X-ray Microtomographic Characterisation of Damages in Carbon Fibre Reinforced Composites Subjected to Bending

Ruoxuan HUANG 1,2, Zhe LIU 1, Peifeng LI 1,* , Tong LIU 2

1 School of Mechanical and Aerospace Engineering; Nanyang Technological University; Singapore
* Phone: +65 6790 4766, Fax: +65 6792 4062; e-mail: peifeng.li@ntu.edu.sg
2 Singapore Institute of Manufacturing Technology, Singapore

Abstract
Carbon fibre reinforced polymer composites (CFRP) have been increasingly used in aerospace applications due to the high strength-to-weight ratio. X-ray microtomography (XMT) enables the detection of 3D internal damages in CFRP. In this work, an in-house algorithm was developed to rebuild the reconstructed XMT volume to better visualise the curved damage features in CFRP subjected to three point bending tests. The damages in the bended (curved) plies and interfaces were mapped to a plane. It was found that the various damages, such as delamination, matrix cracking and fibre fracture, can be clearly revealed in the new XMT slice, thus validating the applicability of the surface fitting procedure to flatten a bended CFRP.

Keywords: X-ray microtomography, carbon fibre reinforced polymer composites, delamination, B-spline surface fitting

1. Introduction

Carbon fibre reinforced polymer composites (CFRP) have been increasingly used in aerospace applications due to the high strength-to-weight ratio. Non-destructive techniques, such as ultrasonic inspection, have been applied to understand various failure modes (e.g., delamination, fibre fracture, matrix cracking, and fibre/matrix debonding) in CFRP subjected to different loadings [1-3]. However, the low resolution using ultrasonic limits some failure modes to be detected.

X-ray microtomography (XMT) allows for the 3D observation of internal microstructural features in materials [1-5]. A number of studies used XMT and image processing technique to reveal various types of damages in CFRP. However, the curved feature of a CFRP specimen subjected to bending at quasi-static or dynamic loading rates makes difficult the XMT characterisation because damages are generally not in a plane. 3D visualisation of these damages (such as delamination, fibre/matrix debonding) may also be challenging due to the thin nature. Moreover, a curved damage after bending may be divided into several segments if examined by a planar slice.

This study aims to clearly visualise curved damages in CFRP subjected to bending by mapping them to a plane. An in-house algorithm was developed to rebuild the reconstructed XMT volume.

2. Experimental procedure

2.1 Three point bending test

CFRP laminate specimens (120×10×1.3 mm) with [0°/+45°/-45°/90°], layups were fabricated using the prepreg technique. Three point bending tests (ASTM-D790) were then performed in an INSTRON 5569 machine (Figure 1(a)). The span length was 53 mm, making a span to depth ratio of ~41:1.
Figure 1. (a) A typical three point test of CFRP specimens and (b) a 2D projection of the CFRP specimen after bending testing.

2.2 X-ray microtomography and curved object fitting

X-ray microtomography at an accelerating voltage of 60 kV and a tube current of 30 μA was conducted on the central (also fractured) portion of CFRP specimens after bending tests. 3D images were then reconstructed from the recorded 720 projections using in-house software [6]. A delamination in CFRP specimens will appear to be several segments in a slice normal to the projection shown in Figure 1(b).

Figure 2 summarises the procedure to rebuild an XMT image from the original reconstructed volume. The procedure was developed using MatLab codes. Finally, the 3D volume is regenerated to map the curved features to a plane (e.g., the plies and the interface between them).

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Initial reconstruction of an XMT image
Choose representative points in a curved object and fit them into a B-spline surface
Obtain normal vectors of the points
Map the curved surface to a new plane along the vectors
Map the curved object to the new plane and rebuild the reconstructed volume
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Figure 2. The procedure to rebuild the XMT image from an original reconstructed volume by mapping curved features to a plane.
3. Results and discussion

2.1 Observation of internal damages

Figure 3 shows a typical longitudinal slice from the reconstructed XMT image without B-spline surface fitting. Various damage features can be clearly detected in the XMT slice, such as matrix cracking and delamination. However, the current XMT scan (the resolution about 15 to 20 μm) is not able to resolve the carbon fibres (diameter typically <10 μm).

The damages in a bended CFRP often occur in various curved planes, e.g., 0°, +45° and -45° plies, and their interfaces, which are otherwise planar before bending deformation. Thus some of the damage features cannot appear in an XMT slice (see Figure 3). For example, only part of the delamination (the unmarked black area in the slice) between 0° and +45° plies is resolved in the slice. Therefore, the internal structure of a bended CFRP specimen may not be effectively observed in the conventional slices from a reconstructed XMT image.

![Figure 3](image.png)

Figure 3. A typical longitudinal XMT slice showing the internal damages in various plies in a CFRP specimen subjected to bending tests.

2.2 Mapping internal damages to a plane

Using modified B-spline surface fitting, the curved features after bending were flattened to the original longitudinal plane of CFRP prior to bending. Figure 4 illustrates the XMT slices in different plies and interfaces. Each slice reveals the features in the plies/interfaces even though they are curved in the specimen. The damage process depends on the layup of plies and the stress field in bending (compressive in the top and tensile in the bottom). The compressive failure of fibres occurs in the top ply (0°). In the +45° ply, major matrix cracking is observed along the fibre direction.

Almost the full delamination between the 0° and +45° plies can be observed in the modified XMT slice (Figure 4). It should be noted that some bright areas occur in the central part of the specimen due to the tilted neighbouring plies that are already fractured.
4. Conclusions

Damages in carbon fibre reinforced polymer composites were characterised using x-ray microtomography. The curved features of bended specimens were flattened to avoid showing multiple plies in a single slice. It was found that the various types of damages, such as delamination, matrix cracking and fibre fracture, can be clearly revealed in the new XMT slice, thus validating the applicability of the surface fitting procedure to flattening a bended XMT volume.

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