AN INNOVATIVE USE OF X-RAY COMPUTED TOMOGRAPHY IN COMPOSITE IMPACT DAMAGE CHARACTERISATION

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Abstract

This study presents how X-ray computed tomography (CT) can be employed to obtain a more complete 3-dimensional description of damage in carbon fibre reinforced polymer (CFRP) composites. Impact damage was produced with energies ranging from 5 J to 20 J on coupon size (89 mm x 55 mm) composite laminates aimed for primary structures in aerospace applications. CT has been employed to characterise in 3D, non-destructively the impact damage generated. An innovative data processing methodology has been developed to obtain a better description of the complex damage structure. This data processing provides the through-thickness damage distribution of the full laminate and allows the individual ply-by-ply damage to be visualised and assessed.

1. Introduction

When facing a composite damage tolerance problem, the geometric structure of the damage is key in understanding the basic damage mechanisms. It is only when such mechanisms are understood that the critical composites properties in regards to damage can be defined and the damage tolerance improvements implemented. Damage in CFRP panels is commonly characterised by non-destructive techniques such as C-scan, thermography, or shearography that only give access to a limited amount of information, *e.g.* damage projected area. X-ray computed tomography (CT) is a technique with great potential towards providing a much greater amount of information as it can fully capture in 3D the internal structure of a sample in a non-destructive manner. An increasing number of studies are performed using CT to characterise composites materials, mainly for the characterisation of porosity and defects [1, 2, 3]. However, the use of X-ray CT for studying impact damage in composite structures has received only little attention [4, 5] and few attempts have been made at using CT results to qualitatively and quantitatively describe the 3D distribution of defect in either metal [6] or composite materials [7]. In this paper, we present an innovative CT data processing methodology that provides the through-thickness damage profile of a composite laminate subjected to impact damage. We also demonstrate that the damage profile can be used to automatically separate the segmented damage and generate a 3D visualisation of the damage in the individual laminate plies.

2. Experimental

2.1. Material and panel manufacturing

The composite material under investigation is aimed at primary structures for aerospace applications. The matrix was composed of triglycidylaminophenol; TGAP (Araldite® MY0510, Huntsman) and tetraglycidyl-4,4'-diaminodiphenylmethane; TGDDM (Araldite® MY721, Huntsman) and the hardener was 4,4'-diaminophenyl sulfone; DDS (Aradur® 976-1, Huntsman). The reinforcement was a unidirectional carbon fibre fabric with 22 Tex glass filaments yarn woven at 6 mm intervals into the fabric to hold together 12 k carbon tows. The fabric areal density was 445 g/m^2 and the average density of carbon fibre was 1.76 g/cm^3.

Composite laminates were manufactured by resin film infusion (RFI), the infusion set-up and the cure cycle have been detailed in [7]. Each panel consisted of 8 plies (7 ply interfaces) with 0° and 90° ply angles being used, giving a complete stacking sequence of $[(0^\circ/90^\circ)_2]_s$. The panel lay-up lay-out and the interface number (as referred to in section 3) are shown in Figure 1.

Ply No.	Orientation (°)	Interface No.
1	0	1
2	90	2
3	0	3
4	90	4
5	90	5
6	0	6
7	90	7
8	0	

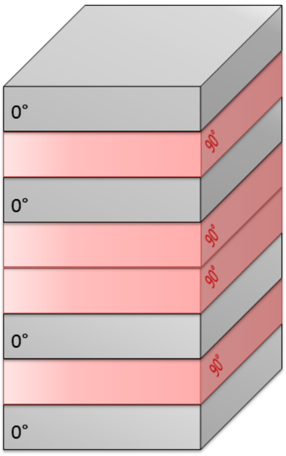


Figure 1. $[(0^\circ/90^\circ)_2]_s$ stacking sequence of the composite panels.

2.2. Impact testing

Impact testing was performed on an Instron Ceast 9350 High Velocity Impact Testing machine controlled by CeastVIEW 5.94 3C software. The tests were carried out according to the methodology of Prichard and Hogg [8] with a specimen size of 89 mm x 55 mm. The testing was performed on several specimens at four different energies which were 5 J, 10 J, 15 J, and 20 J; and the impact rig was equipped with a sensing device to eliminate multiple impacts.

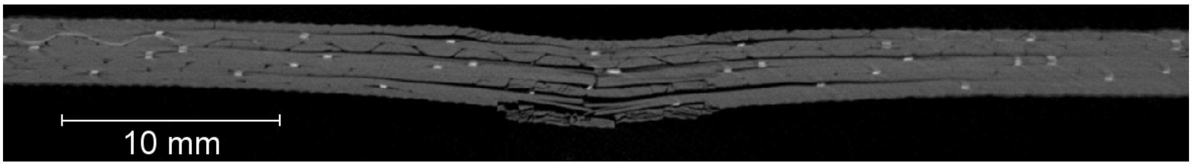
2.3. X-ray computed tomography

The impact specimens were scanned at the Henry Moseley X-ray Imaging Facility on the Nikon Metrology 225/320 kV Custom Bay system [9] equipped with a 225 kV static multi-metal anode source (minimum focal spot size of 3 µm [10]) and a PerkinElmer 2000 x 2000 pixels 16-bit amorphous silicon flat panel detector. The system is shown in Figure 2.

Figure 2. Nikon Metrology Custom Bay system.

The scanning was performed with the copper target using a voltage of 60 kV and a current of 175 μA. The data acquisition was carried out with an exposure time of 1415 ms, and no filtration. The number of projections was set to 3142 and the number of frames per projection was 1. The entire volume was reconstructed at full resolution with a voxel size of 35.7 μm along the *x*, *y*, and *z* directions.

The data processing was performed with Avizo Fire 7.0.1 software [11]. The methodology to obtain a description of the through-thickness damage evolution is based on the measurement of the shortest distance from each voxel segmented as damage to the impact face. The corresponding workflow is summarised in Figure 3.



(a) Raw 2D CT slice

(b) Segmented damage

(c) Damage distance transform (brighter colour indicates larger distance)

Figure 3. Workflow to obtain the damage distance transform (impact face on top).

3. Results and discussion

The methodology presented here, namely the damage distance transform (Figure 3c), provides an improved characterisation of the damage distribution in three-dimensions by taking into account the panel residual out-of-plane deformation after impact. This allows the damage volume per slice, which is the output from a standard CT data analysis, to be converted into the ply-by-ply delaminations and matrix cracking. The through-thickness damage profile, *i.e.* the damage volume plotted as a function of the distance from the impact face, corresponding to the 4 energies tested are given in Figure 4.

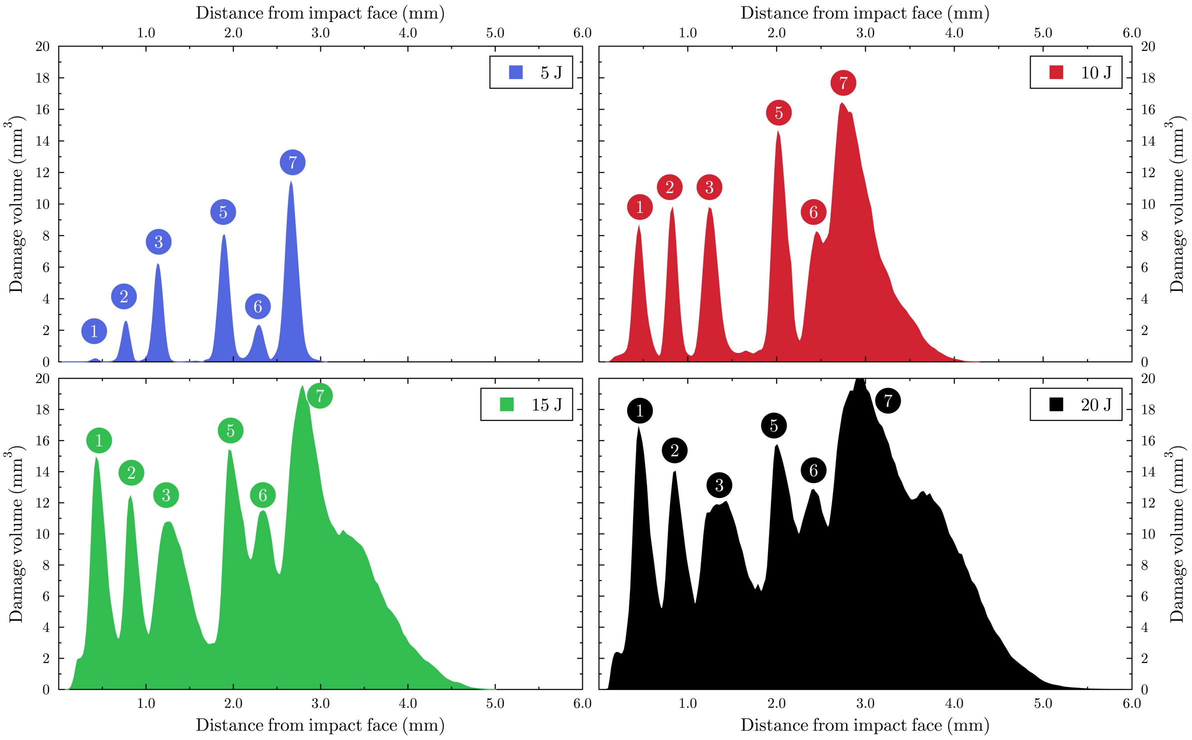


Figure 4. Damage profiles for all 4 energies. The peak numbers correspond to the interface number (1, 3, 6 are 0°/90° interface type; 2, 5, 7 are 90°/0° interface type, as shown in Figure 1).

The results in Figure 4 demonstrate that for all energies, the damage profiles are composed of six main peaks corresponding to six of the ply interfaces (0°/90° and 90°/0° alternatively). No damage peak is observed for ply interface number 4 (Figure 1), which is the 90°/90° ply interface. The increase in damage resulting from the increase in impact energy is not distributed isotropically throughout the laminate structure (due to the three-dimensional stress field), highlighting the complexity of the impact damage process on polymer composites. As the impact energy increases, the peak intensity increases and the peaks broaden but the evolution is different for each peak. Larger length splits and hence induced delaminations develop in the lower part of the laminate since it is loaded in tension. The damage profiles extracted from the damage distance transform are an easy and convenient way to describe, qualitatively and quantitatively, the distribution of the impact damage through the thickness of the impacted laminate.

The full damage can be separated into the damage in each ply based on the peaks from the through-thickness damage profile. The voxels corresponding to each peak are applied to different colour labels, so that the damage corresponding to each ply can be visualised independently.

An overview of the 3D rendering of the specimen tested at 20 J is given in Figure 5. The results of the semi-automated separation are detailed in Figure 6 and 7 for the specimens tested at 5 J and 20 J, respectively.

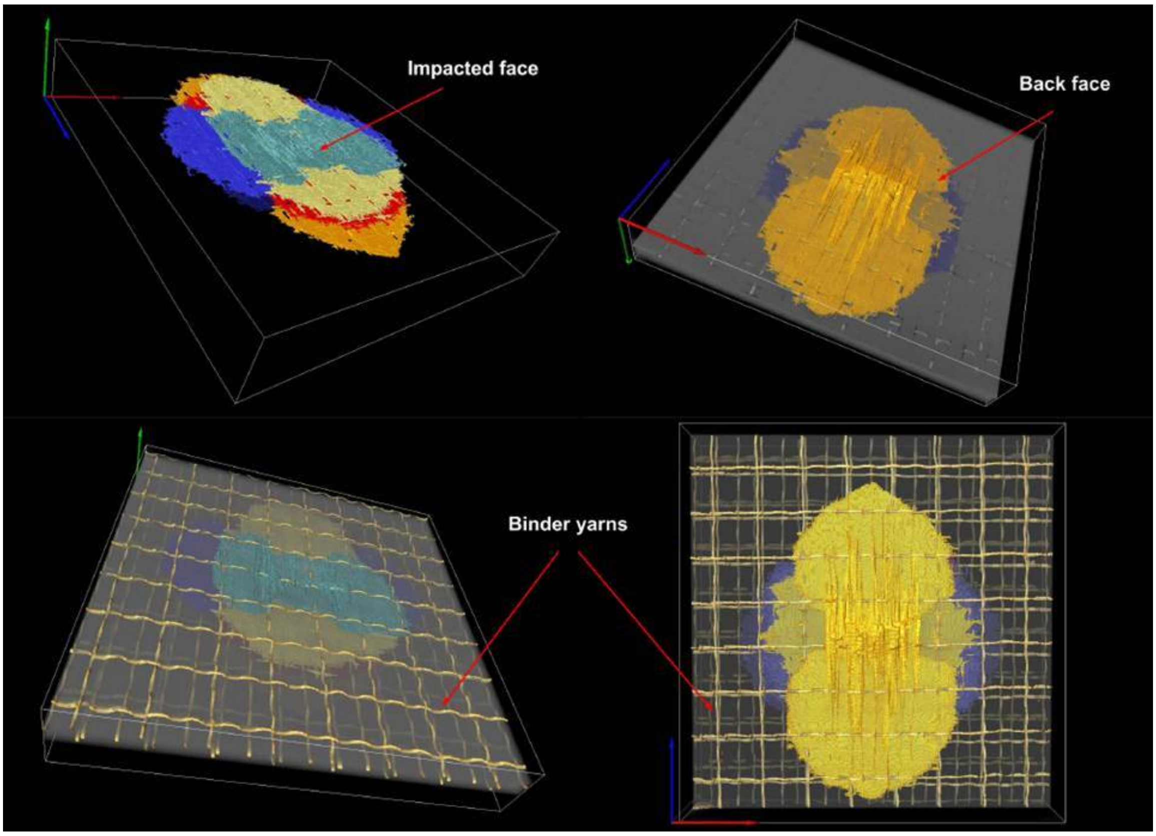
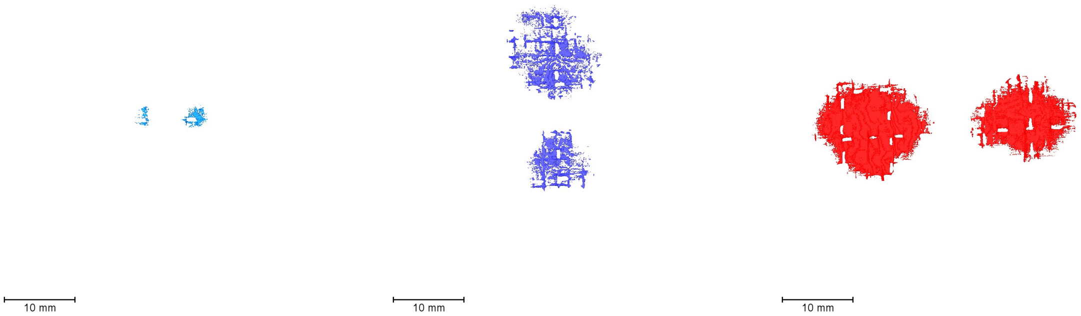


Figure 5. 3D rendering of specimen tested at 20 J.

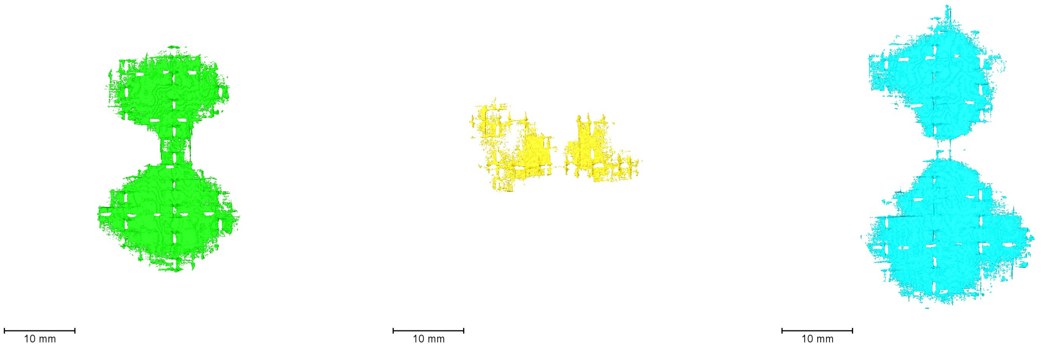
Figure 6 and 7 demonstrate that the ply-by-ply separation of the impact damage can be performed over the range of impact energy investigated. At 5 J, the delamination volumes are peanut-shaped, as reported in the literature [12, 13], with their main axis being coincident with the fibre orientation of the layer below the interface. The alternation of the main axes appears to be consistent with the lay-up of the laminate. At 20 J, the delamination volumes are more oblong-shaped due to extensive damage yet, they follow the same alternation of their main axes as the panel structure remains identical.

4. Conclusions

This study was aimed at demonstrating the potential of X-ray computed tomography to provide novel 3D insights of impact damage in composite panels. The main strength of CT is its ability to deliver a 3D analysis non destructively. However, CT being an emerging technology, particularly in materials science, it requires the development of data processing methodologies to generate new tools for the composite community. This paper introduced the damage distance transform methodology. It provides an easy and convenient way to describe, qualitatively and quantitatively, the distribution of the impact damage through the thickness of the impacted laminate. It can also be used to automatically separate the segmented impact damage on a ply-by-ply basis to further the understanding of impact damage that can be gained from 3D visualisation [14].

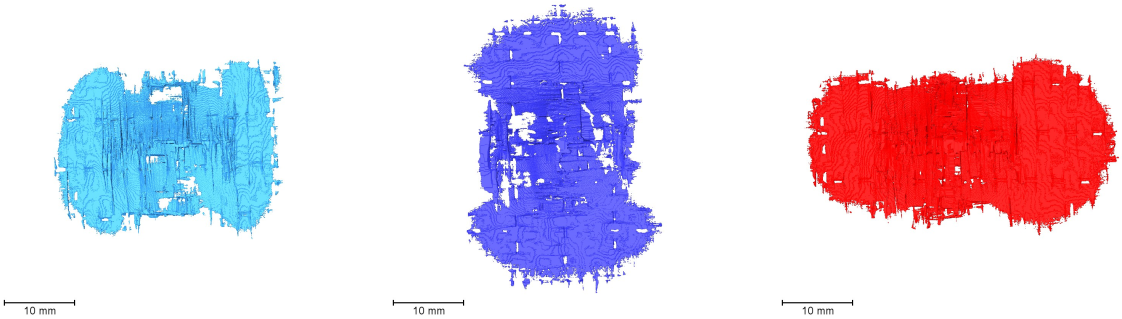


(a) interface 1 (0°/90°) (b) interface 2 (90°/0°) (c) interface 3 (0°/90°)

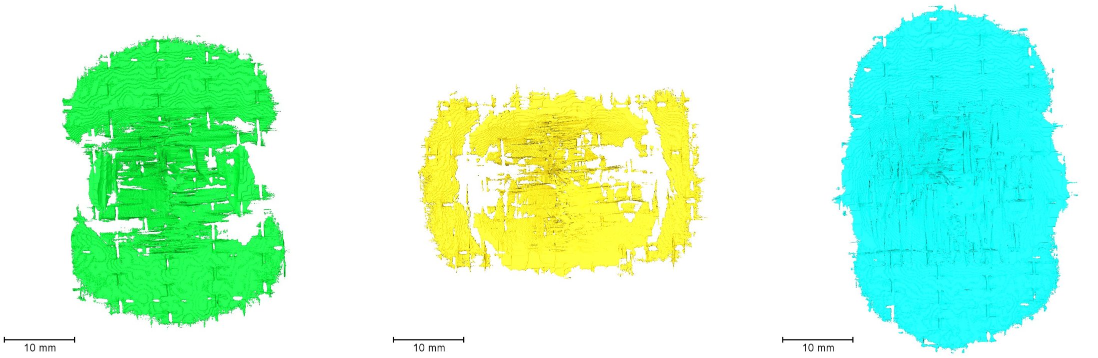


(d) interface 5 (90°/0°) (e) interface 6 (0°/90°) (f) interface 7 (90°/0°)

Figure 6. Ply-by-ply damage separation according to individual peaks from damage profile for 5 J impact energy.



(a) interface 1 (0°/90°) (b) interface 2 (90°/0°) (c) interface 3 (0°/90°)



(d) interface 5 (90°/0°) (e) interface 6 (0°/90°) (f) interface 7 (90°/0°)

Figure 7. Ply-by-ply damage separation according to individual peaks from damage profile for 20 J impact energy.

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