Estimation of Damage Due to Fatigue, Impact Loading in CFRP Laminates Through Multi-sampling Image Analysis Technique

Raghu V. Prakash, Mathew John and Michele Carboni

Abstract The carbon fiber-reinforced polymeric (CFRP) composite materials are the material of choice for the aircraft structures as the designers require lightweight structures with enhanced mechanical properties. These materials are susceptible to accidental impacts during service and maintenance, and the damage will progress under varying static or dynamic service load conditions leading to the ultimate failure of the component. Recent advancement in non-destructive techniques such as X-ray computed tomography provide excellent details about the presence of damages in 3-Dimension in a component, which is an useful input for failure prediction and remaining life estimation. However, the quality of X-ray CT imaging is dependent on the equipment used, its calibration and image settings which, in turn, may affect the reliability and repeatability of damage quantification, if damage analysis is done in a routine way using binarization algorithms. In this study, the defects as well as the damage present in the low-velocity impacted CFRP laminates subjected to fatigue loading conditions are quantified and analyzed by the analysis of CT scan images obtained from two different CT systems with images of different resolution and contrast. The results of the comparative study show that the damage analysis of polymer composites using X-ray CT depends largely on the image quality and the choice of right threshold level is important for accurate damage estimation.

Keywords CFRP · Low-velocity impact · Fatigue damage · X-ray computed tomography · Image analysis

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1 Introduction

Carbon fiber-reinforced polymeric (CFRP) composites are widely used in aircraft industry due to its high specific stiffness and strength. However, they are susceptible to low-velocity impact during manufacturing, service or maintenance which results in barely visible impact damage (BVID). When the low-velocity impacted structural components are subjected to cyclic service loads, the impact damage can trigger the fatigue failure mechanism causing damage progression; damage can be due to intra-laminar defects such as matrix cracking, fiber–matrix interfacial de-bonding, fiber breakage, and inter-laminar defect of delamination. Several non-destructive testing methods (NDT) such as infrared thermography, ultrasonic testing, and X-ray computed tomography (CT) are being widely employed for the qualitative as well as quantitative analysis of voids/defects formed during manufacturing or damage progression due to mechanical loadings mentioned above.

A non-destructive technique like X-ray CT recently finds wide application in damage analysis or characterization of various engineering materials, as, it provides complete information about the material as three-dimensional (3-D) images. X-ray CT is used in manufacturing sectors for the quality control of polymer products, as, it helps visualize the interior features within solid objects and gives it in the digital form in a three-dimensional manner [1]. But the reliability and repeatability of the defect/damage measurement are very important which depends on many factors. Pavana et al. have reported that the porosity measurement of polyamide-12 material produced by laser sintering [2] through the X-ray CT image is influenced by parameters such as selection of target material, influence of tube power, noise reduction algorithm, and influence of voxel size.

In this study, quasi-isotropic CFRP specimens taken from three different laminates are considered; they were subjected to different mechanical loading conditions (impact, fatigue, and impact followed by fatigue). The CT imaging of the specimens was done using two different systems—one at IIT Madras, India, and another at PoliMi, Italy. The defect/damage quantification of the specimens was done through digital image processing of the 2D X-ray CT images of chosen specimens. The main aim of this work is to understand the effect of X-ray CT system, specimen variables on the CT image quality, and its role on the subsequent damage estimation through the image processing.

2 Experimental Methodology

2.1 Materials and Specimen Fabrication

The CFRP laminates were prepared using carbon fiber (woven roving mat) of 480 gsm (g/m^2) as reinforcement and epoxy as the matrix with fiber–matrix ratio of 1:1. The mixing ratio of epoxy (Araldite® LY556—unmodified liquid epoxy resin
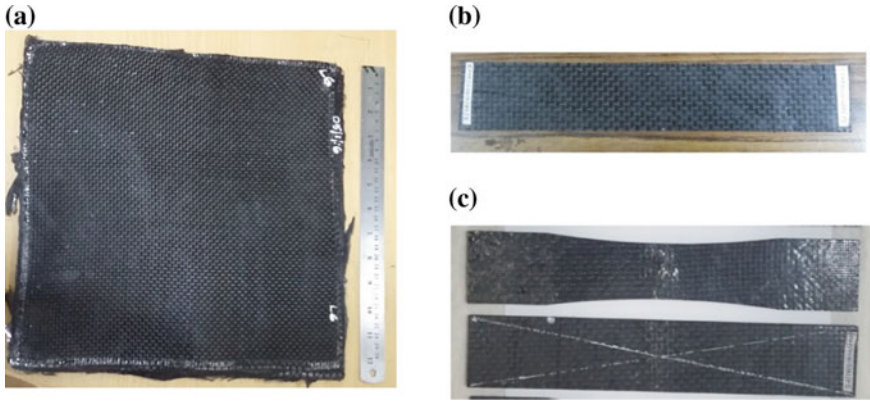
Fig. 1 a Quasi-isotropic CFRP laminate of 300 mm × 300 mm size; **b** The un-impacted fatigue specimen; **c** The 35 J impacted fatigue specimens of hourglass and flat shape

based on Bisphenol-A) to the curing agent Aradur® HY951 (unmodified aliphatic polyamine—try ethylene tetra amine) was 10:1 by weight. Hand-layup technique was used for making the laminates with quasi-isotropic (QI) stacking sequence of [0#90/±45/0#90/±45]s. The laminates of size 300 mm × 300 mm with 4.5 mm thickness were prepared; they were cured at 80 °C for 3 h in a compression molding machine. Tensile test specimens of size 250 mm × 25 mm × 4.5 mm and fatigue test specimens of size of 250 mm × 45 mm × 4.5 mm were cut from the laminates. Some of the fatigue specimens were machined to an hourglass shape with 35 mm width at the center to ensure damage concentration at the minimum width region. The specimens were cut using a CNC router from the three different laminates prepared (Refer Fig. 1) and subjected to different mechanical loadings conditions—impact, fatigue, impact + fatigue.

2.2 Mechanical Testing

The CFRP specimens were subjected to 35 J impact loading using drop weight impact testing machine with a drop weight impactor of mass 5.2 kg. It is ensured that the impactor did only single impact at the geometric center of the specimen. The load and corresponding displacement during impact for specimens from two different laminates were measured and plotted (Fig. 2). The average value of the actual energy absorbed by the specimens for the low-velocity impact with drop weight velocity of 3.66 m/s is found to be 2.75 J.

The tensile tests were conducted on the un-impacted and impacted specimens for determining the load range for the fatigue tests. The ultimate tensile strength of the specimens with quasi-isotropic stacking sequence is found to be 313 MPa. The constant amplitude (CA) fatigue tests on the specimens prepared were carried out at
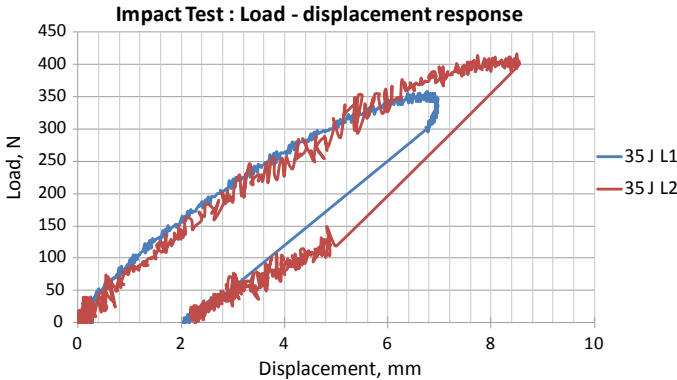
Fig. 2 Typical load–displacement curves for two CFRP specimens impacted with 35 J of energy

a stress ratio ($R = P_{min}/P_{max}$) of 0.1 and at a sinusoidal frequency of 5 Hz. The cyclic load range chosen for different specimens is as given as; (a) 0.882–8.82 kN for 35 J impacted hourglass specimen (b) 1.134–11.34 kN for 35 J impacted flat specimen and (c) 2.25–22.5 kN for the un-impacted flat specimen. The load and displacement data during the fatigue tests were continuously monitored for the purpose of stiffness estimation. The stiffness was estimated from the unloading segment of the load–displacement loop over a window of 50–90% of maximum load. The fatigue tests were stopped at half million cycles for an un-impacted specimen and at 0.1 million cycles for an impacted specimen, and the stiffness degradation due to fatigue loading for these specimens was estimated as 0.07 and 36.6%, respectively, for these specimens.

2.3 Computed X-Ray CT

3-D reconstructed X-ray CT images of damaged specimens that were extracted from three different laminates after different mechanical loading conditions were multiply sampled using two different CT imaging systems: (1) North Star Imaging 3D X-ray CT X25 tomographic system at PoliMi, Italy (referred to as XCT-A) and (2) GE make pheonix v-tomex-x s model tomographic system at CNDE lab, IIT Madras (referred to as XCT-B). The X-ray CT scanning of specimens A1, A2, A3, and A4 (refer Table 1 for specimen IDs and corresponding loading condition) are done with XCT-A; the specimens B1 and B2 with XCT-B. The scanning of specimens with XCT-A is done with a voltage of 76 kV and current 40 μA at the X-ray source and the scanning using XCT-B is done with a voltage of 50 kV and current of 100 μA at the X-ray source. The final voxel size (resolution) of the reconstructed images from machines XCT-A and XCT-B are 26 and 75 μm, respectively.

The 3-D reconstructed X-ray CT images of each specimen from these CT machines are sliced into multiple 2-D snapshots along the front (F) direction (planar

Table 1 Damage estimated for the specimens scanned with XCT-A and XCT-B with different threshold values

Specimen ID	Mechanical loading condition	X-ray CT machine used	Area considered Width × Height (mm × mm)	Damage volume percentage (Inter-modes algorithm)	Damage volume percentage (Threshold 100)	Void content percentage [$(\mu - 3\sigma)$ criteria]
A1	Un-impacted	XCT-A	44 × 34	6.47	22.05	0.89
A2	35 J Impact	XCT-A	44 × 34	3.54	10.55	–
A3	Fatigue	XCT-A	44 × 34	2.05	17.09	–
A4	35 J Impact, Fatigue	XCT-A	44 × 34	16.03	19.12	–
B1	Un-Impacted	XCT-B	24 × 44	0.86	1.14	0.97
B2	35 J Impact	XCT-B	34 × 44	1.59	1.47	–

sections). Such 272 numbers of orthographic snapshots (2-D slices) of the damaged region of the specimens (A1, A2, etc.) are taken along the F-direction from the 3-D computed tomography obtained from XCT-A. Similarly, the 3-D tomography obtained from XCT-B was sliced into 10 orthographic images for specimen B1 and 20 images for specimen B2. These images are converted to 8-bit grayscale images with pixel values in the range 0–255 by using the public domain image processing and analysis software ImageJ [3]. Typical 2-D CT slice images along the through thickness (F) direction of un-impacted and 35 J impacted specimens taken from the two X-ray CT systems are shown in Figs. 3 and 4 along with respective histogram of grayscale pixel intensities.

The 2-D X-ray CT image quality is evaluated from the histogram of the pixel intensity values of respective images. By comparing the images of un-impacted specimen taken from two different X-CT systems and image settings (Figs. 3 and 4), it is seen that the A1 specimen (from XCT-A) is of poor quality as its spread (or standard deviation) is more compared to specimen B1 from XCT-B as the former has more noise. Under such conditions, one needs to set different threshold levels for damage area measurement through digital image processing techniques. Thus, one may say that the repeatability of damage estimation through image processing is dependent on the right selection of threshold for binarization of the image.

In this study, the damage quantification of the specimens is done with digital image processing of the X-ray CT images with ImageJ software. The intra-laminar damage caused by impact, fatigue loading is estimated for its volume using the average area method which has been validated and reported earlier [4, 5]. The void
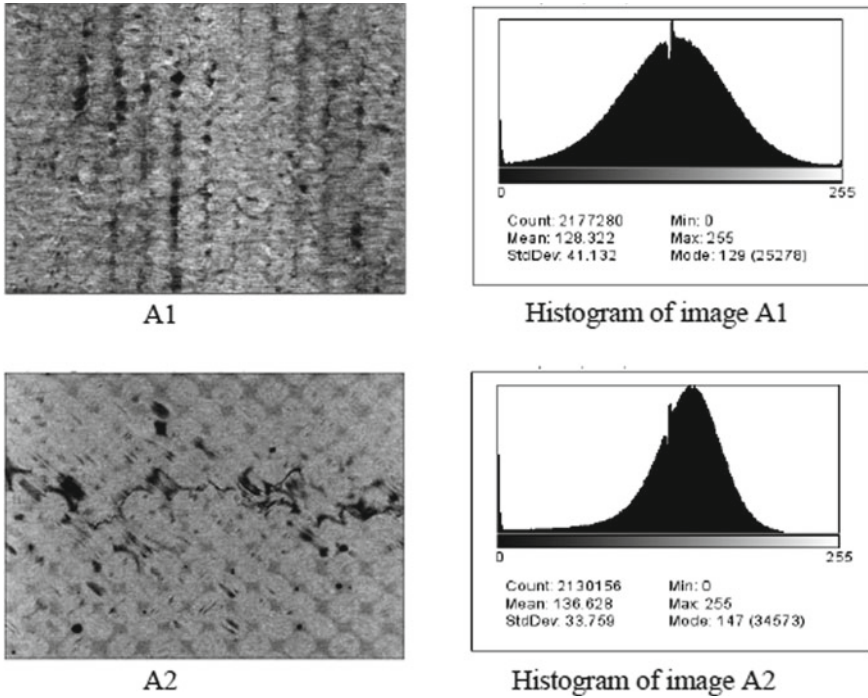
Fig. 3 CT images of Un-impacted (A1) and 35 J impacted (A2) specimens taken with XCT-A

and damage fraction of the specimens are estimated with the three different threshold values chosen; (a) using Intermodes algorithm (b) using Otsu algorithm [6] and (c) a fixed threshold value of 100. Here the threshold setting for (a) and (b) is based on the statistical parameters of the histogram of all the images as it ensures repeatable damage quantification.

3 Results and Discussion

The damage quantified through the image processing of the specimens for the different threshold values chosen are given in Table 1. The damage volume fraction estimated with a common threshold value of 100 overestimates the damage and is far from physical observations of damage. The quantification based on thresholding using Otsu algorithm for specimens scanned with XCT-A overestimate the damage, as, threshold value for all cases (A1, A2, A3, A4) are higher than those estimated using a threshold level of 100 and hence not shown in Table 1. In case of specimens (B1 and B2) scanned with XCT-B, the threshold based on Intermodes algorithm estimates relatively lesser damage. But the Otsu algorithm gives reasonably good results
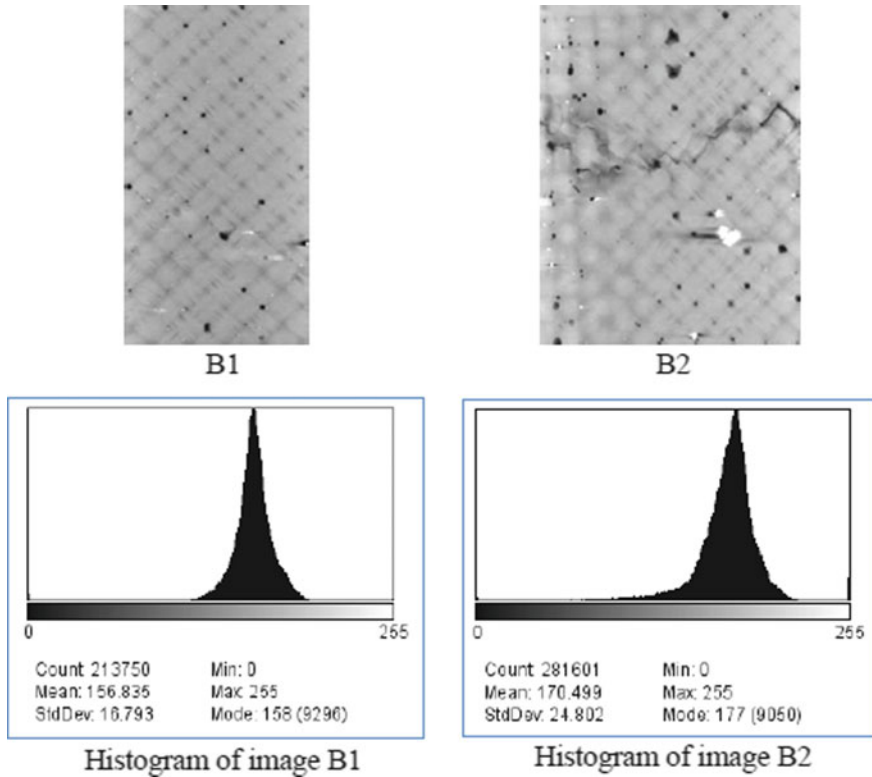
Fig. 4 CT images of Un-impacted (B1) and 35 J impacted (B2) specimens taken with XCT-B

for B2 specimen as it gives damage fraction of 4% which is a reasonable agreement. Hence, the choice of thresholding algorithm depends on the respective histogram and demands manual interpretation for reliable estimation of damage. However, the void contents in the two laminates (L1 and L2) are estimated by choosing the right threshold through a statistical analysis [7] from the mean (μ) and standard deviation (σ) of the pixel intensity value of the X-ray CT binary images of pristine specimens and the same is shown in Table 1. It is seen that the void content measured for the laminates through the binary images from machines XCT-A and XCT-B through this threshold criteria is comparable and is within the specified limits of 1.5%—where the mechanical properties are not affected by the presence of voids [8].

It is to be noted that the mechanical loading can impart both intra-laminar and inter-laminar damages. These two modes can be clearly distinguished from the histograms of the X-ray CT binary images [7]. In this study, the intra-laminar damage caused to the specimens by impact, fatigue loading is quantified by digital image processing of the CT images through the average area method. Since the damage quantification is very much sensitive to image characteristics, thresholding has been done by going through images one after another with auto-thresholding and by manu-
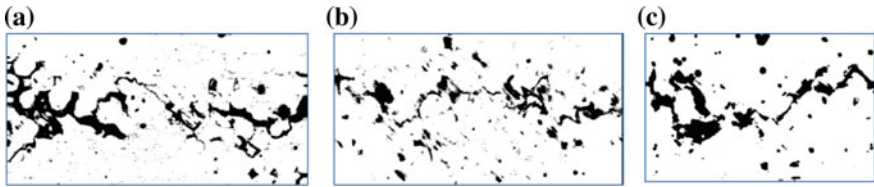
Fig. 5 Binary image of **a** 35 J Impact, Fatigue specimen XCT-A, **b** 35 J Impact only XCT-A, (c) 35 J Impact only specimen XCT-B

Table 2 Intra-laminar damage due to impact, fatigue loading quantified through digital image processing

Specimen ID	Mechanical loading condition	X-ray CT machine used	Area considered Width × Height (mm × mm)	Damage volume estimated (mm^3)	Damage volume fraction (%)
A2	35 J Impact	XCT-A	44 × 22	186.13	4.27
A4	35 J Impact, Fatigue	XCT-A	44 × 22	228.94	5.25
B2	35 J Impact	XCT-B	34 × 22	141.07	4.10

ally checking the respective histograms for its correctness to avoid any overestimation of intra-laminar damage due to the inclusion of explicit inter-laminar delamination damage captured in the images. The digital image processing of planar section 2-D CT images gives intra-laminar damage volume which is the main focus of this study; it appears to be correlated with the stiffness degradation due to fatigue loading after specimen impact [9]. The damage area is measured from the binary image based on the right threshold which is set by evaluating the histogram of each image. For this purpose, a 44 mm × 22 mm window for flat specimens (A2 and A4) and 34 × 22 mm for hourglass specimen (B2) is chosen at the impacted region where the damage is mostly concentrated. The damage area identified through binarization at approximately 0.45 mm depth from the impacted surface for the specimens is as shown in Fig. 5. The damage thus quantified through the image processing is presented in Table 2.

The comparison of damage quantified through the image processing for 35 J post-impacted fatigue specimens shows that the manual thresholding instead of auto-thresholding using any algorithm may be preferred even though the images are from different machines with different image settings. It is seen that the damage quantified for A2 and B2 for 35 J impacted specimens are more or less equal (Table 2) even though the images are from two different CT machines.

4   Conclusions

The quantification of damage through multiple sampling (different samples with varying physical conditions scanned with CT scan machines of different make with different parameter settings) is carried out. It is understood that the area measurement through image processing is highly sensitive to the threshold levels chosen for the measurement; use of a common threshold for specimens scanned with the same system (say XCT-A, Threshold 100) does not provide reliable damage estimation. This is because the 2-D CT image quality may vary depending on machine settings, slicing, and 3-D reconstruction settings, number of slices from the CT reconstructed image, brightness/contrast settings of 2-D CT image settings, physical conditions of the specimen, etc. Hence if the images are from the same machine, the auto-thresholding using suitable algorithm can be employed for damage analysis purpose by way of intra-laminar impact, fatigue damage (in the absence of delamination defect) provided the image setting parameters are consistent. But when the CT images are from different machines that have different machine parameter settings, proper choice of threshold is to be selected manually on a case-to-case basis (depending on the aim of the analysis) for the purpose of meaningful comparative damage analysis. Use of such an approach resulted in similar damage parameter quantification for 35 J impacted specimens scanned using two different X-Ray CT systems.

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