IMAGING IMPACT DAMAGE IN HIGH ASPECT RATIO COMPOSITE PLATES

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1 Introduction

Three-dimensional x-ray computed tomography (CT) is an excellent method for investigating the internal damage in engineering components. The method provides a non-destructive way to visualise and quantify damage areas, such as delaminations in fibre reinforced composite plates [1][2].

CT involves the acquisition of a series of radiographs of an object, which is rotated 360º around a vertical axis. These radiographs are known as 'projections', and several thousand may be obtained. Mathematical algorithms are employed which allow the reconstruction of cross sections through the object from these projections [3]. Figure 1 illustrates a typical experimental setup, where the x-ray source and digital detector are stationary.

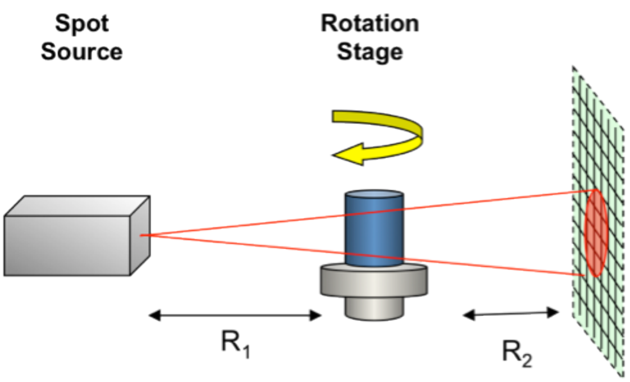

Figure 1 Cone beam CT geometry

The x-ray geometry is known as a cone beam system, and the sample projection on the detector can be magnified by varying R_1 and R_2. The magnification, M, is given by:

$$M = (R_1 + R_2)/ R_1 \qquad (1)$$

Resolutions on the system used in this study (Nikon Metrology 225kV) are possible down to approximately 10μm.

With regards to damage characterisation,the type of failure, and residual properties as a result of impact events have been studied for many years, but only recently has the ability to investigate the damage using CT in a laboratory environment been possible.

However, several problems are inherent in the CT process on laboratory-based systems when imaging high aspect ratio objects. Image quality of the radiographs depends on a certain level of x-ray absorption, which is dependant on the x-ray path length through the object. The result is that a CT scan is performed at a compromise between the voltages required for optimum contrast in the thick and thin directions. As a result, the individual radiographs are not optimized for all projection angles, which can degrade the quality of the reconstructed CT volume.

This study has illustrated how a method of combining multiple CT scans, each optimised for a particular material thickness, can provide improved image quality. The benefit is the ability to identify features such as impact-induced delaminations and matrix cracks in a composite plate more easily.

Unidirectional carbon fibre reinforced plastic (CFRP) has been studied in this paper. The material under examination is MTM-45 manufactured by Advanced Composites Group (Heanor, UK).

2 Theoretical Background to Dual Energy Approach

2.1 Optimizing Signal to Noise Ratio

Each spectral component of a polychromatic x-ray beam is exponentially attenuated, resulting in the number of photons N reaching the detector being:

$$N(\lambda) = N_{ref}(\lambda)e^{-\int \mu_{abs}(\lambda,l)dl} \qquad (2)$$

Where λ is the x-ray wavelength, N_{ref} is the number of photons when no object is present (i.e. white reference), μ_{abs} is the absorption coefficient, and the integral is over the path l through the object. N_{ref} takes into account the source spectrum and the detection efficiency at each wavelength.

The number of detected photons at each wavelength can be modelled as a Poisson distribution, and since the sum of independent Poisson distributed random variables also follows the Poisson distribution so does the total detected counts (summed over all wavelengths):

$$N^{tot} = \int_0^\infty N(\lambda)d\lambda = \int_0^\infty d\lambda N_{ref}(\lambda)e^{-\int \mu_{abs}(\lambda,l)dl} \qquad (3)$$

For a Poisson distribution with mean N^{tot}, the standard deviation is given by the square root of N^{tot}, and the probability distribution tends to the normal (Gaussian) distribution.

The transmittance for the polychromatic case is given by T:

$$T = \frac{N^{tot}}{N^{tot}_{ref}} \qquad (4)$$

The standard deviation for T can be calculated by combining the errors in N^{tot} and N_{ref}, which for large photon counts (i.e. Gaussian distribution), is given by:

$$\sigma_T = \frac{T}{\sqrt{N^{tot}_{ref}}}\sqrt{\frac{1}{T} + \frac{\sigma^{tot\,2}_{ref}}{N^{tot}_{ref}}} \qquad (5)$$

The reference image is typically an average of a number of exposures in order to reduce the image noise σ^{tot}_{ref}.

The polychromatic absorbance is A =-ln(T) and has standard deviation:

$$\sigma_A = \frac{\sigma_T}{T} = \frac{1}{\sqrt{N^{tot}_{ref}}}\sqrt{\left(\frac{1}{T} + \frac{\sigma^{tot\,2}_{ref}}{N^{tot}_{ref}}\right)} \qquad (6)$$

The signal to noise ratio for the radiographs is therefore given by:

$$\frac{A}{\sigma_A} = -\sqrt{T}\ln(T)\frac{N^{tot}_{ref}}{\sqrt{N^{tot}_{ref} + T\sigma^{tot\,2}_{ref}}} \qquad (7)$$

Reconstruction using the Feldkamp-Davis-Kress cone-beam algorithm [3] has a backprojection step, involving summing absorbances after applying a Fourier filter, so the reconstruction noise is related to that in A.

In the simplest case, where the white reference has the same noise as the radiographs (reference is obtained from a single exposure):

$$\frac{A}{\sigma_A} = -\sqrt{N^{tot}_{ref}}\ln(T)\sqrt{\frac{T}{1+T}} \qquad (8)$$

This function varies with T as shown in figure 2. It can be seen that the SNR has a peak at

T=0.109, i.e. approximately 11% beam transmission.

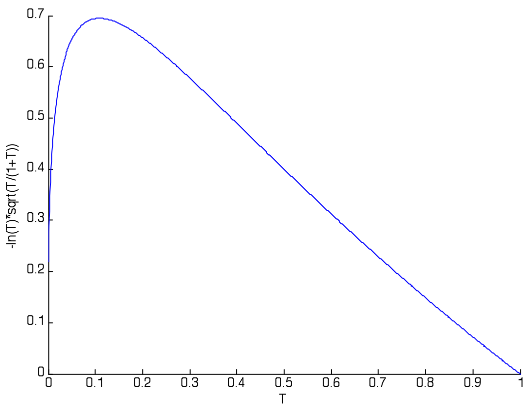

Figure 2 SNR as a function of transmittance when the noise in the white reference is equal to that in the radiographs

It can therefore be supposed that for an object with a high aspect ratio, the optimum SNR for the maximum and minimum material thicknesses would occur at drastically different beam energies. By correcting for beam hardening effects, two CT scans performed at two beam energies can be combined to give improved SNR for a high aspect ratio object.

2.2 Beam Hardening

The Nikon Metrology 225kV CT system used in this study generates a polychromatic beam of x-rays, which results in a phenomenon known as *beam hardening*. The absorption coefficient, μ_{abs}, of a material generally decreases with increasing x-ray energy; the absorbance is therefore a non-linear function of the distance through the material, l, as shown by Equation 2.

By determining the absorbance, A, experimentally over a range of thickness and voltage, polynomial calibration curves to correct for beam hardening can be obtained. Correction is achieved by calculating the actual path length l for each pixel in the radiographs taken during the CT scan.

3 Experimental

3.1 Beam Hardening Measurements

In order to determine the beam hardening correction coefficients of the MTM-45 material, a step-wedge was manufactured as shown in figure 3. A panel was manufactured from 10 plies in a 0/90 symmetrical and balanced lay-up (autoclaved cured at 180ºC for 2 hours). The panel was sectioned with a diamond saw to give 9 steps of material thickness, ranging from 1 mm to 256 mm. Each step doubles in thickness from the previous one.

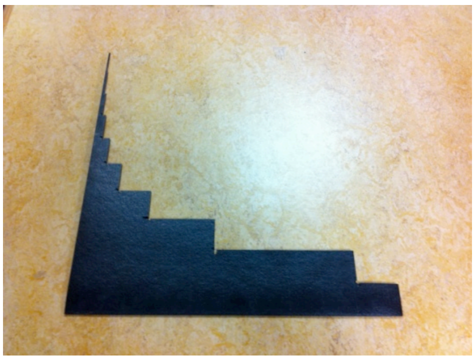

Figure 3 CFRP Step Wedge, with thicknesses ranging from 1mm to 256mm

Radiographs were taken of each step at voltages ranging from 40 kV to 225 kV in 10 kV increments. Absorbance curves were then generated from these images to give relationships between absorbance and material thickness over a range of voltages. Fitting a third order polynomial to these curves gives the beam hardening calibration curve. Figure 4 illustrates absorbance versus thickness plots for 40 kV, 80 kV and 120 kV along with associated beam hardening correction equations.

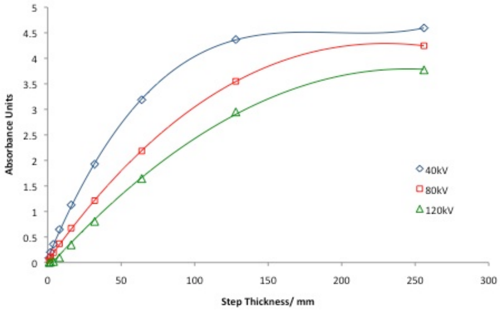

Figure 4 Examples of absorbance versus thickness for various beam energies and associated 3rd order polynomial fits

3.2 Impact Testing

To assess the practical application of the dual energy scans, drop weight impact tests were performed on the MTM-45 CFRP material under a range of energies. Coupons of dimensions 89 mm x 55 mm were manufactured to a thickness of approximately 2.5 mm by using 10 plies in a 0/90º lay-up, according to the Hogg and Pritchard test method [4]. Impact energies of 3 J, 6 J, 9 J and 12 J were used. Five samples were tested at each energy.

3.3 Dual energy CT scans

Two CT scans were performed on each of the impact samples at energies optimised for the thin and thick directions (40 kV and 110 kV). The optimised energies were selected for 10% beam transmission from the data collected from the step-wedge experiment.

The radiographs from the low energy (40 kV) and high energy (110 kV) scans were combined to obtain an improved SNR for all angles.. Radiographs from corresponding angular positions in each scan were converted to an absorbance image and the appropriate beam hardening correction applied. The corrected absorbance images were combined by averaging and were then converted back into a transmission radiograph for reconstruction using the FDK algorithm, as implemented in CT-Pro software (Nikon Metrology, Tring, UK).

Essentially this process extends the dynamic range of the CT system to allow for the large change in x-ray path length (and hence beam energy) over the dimensions of the sample.

The process was implemented in Matlab and the code was initially tested on an undamaged section of material from the step-wedge described in Section 3.1. After successful implementation, the method has been applied to the impacted samples.

4 Results

4.1 General Observations

The 'dual energy' CT volumes show improved image quality over the low and high energy individual CT scans. This improvement is observed by a reduction in image noise and increased contrast. Ply boundaries and features such as porosity and cracks can be observed more easily in the reconstructed cross-sections. Image segmentation becomes easier, and allows more accurate 3D renders of the impact damage.

4.2 Image Quality of Dual Energy Approach

Image analysis in terms of noise and contrast was performed on the dual energy scan of the undamaged material with respect to a compromised energy scan. Figure 5 shows reconstructed cross sections of the undamaged section under the various beam conditions. Figures 6 and 7 then illustrate the image analysis results.

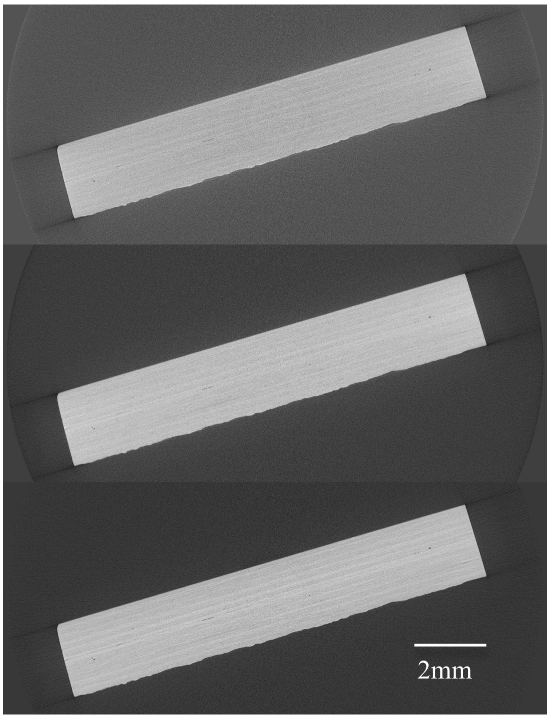

Figure 5 Reconstructed Cross Sections of undamaged test section at 40 kV (top), 110kV (bottom) and combined (bottom)

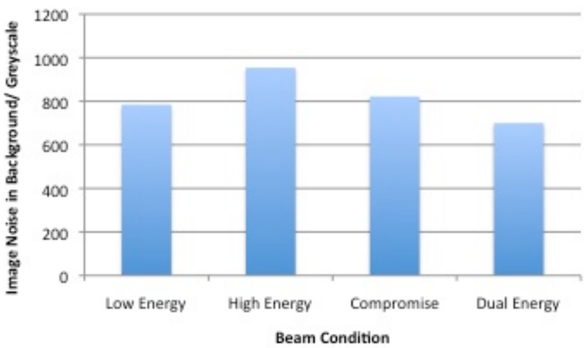

Figure 6 Background Noise in reconstructed slices for different beam conditions

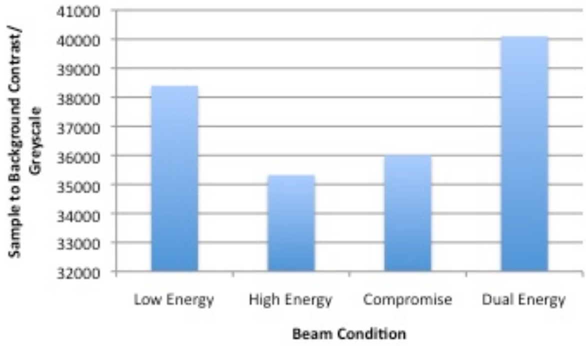

Figure 7 Image contrast between background and object

4.3 Assessment and Visualization of Impact Damage

The reconstructed CT slices allow visualization, segmentation and measurement of the damage found in the CFRP laminates. Figure 8 shows a reconstructed cross section after a 6 J impact. Characteristic damage of delaminations (running left to right) and through thickness matrix cracks can be observed.

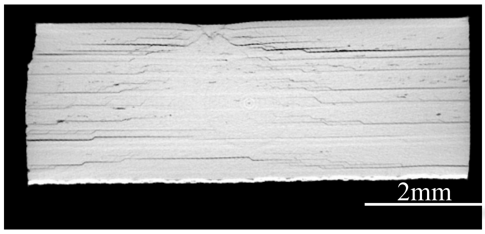

Figure 8 Reconstructed cross section of 6 J impact damage (cropped to show impact damage area)

Image processing and 3D visualization software (Avizo) was used to segment and render the damage zones by selecting appropriate grey-level thresholds. In terms of greyscale values, damage is effectively imaged as air (i.e. the background grey level). Therefore using the dual energy approach has improved the contrast between the sample and damage. Figure 9 shows the maximum damage area at 3J and 6J for representative damage. The areas are then plotted in figure 10.

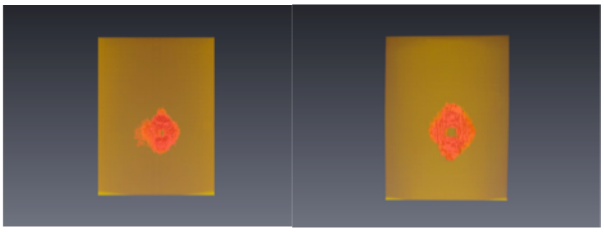

Figure 10 Typical maximum damage areas for 3J and 6J impact energies

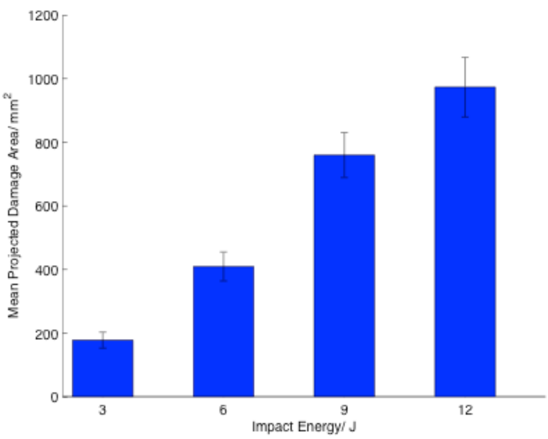

Figure 9 Mean maximum damage area versus impact energy

5 Conclusions

3D x-ray tomography provides an excellent method of non-destructive imaging of internal impact damage in CFRP samples. A dual energy approach has been shown to improve image quality and facilitate segmentation and rendering of damage in impact test samples. Correlation between the impact energy and damage area has been demonstrated which agrees with other literature on the topic [4].

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