ESRF	**Experiment title:** *Laminography investigation of impact damage evolution in high performance composite panel*	**Experiment number**: MA1835
Beamline: ID19	**Date of experiment**: from: 19-04-13 to: 23-04-13	**Date of report**: 30-3-15 *Received at ESRF:*
Shifts: 12	**Local contact(s)**: Lukas Helfen	

Names and affiliations of applicants (* indicates experimentalists):

Lukas Helfen, Institute for Synchrotron Radiation (ISS), Karlsruhe

Feng Xu, ANKA Karlsruhe Institute of Technology

Report:

The aim of this research is to obtain high-resolution three-dimensional (3D) images of high performance composites commonly used in novel aircraft structures, such as bird strike resistant leading edges, and fuselage and engine protection for fragment impacts. Experiments were ultimately performed on both composite materials utilizing high tenacity fibres (*e.g.* Dyneema, containing polyethylene fibres), and carbon fibre materials containing advanced toughening phases to ameliorate impact damage. To date, results have been most fully analysised in relation to the carbon fibre-based systems, appearing in the following ISI journal publication (and summarised briefly below):

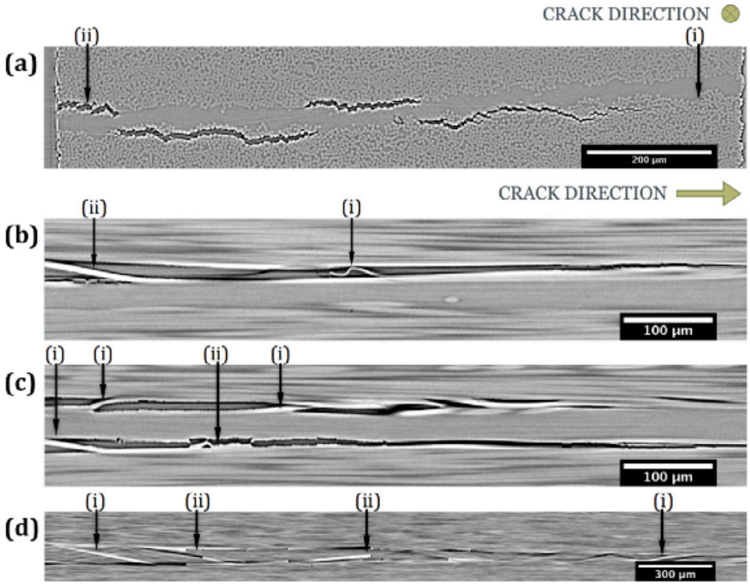
Interlaminar fracture micro-mechanisms in toughened carbon fibre reinforced plastics investigated via synchrotron radiation computed tomography and laminography
By:Borstnar, G (Borstnar, G.); Mavrogordato, MN (Mavrogordato, M. N.); Helfen, L (Helfen, L.); Sincla, I (Sinclair, I.); Spearing, SM (Spearing, S. M.)
COMPOSITES PART A-APPLIED SCIENCE AND MANUFACTURING, Volume: 71, Pages: 176-183, Published: APR 2015

Abstract Synchrotron Radiation Computed Tomography (SRCT) and Synchrotron Radiation Computed Laminography (SRCL) permit 3D non-destructive evaluation of fracture micro-mechanisms at high spatial resolutions. Two types of particle-toughened Carbon Fibre Reinforced Polymer (CFRP) composites were loaded to allow crack growth in Modes I and II to be isolated and observed in standard and non-standard specimen geometries. Both materials failed in complex and distinct failure modes, showing that interlaminar fracture in these materials involves a process zone rather than a singular crack tip. The work indicates that incorporating particle/resin, fibre/interlayer and neat resin failure is essential within models for material response, since the competition between these mechanisms to provide the energetically favourable crack path influences the macro-scale toughness. The work uniquely combines the strengths of SRCT and SRCL to compare failure micro-mechanisms between two specimen geometries, whilst assessing any edge effects and providing powerful insight into the complex micro-mechanical behaviour of these materials.

The high specific stiffness and strength of CFRPs has led to their use in aerospace applications, where a reduction in weight has a direct impact on the payload and range of the aircraft. However, composites may suffer from low velocity impact damage whilst in service that can have a significant effect on the residual mechanical properties. Such events may cause significant internal damage in the form of delaminations, which are difficult to identify from surface inspections and may reduce compressive properties by up to 60%. Given that Mode I and Mode II dominated loading conditions have been identified to occur under low velocity impacts, modelling such Mode I and II fracture is a key first step in developing models for impact damage resistance and post-impact damage tolerance.

The experiments documented here represent the first to capture *in situ* toughening mechanisms operating in Mode I interlaminar cracks in particle-toughened composite laminates, tested in both standard and non-standard geometries. They permit the direct identification of micro-mechanical features and mechanisms that affect the global Mode I fracture toughness. Mode II identification of micro-mechanisms was conducted *ex situ*, but the SRCL and SRCT techniques used still provided invaluable information without changing the stress state on the sectioning plane that may introduce out-of-plane displacements.

MATERIALS CFRP test coupons, provided by Cytec Engineered Materials, were manufactured from developmental particle-toughened material systems. The toughening was confined to a ~30 µm thick particle-toughened interlayer in each system. The primary reinforcement was a proprietary intermediate modulus carbon fibre (~5.4 µm in diameter). British Standard geometries (BS ISO 15024:2001) were employed in the fracture toughness testing and SRCL imaging, which permits the use of laterally extended specimens that are closer to practical component and structural length-scales



RESULTS Figure 1 Illustrates Mode I crack paths captured in toughened CFRP captured via SRCT & SRCL showing; (a) a top down view of the crack showing a Mode I crack propagating on either side of the interlayer, (b) a side view of a representative slice featuring a fibre bridge and fibre/matrix 'peeling', (c) a region of an overlapping crack with fibre bridging and fibre/matrix interface failure, and (d) an SRCL slice identifying bridging and broken fibres in the crack wake.

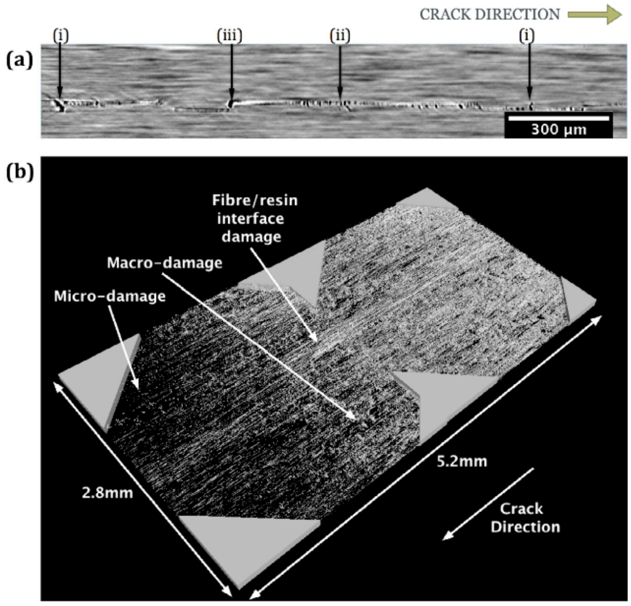


Figure 2 Illustrates Mode II interlaminar cracking in toughened CFRP via SRCL featuring; (a) echelon crack arrangements and the crack path swapping between the top and bottom of the toughened interlayer, and (b) a 3D crack segmentation emphasizing the extreme length of the process zone in Mode II and showing significant damage occurring within the interlayer across almost the entire volume, at a scale and sample size that cannot readily be captured via conventional tomography.

CONCLUSIONS The unique ability of SRCL to scan laterally extended objects proved invaluable in validating the observations made in the sub-sized specimen geometries commonly used for SRCT, and has indeed highlighted that in some materials and loading conditions the micro-mechanisms can be significantly different. Therefore, all work on narrow CFRP specimens should always be validated with standard engineering test geometries