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Multiscale Stochastic Fracture Mechanics of Composites Informed by In-situ XCT Tests

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14. ABSTRACT

In this project, the characterization of the microstructures, damage and fracture behavior of CFRP using state-of-the-art X-Ray Computed Tomography (XCT) was investigated experimentally in order to develop an innovative multiscale fracture mechanics (MustFrame) framework and associated computer codes for accurately modeling the damage and fracture in these materials in order to critically evaluate the reliability and performance of small- to large-scale engineering structures and systems. The ultimate aim is optimize microstructures and structural designs for better quality, greater reliability and lower cost. The funded research led to three PhD theses.

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AFOSR/EOARD Project No. FA8655-12-1-2100
Multiscale Stochastic Fracture Mechanics of Composites Informed by In-situ XCT Tests

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1. Introduction

High-strength lightweight composites have been widely used in aeroplanes now. For example, in the new Boing Dreamliner 787, carbon fibre reinforced polymers (CFRP) accounts for 80% by volume and 50% by weight of the main load-carrying structures including fuselage and wings. Most of the ribs in the wings of the Airbus 380 are CFRP as well. However, delamination (fibre-matrix interfacial fracture) in CFRP was recently found in the fuselages of Dreamliner 787, and two types of cracks were found in the rib feet brackets connecting the CFRP ribs and metal claddings of wings. Therefore, there is still an urgent need to get better understanding of the mechanical behaviour of CFRP, particularly the delamination/crack initiation and propagation until failure under progressive loadings in aeroplane structures, so that the structural integrity can be assured.

This project aims to characterise the microstructures, the damage and fracture behaviour of CFRP using the state-of-the-art in-situ X-Ray Computed Tomography (XCT) facility, and to develop an innovative Multiscale Stochastic Fracture Mechanics (MustFrame) framework and associated computer codes for accurately modelling the damage and fracture in these materials and critically evaluating the reliability and performance of small- to large-scale engineering structures and systems, with an ultimate view of optimising material microstructures and structural designs for better quality, greater reliability and lower cost.

The specific objectives are:

- To conduct in-situ XCT tests for high-resolution internal microstructures of fibre reinforced composites
- To build and validate XCT-image based finite element models for complex fracture in these materials
- To develop multiscale models considering heterogeneity and randomness of phases in these materials
- To assess uncertainty and reliability of large aerospace structures made of these materials against external loads

2. Main outcomes

In the past three years (2013-2015), tremendous efforts in advanced experiments and numerical modelling have been made towards realising the above objectives in relation to various composite materials including CFRP, concrete, and ultra high performance fibre reinforced concrete (UHPFRC), by the PI’s research team at the University of Manchester, which consists of 1 postdoctoral research associate and 5 PhD students funded by various sources. Among them, 3 PhD students have been fully or partially funded by this AFOSR/EOARD grant. It can be said that the first three objectives in relation to CFRP have been fully realised, with additional outcomes in related topics such as studies of UHPFRC and development of new nano-graphene platelet modified polymers. The main outcomes related to CFRP are briefly presented below.

2.1 In-situ XCT tests

To better understanding the complicated failure processes in fibre reinforced composite materials and also to validate numerical models, in-situ 3D images of small-sized specimens, showing the internal micro-/meso-structures, crack initiation, propagation, closing and merging, and final failure, were obtained by the non-destructive XCT technique.

It is known that the images of CFRP obtained from conventional XCT machines have relatively poor phase-contrast, due to similar material densities between the carbon fibres and the epoxy resin. Therefore, the third generation synchrotron radiation sources at Diamond Light Source in Oxfordshire, UK with high brilliance were used to enhance the phase contrast. An in-house testing rig was designed and used for the in-situ uniaxial tensile test, shown in Figure 1.

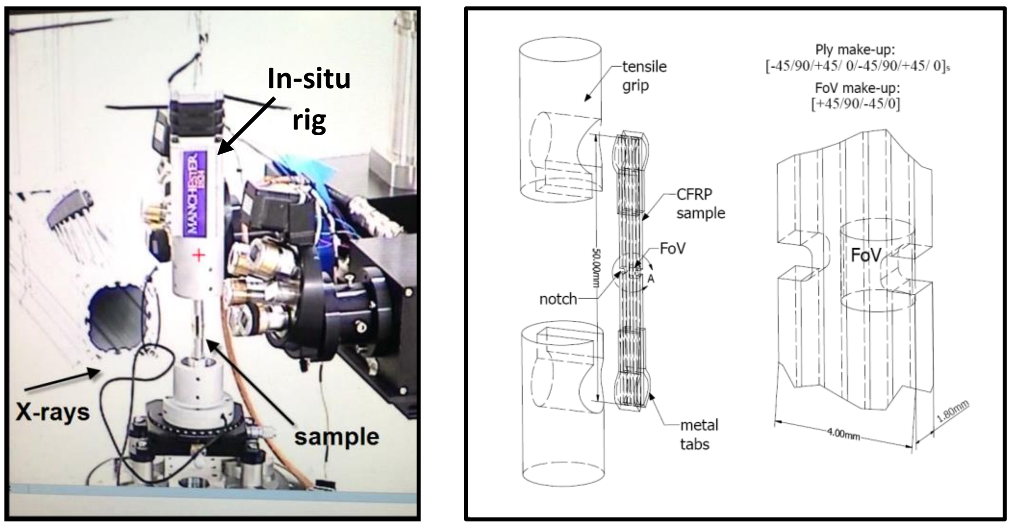


Figure 1: In-situ XCT tensile test setup and sample configuration using an in-house loading rig.

The investigated material is a carbon fibre /epoxy resin cross-ply composite, with 250μm-thick, 16 multidirectional plies of $[-45/90/+45/\ 0/-45/90/+45/\ 0]_s$. The fibre diameter is approximately 5μm (aerospace grade). The matrix is a pre-impregnated epoxy resin with a tensile strength of 50MPa. The average fibre volume fraction specified for the individual unidirectional plies is 50%. The sample is prepared using a diamond water blade. The nominal thickness of the sample is 1.8mm. Reconstruction of 3D images from the X-ray CT attenuation data is conducted using the filtered back projection approach. The CT dataset consists of a stack of 2160 slices each comprising 2560x2560 pixels with a resolution of 330nm/pixel. The field of view is approximately 712 µm (height) x 840 µm (diameter). Figure 2 shows the rendered 3D image with the final crack pattern in Avizo. It contains over 10,000 fibres in total. More detailed image analyses are still needed to reveal the whole fracture process. This is one of a few in-situ sub-micron XCT tests on CFRP conducted so far in the world.

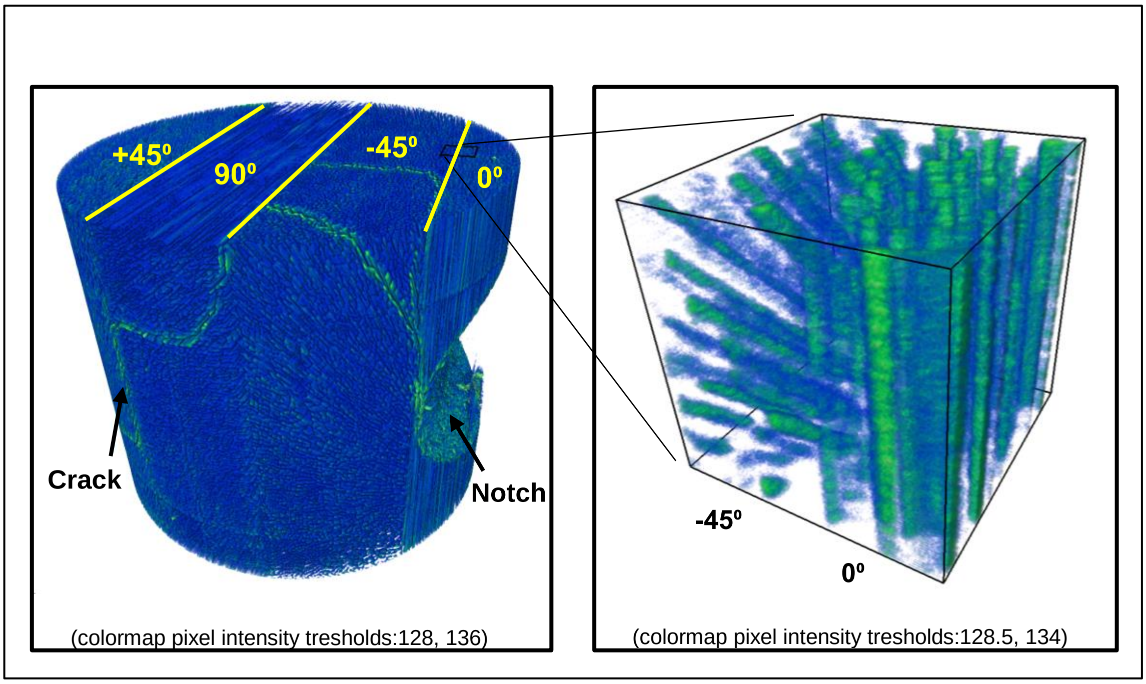
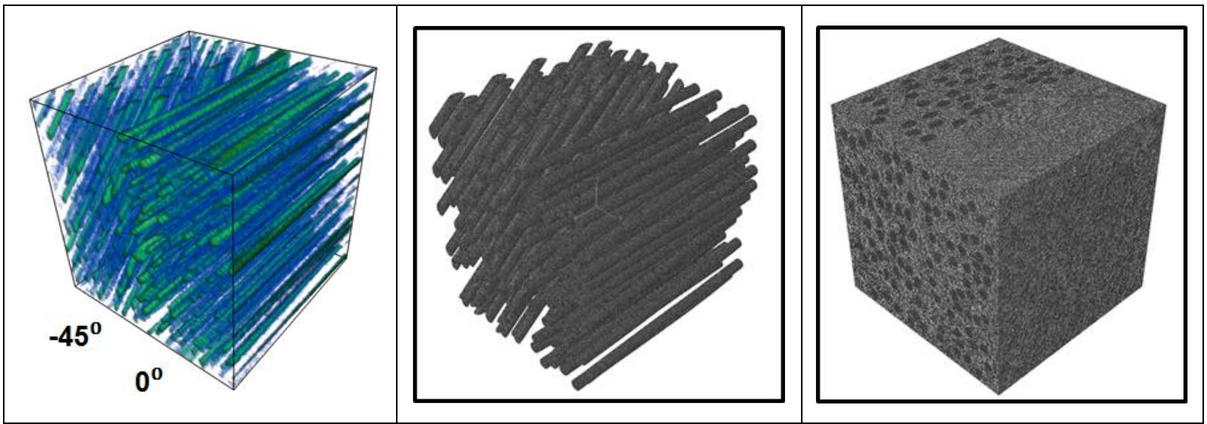


Figure 2: An X-ray CT volume render of the cross-ply CFRP

2.2 Generation of XCT image-based numerical models for CFRP

A procedure for the generation of image-based models of cross-ply CFRP laminates is established. Conventional segmentation routines are unable to accurately resolve the fine details associated with the many thousands of individual fibres in the reconstructed volume. Effective algorithms have been proposed to identify the individual fibre centres using a local maxima method and a Bayesian inference model applied to the stack of images. It is shown that the proposed method is able to provide high quality fibre centrelines (skeletons) from XCT cans of CFRP multidirectional laminate sample. The fibre centrelines are then used to reconstruct the CFRP composite 3D geometry to generate partitioned mesh models for multi-scale damage evolution modelling. The results are shown in Fig. 3 for the [+45/90/-45/0] carbon fibre reinforced laminae with 100 µm length (Fig. 2b). The mesh in Fig.3c consist of about 20 million of C3D4 elements. For the FoV domain (712 µm (height) x 840 µm (diameter)) studied here, there are over 10,000 number of fibres. Converting the whole FoV will lead to a gigantic number of finite elements that even supercomputers will struggle to model. This makes multi-scale modelling a necessity.



(a) Reconstructed fibres of Figure 2(b) | (b) Mesh in fibres only | (c) Mesh in fibres + polymer resin

Figure 3: reconstructed fibres and generated finite element meshes for the 100 μm cube

2.3 Development of a multi-scale method for complicated fracture modelling of CFRP

An adaptive stochastic multi-scale method has been developed for cohesive fracture modelling of quasi-brittle heterogeneous materials under uniaxial tension. In this method, a macro-domain is first discretised into a number of non-overlapping meso-scale elements (MeEs) each of which containing detailed micro-scale finite element meshes. Potential discrete cracks in the MeEs are modelled by pre-inserted cohesive interface elements (CIEs). Nonlinear simulations are conducted for the MeEs to obtain the crack patterns under different boundary conditions. The macro-domain with the same number of overlapped, adaptively size-increasing MeEs are then simulated, until the potential cracks seamlessly cross the boundaries of adjacent MeEs. The resultant cracks, after being filtered by the Bayes inference algorithm to remove spurious cracks wherever necessary, are then integrated as CIEs into a final anisotropic macro-model for global mechanical responses. Figure 4 illustrates the flow chart of the developed multiscale method. A two-dimensional example of carbon fibre reinforced polymers was modelled under two types of uniaxial tension boundaries. The developed method predicted crack patterns and load-displacement curves in excellent agreement with those from a full micro-scale simulation, but consuming considerably less computation time of the latter, as demonstrated in Figure 5 as an example.

3D finite element models have also been built based on XCT images and complicated fracture process has been successfully simulated, with an example for the 100 μm sample (Fig. 3) shown in Fig. 6. The multiscale method developed for 2D cases is being extended and applied to model the full 3D CFRP specimen (Fig. 2a), but this is extremely challenging.

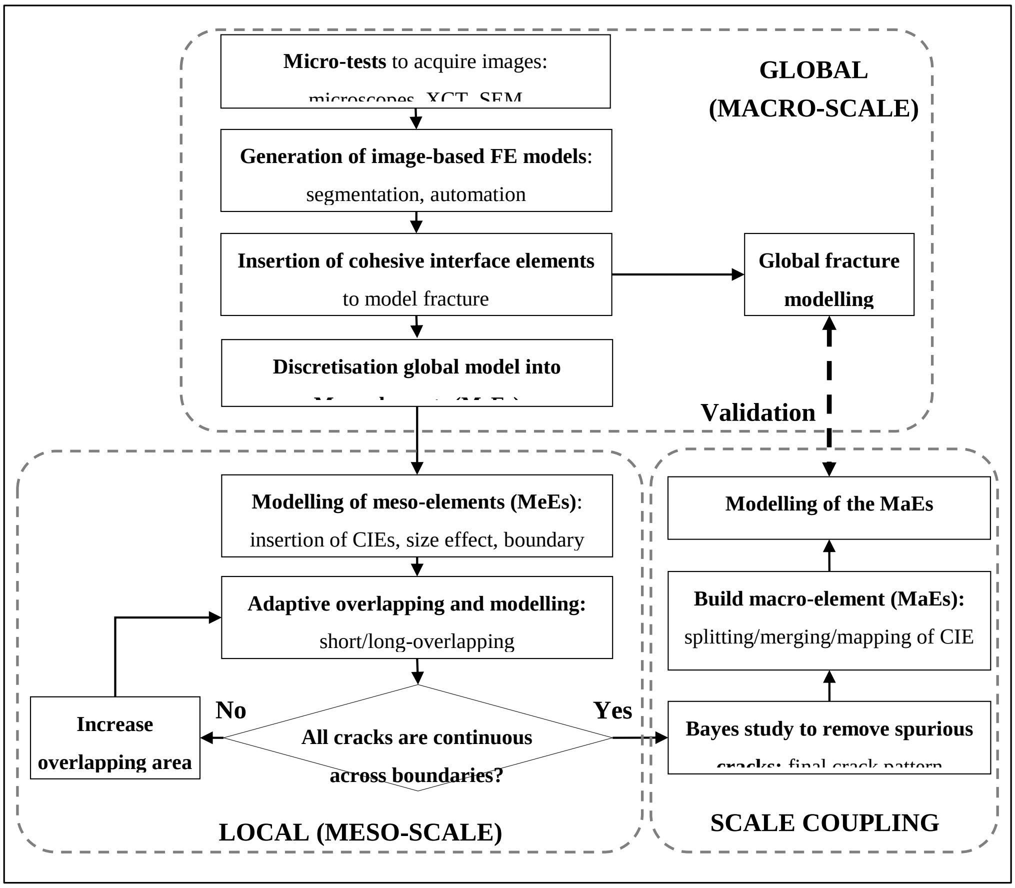


Figure 4 A two-scale coupling scheme for stochastic fracture mechanics.

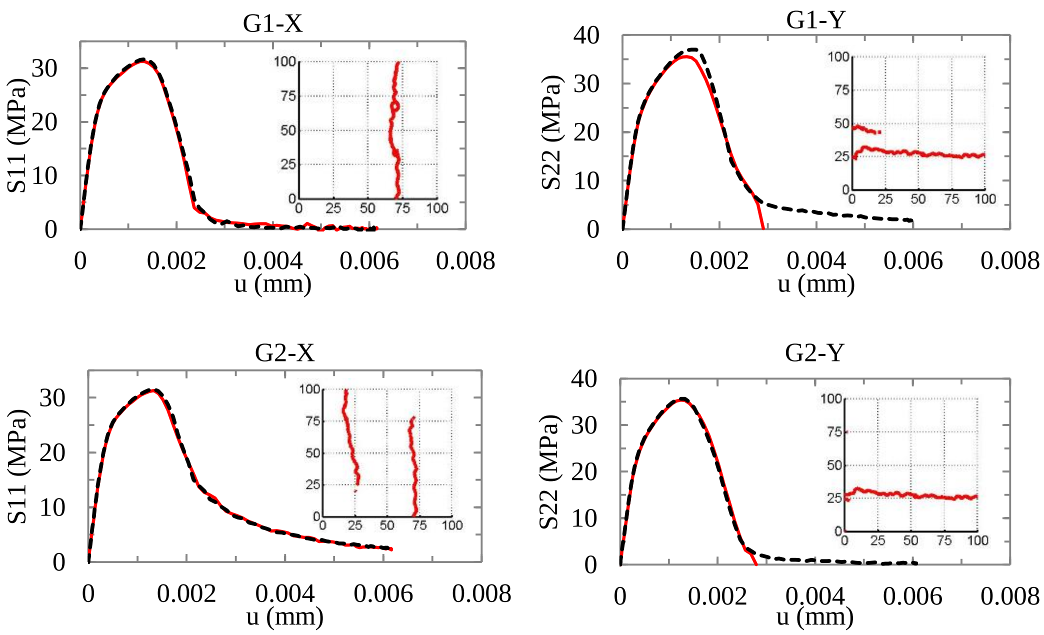


Figure 5. Comparison of simulation results using the multi-scale stochastic coupling strategy for weak interface properties. The solid curves represent the detailed geometry models (i.e. MeE size 100 μm^2) and dashed curves are the Bayes multi-scale models.

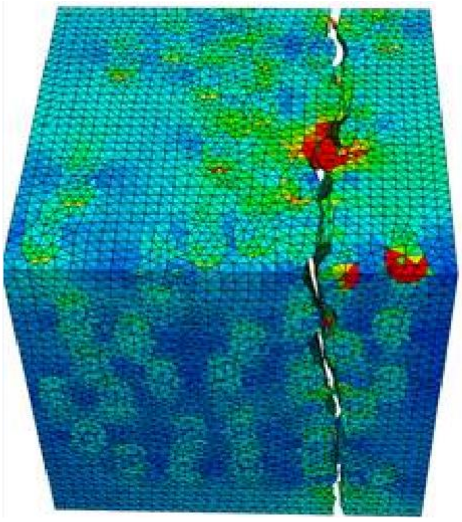


Figure 6. 3D cohesive fracture modelling of CFRP

3. Conclusions

The multiscale stochastic fracture mechanics framework developed in this project is a brand new concept, which, for the first time, has closely linked experimental study, numerical modelling and structural design which are currently investigated largely independently. The project is the first systematic research in the world to bridge the gap between the experimental advances in XCT and computational modelling of damage and fracture in fibre reinforced composite materials, so that numerical simulations can be directly validated. The ultimate marriage of multi-scale modelling approach and stochastic theories will provide a physically sound modelling tool for reliability assessment of normal to large sized structures with reasonable computational cost.

This project is a truly interdisciplinary one, spanning material engineering, computational mechanics, stochasticity and reliability, and structural design. Many aspects in this project, including the XCT technique, the nonlinear fracture modelling, the multiscale modelling approaches, the stochastic theories, are at present hot research areas, and each alone presents considerable challenges. However, it is believed that under the umbrella of the multiscale stochastic fracture mechanics framework, powerful synergy has been achieved to some extent, which has the potential to revolutionize the present design practices of fibre reinforced composite materials and structure systems in aerospace industry after further, more in-depth research.

This funded research will lead to three PhD theses, with two to be submitted for defending very soon.

4. Publications

The following publications have or will indicate the funding of this AFOSR/EOARD grant.

Book chapters / conference papers

[1] Sencu RM, Yang ZJ and Wang YC (2015). “Chapter 5: from micro to macro: simulating crack propagation in carbon fibre composites” in Structural Integrity and Durability of Advanced Composites, Beaumont P etc ed., Woodhead Publishing.

[2] Sencu RM, Yang ZJ, Wang YC (2014). A Multiscale Stochastic Fracture Modelling Calibration Using Monte Carlo Simulations. 22nd UK National Conference on Computational Mechanics in Engineering. Exeter, April 2014.

[3] Qsymah A, Sharma R, Yang ZJ, Margetts L and McDonald SA (2015). XCT Image-based Homogenisation of Elastic Properties of Ultra High Performance Fibre Reinforced Concrete (UHPFRC). 23rd UK National Conference on Computational Mechanics in Engineering. Swansea, April 2015.

Journal papers

[4] Sencu RM, Yang ZJ* and Wang YC. A multi-scale stochastic method for crack growth modelling in heterogeneous quasi-brittle materials, *Engineering Fracture Mechanics*, under revision.

[5] Sencu RM, Yang ZJ* and Wang YC, Phillip Withers,Cristoph Rau, Aaron Parson, Costas Soutis. X-ray CT image-based model generation of carbon fibre reinforced polymer composites. Nearly finished and will be submitted soon.

[6] Qsymah A, Sharma R, Yang ZJ* and Margetts L. XCT image-based two-step scale homogenisation for elastic properties of ultra high performance fibre reinforced concrete considering pore sizes. Nearly finished and will be submitted soon.

[7] Qsymah A, Sharma R, Yang ZJ*, Margetts L and McDonald S. 3D characterisation of the cracking behaviour of high performance fibre rieinforced concrete using x-ray computed tomography. under preparation.

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Abstract

In this project, the characterization of the microstructures, damage and fracture behavior of CFRP using state-of-the-art X-Ray Computed Tomography (XCT) was investigated experimentally in order to develop an innovative multiscale fracture mechanics (MustFrame) framework and associated computer codes for accurately modeling the damage and fracture in these materials in order to critically evaluate the reliability and performance of small- to large-scale engineering structures and systems. The ultimate aim is optimize microstructures and structural designs for better quality, greater reliability and lower cost. The funded research led to three PhD theses.

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Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

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Equipment/Facilities			
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Total			

Report Document

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Appendix Documents

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