

Modelling and Characterization of Impact Damage in Quickstep cured single lap joints.

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Introduction

In-service loading such as impact can significantly degrade fibre-reinforced plastics. Even if the loading is not severe enough to cause immediate failure it may reduce compression or fatigue strength of the part. These problems get more pronounced for structures with bonded joints. No single test method is sufficient to quantify all the possible impact situations because the composite materials can vary widely in composition (and hence properties) and application areas. Extensive and periodic non destructive testing (NDT) is often required at all stages of development and also in service due to the lack of confidence in residual strength after impact and the catastrophic nature of failure in these materials [1, 2].

Current modelling techniques used for simulating damage growth after impact in composites suffer from various pit falls. In fact there is still to emerge a universally accepted failure theory for these materials[3]. The real problem with composites is this that damage has to be modelled at various length scale ranging from few micro meters (such as micro cracks, and fiber splitting) to centimetres or even meters in larger structures. How the damage propagates from one mode to other is not always clearly understood. Hence there are numerical as well as conceptual difficulties associated with modelling of composites.

A need exists to correctly characterize various damage modes and to understand how one damage mode interacts with other damage modes. Hence this study aims at experimentally studying the impact damage at a micro level in 3D within the material, with a view to correctly characterize the post impact damage modes and then developing corresponding numerical models that can accurately simulate the damage growth. The development of reliable numerical models is the only way that can lead to reduced reliance on extensive experimentation with obvious benefits of reduced developmental and maintenance cost.

Methodology

This study uses x-ray micro tomography (XMT) to create 3D models of damaged surface for various impact energy levels. These models will allow damage mode characterization at a micro level. Macro level damage is being studied by using digital imaging, ultrasound C-scanning and x-ray tomography at a lower resolution. Finite element method is being used to simulate impact damage response of the structure. The impact test specimens have been made using the facilities available at the North West Composite Centre specifically the Quickstep plant.

On the modelling side failure models based on Strain Invariant Failure Theory (SIFT), Tsai Wu failure criteria and continuum damage mechanics are being compared with a view to determine the more suitable damage growth model at all damage scales (micro and macro). An attempt will be made to study the effectiveness of using Element Failure Methodology (EFM) rather than the more widely used Mechanical Property Degradation Methods (MPDM).

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In summary the study uses the following methods which as also illustrated in the figure 1.

1. Damage Characterisation using,
 - Digital Imaging
 - C-Scanning
 - X-ray Micro-Tomography
2. Tensile tests of damaged and undamaged zone to determine the residual strength of bond.
3. Numerical Modelling
 - Predictive models using at-least two different failure models.

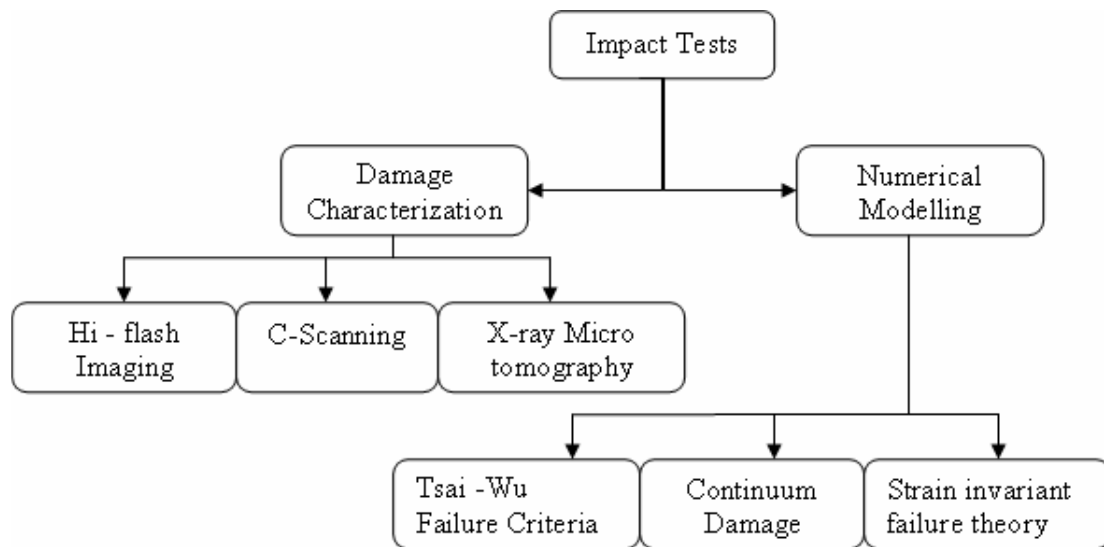


Figure 1 Experimental and Numerical techniques used for the study

Summary of planned test

1. Total number of impact tests: 48
2. Overlap Widths to be tested
 - 20 mm
 - 25 mm
 - 35 mm
 - 45 mm
 (Three repeats for each energy level)
3. Range for tests
 - Energy: 0.5J – 8J
 - Velocity: 2.2m/s – 7.8m/s

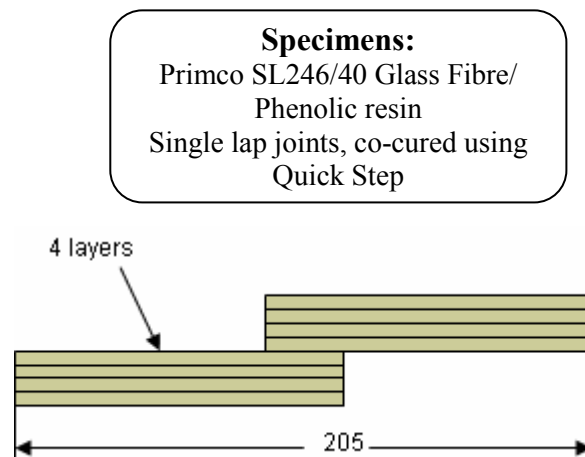


Figure 2 Specimen for testing

X-ray Micro Tomography (XMT)

This study is using XMT as the main technique for micro level damage characterization. XMT is one of the computed tomography (CT) techniques. CT refers to the cross-sectional imaging of an object from either transmission or reflection data [4]. It involves reconstructing an image from its cross sectional projections. There are various types of tomography depending on the type of technique used to obtain the projections. For example if the projections are obtained by illuminating the object using X-rays the process is called X-ray tomography (X – ray CT or XCT). Whereas if the reflection or transmission data of sound

waves travelling through a material is used to obtain the projections, the process is called Ultrasound CT.

XMT refers to the version of X – ray CT used to obtain a resolution of less than 100 μm [5]. XMT can be used for detailed damaged characterisation. The principal advantages are

- Ability to extract three dimensional information of damaged zone. Hence damage modes such as delamination can be traced throughout depth.
- High spatial resolution allows for micro-level damage characterization.

(With the equipment that is available for this study, if contrast is significant than features as small as 2 μm can be detected, minimum voxel size 7 μm)

- The 3D model of damaged zone can be imported into FE analysis packages such as ABAQUS. This can be useful in a number of ways, such as;
 - Verifying a numerical model of impacted specimen
 - Getting degraded properties of the impacted specimen

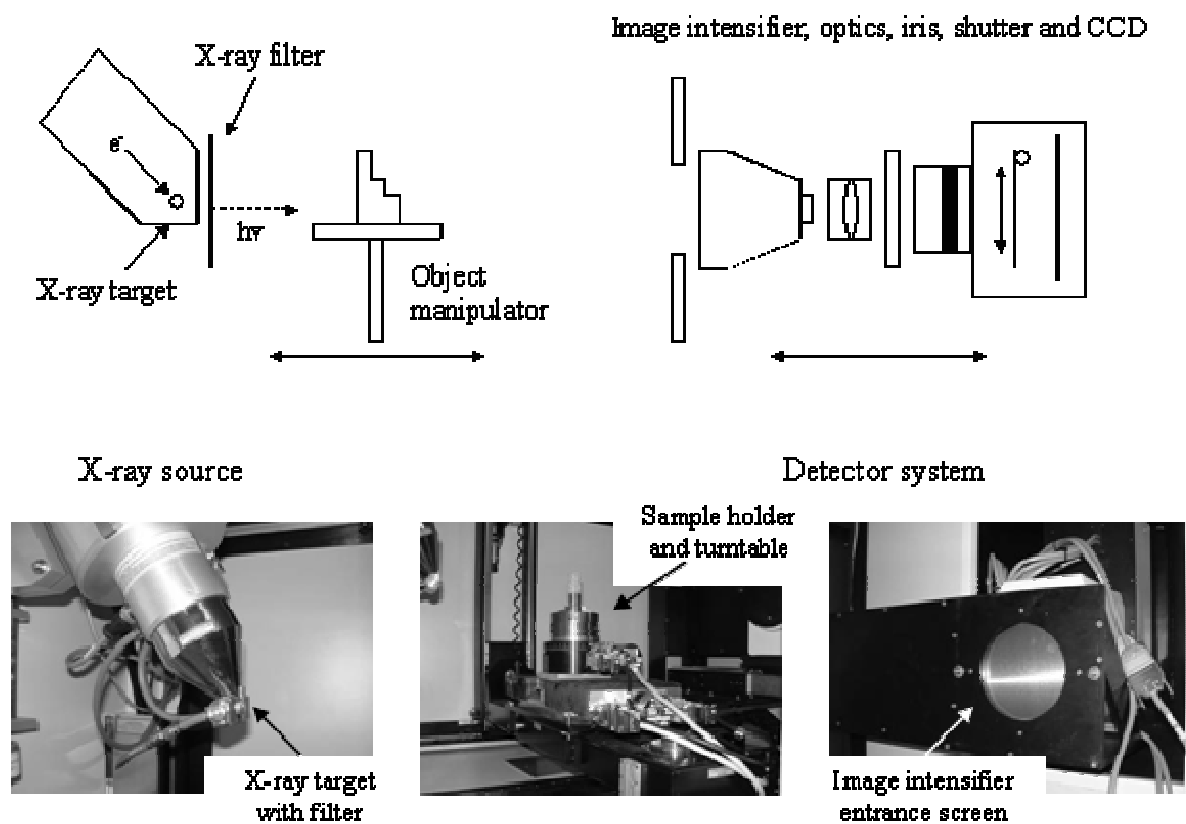


Figure 3 Schematic and corresponding images of various components of XMT system used for this study [6].

Detailed study of XMT with various resin and fibre systems was carried out to determine the limitations of this system.

Results

This study is almost half way through and some useful results have been obtained. These demonstrate that while the XMT technique can be used to study matrix damage (such as micro cracks and delaminations) in any fibre composite, the study of fibre damage is only possible if there is sufficient contrast between matrix and fibres (in terms of x-ray attenuation). Hence material systems such as glass fibre in epoxy resin or boron fibre in epoxy resin can be studied conveniently for micro level fibre damage but the same is not true for carbon or kevlar fibres in epoxy resin. In order to clearly demonstrate this limitation,

cylindrical specimens of epoxy were made with fibres of glass, carbon, boron and kevlar running through the centre of specimens as shown in Figure 4.

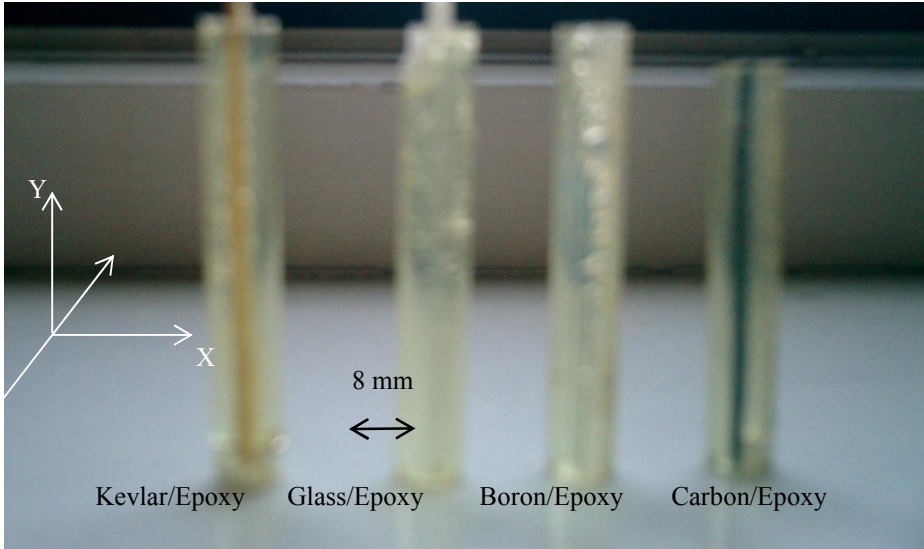


Figure 4 Cylindrical specimens to study the limitations of XMT

When these specimens were scanned using the XMT scanner only boron and glass fibres were visible within the epoxy matrix and the carbon and kevlar fibres in the epoxy matrix were not visible at all. Figure 5 shows a 3D reconstruction from XMT scan of boron-epoxy and glass-epoxy cylinders. The matrix (epoxy) is rendered invisible in this reconstruction to enable a clear view of fibres. The slice in gray marks a section of epoxy cylinders as viewed from top. A similar reconstruction of fibers cannot be achieved for the case where carbon and kevlar fibres run through the epoxy matrix.

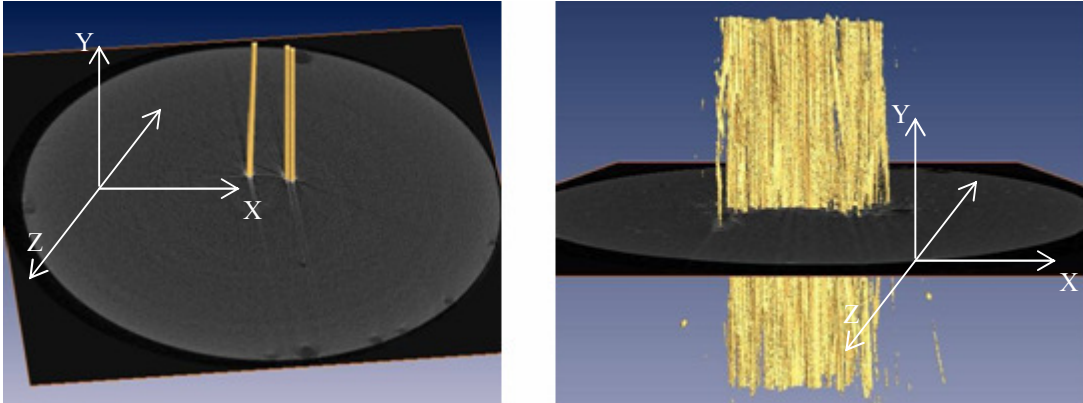


Figure 5, ‘3D’ reconstruction of boron and glass fibres respectively in an epoxy matrix. For clarity only 2D slice of epoxy matrix (cross section – top view) is shown here.

Due to this limitation many specimens were tomographed. Finally it was decided to use glass fibres in phenolic resin, which offers very good contrast difference, for further impact testing. Figure 6 shows a slice through the thickness of an impacted glass phenolic specimen as viewed using tomography. This image has been generated from a scan where minimum voxel size was 11.4um. As can be seen the damage in 3D can be clearly visualized and it can be seen how the crack propagates through the thickness. Since XMT provides 3D information about the whole model such slices can be viewed at any specified depth within the material.

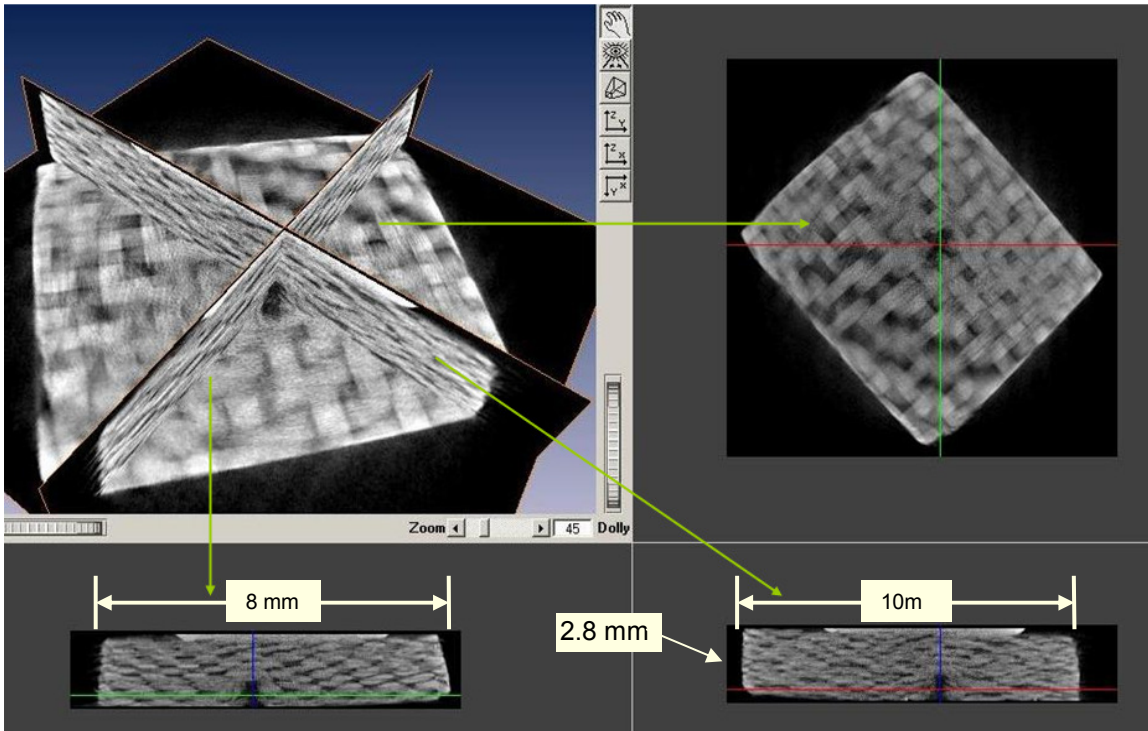
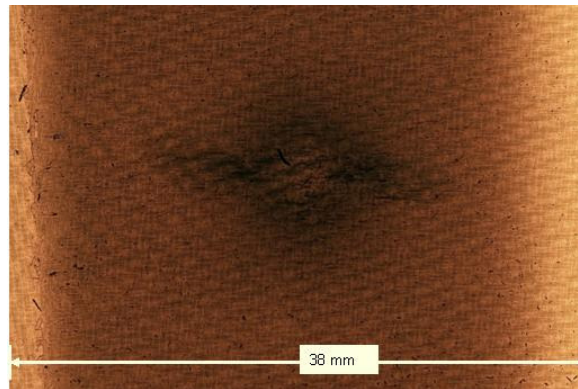
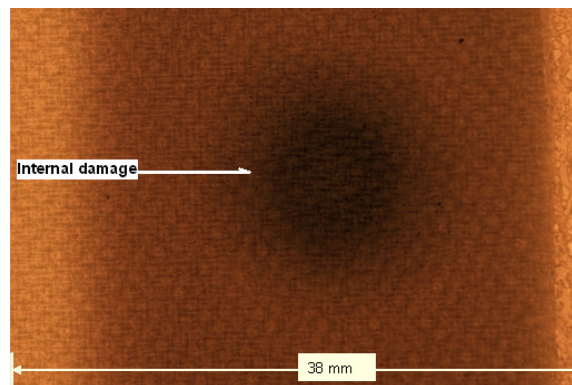


Figure 6 Top, front and side XMT views of the damaged Glass-Phenolic Composite

One additional advantage of using glass/phenolic composites is this that it is semi-transparent and under high flash light good quality digital images of damaged zone can be taken. These images show both internal and external damage. Figure 7 and Figure 8 show two such images of an impacted specimen.



**Figure 7 Front view: Primco SL246/40, co-cured lap joint with 6 layers in each lap. Impact energy =8J
Overlap Width = 38 mm**



**Figure 8 Back View: Primco SL246/40, co-cured lap joint with 6 layers in each lap. Impact energy =8J
Overlap Width = 38 mm**

This study also demonstrated that XMT can be used to correctly estimate the void distribution in a sample. Void distribution in a number of carbon-epoxy samples was studied. Apart from this manufacturing defects can also be identified using XMT.

Some progress has also been made on the modelling side. Figure 9 shows the shear stress distribution in an impacted lap joint². The shear stress profile along the centre of adhesive is plotted in Figure 10^{Error! Reference source not found.} whereas Figure 11 shows the first strain invariant distribution along the middle of adhesive. These models will form the basis of more sophisticated models as the study progresses.

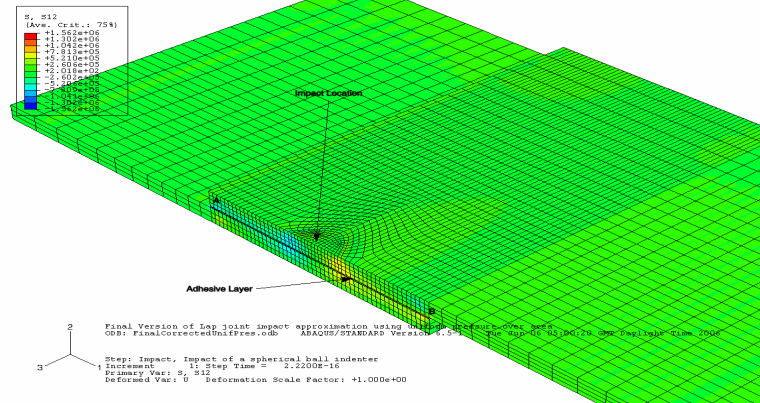


Figure 9 Shear Stress distribution in an adhesively bonded panels

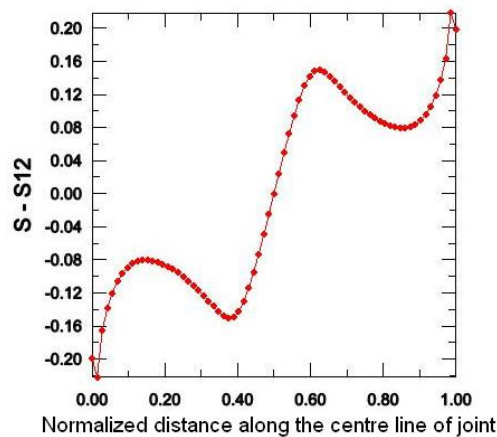


Figure 10 Normalized shear stress profile

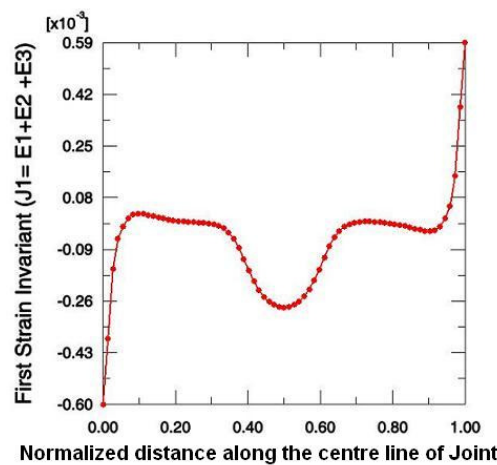


Figure 11 First strain Invariant Profile

² Figure 9, 10 and 11 are from an enhanced resolution done by the author of the problem presented in “Mechanisms of Damage Formation in Transversely Impacted Glass-Epoxy Bonded Lap Joints”, Kim et al. *Journal of Composite Materials*.2005; 39: 2039-2052

Conclusion

In short term the study has demonstrated the uses and limitations of x-ray tomography for NDT of composites. In long term this study aims to give the design and maintenance engineers a reliable modelling approach for simulating impact damage growth. It is hoped this end will be achieved by correctly identifying the damage mechanisms, by understanding the damage mode interactions and by using the most suitable failure criteria for the numerical model. It is for the first time that Quickstep has been used in North West Composites Centre for making lap joints. This study will provide useful data with regards to impact damage tolerance of components made using Quickstep.

References

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