DVC step size and subset size is necessary to find the optimal correlation parameters. Once these two parameters have been studied, further analysis of more complex braided composite structures will be performed.

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