ESRF	**Experiment title:** Computed laminography and tomography for polymer composite failure studies	**Experiment number**: MA 313
Beamline: ID19	**Date of experiment**: from: 16th to 21st Sept 07	**Date of report**: 7/4/08
Shifts: 12	**Local contact(s)**: Greg Johnson	*Received at ESRF:*

Names and affiliations of applicants (* indicates experimentalists):

Prof. Ian SINCLAIR*, University of Southampton
Prof. Dr. Tilo BAUMBACH, Forschungszentrum Karlsruhe GmbH, Institute for Synchrotron Radiation (ISS)
Dr. Lukas HELFEN*, Forschungszentrum Karlsruhe GmbH, Institute for Synchrotron Radiation (ISS)
Dr. Eric MAIRE, INSA-Lyon
Prof. Mark SPEARING, University of Southampton

Report:

Experiment MA313 was based on optimisation of complementary computed tomography and computed laminography imaging conditions for *in situ* testing of polymer composites. Importantly, having established suitable imaging conditions, *in situ* mechanical testing was to be carried out to confirm that failure behaviour was indeed representative of conventional test conditions. *In situ* results were additionally to be used for initial validation of available CZM approaches. A simple means of loading of samples undergoing laminography was additionally implemented. Overall, the experiment progressed closely to the original plan and was a significant success in all main respects. Outcomes to date are summarised in number of initial conference and journal papers, abstracts of which are shown below:

A.J. Moffat, P. Wright, J-Y. Buffière, I. Sinclair, S.M. Spearing , *Micromechanics of damage in 0° splits in a $[90,0]_s$ composite material using synchrotron radiation computed tomography*, SAMPE Fall technical Conference, Sept 08, Memphis, Tennesse.

Carbon fibre reinforced composite materials are increasingly exploited in aerospace applications for their high specific strength and stiffness. As a result there is a requirement for accurate strength and lifing models to reduce development costs. Micromechanical models capture the physics of damage evolution but are computationally expensive. Macro-scale models on the other hand are more computationally efficient but are not easily adaptable to different material configurations. Cohesive zone models (CZM) can be used as a bridging solution between the micro- and macro-mechanical approaches and offer a promising approach for modelling fracture in composites.

To validate the CZMs an experimental study using high resolution (1.4 µm voxel size) X-ray computed tomography (CT) was performed at the European Synchrotron Research Facility (ESRF). A carbon fibre reinforced polymer matrix composite was investigated in two conditions: one material was consolidated using the manufacturers recommended procedure and the second material was cured at a lower temperature and pressure. The samples were laid-up in a $(90,0)_s$ configuration. *In situ* tensile loading on notched specimens was performed: samples were scanned in the loaded and unloaded condition allowing the

evolution of damage and the local strain fields to be monitored.
The three-dimensional nature of damage and its evolution has been elucidated, quantifying the extent of intra- and inter-lamina damage and individual fibre breaks with a confidence not possible using conventional 2-D imaging methods. Intra-laminar damage is seen to occur at relatively low loads (before approximately 30% s_f). Using microstructural features it has been possible to calculate local strain fields around the intra-laminar splits, in addition the CT data provides information on crack opening displacements along the splits. This information has been used to inform the development of a finite element analysis (FEA) model of the intra-lamina damage that incorporates cohesive zone elements in the likely locations of damage. The quantitative data on strains and COD allows the model to be validated for the loading conditions of interest.

A.J. Moffat, P. Wright, J.Y. Buffiere, I. Sinclair, S.M. Spearing, *Micromechanisms of damage in 0˚ splits in a [90/0]s composite material using synchrotron radiation computed tomography*, submitted to Scripta Materialia.
In situ synchrotron radiation computed tomography has been used to investigate 0˚ ply splits in a $[90/0]_s$ carbon fibre-epoxy laminate. This technique allows for direct three-dimensional observations of damage. Micromechanisms such as pinning and bridging have been observed in rubber toughened, resin-rich regions. Crack opening and shear displacements associated with 0˚ splits have been quantified and this work demonstrates that this technique may be particularly useful for determining full field strain maps around damage in composite materials

A.J. Moffat, P. Wright, I. Sinclair, S.M. Spearing, *High resolution computed tomography of damage in laminated composites,* ECCM13, June 08, Stockholm.
Damage in carbon fibre-epoxy $[90/0]_s$ laminates was investigated using *in situ* synchrotron radiation computed tomography. Using this technique it was possible to observe, in three dimensions, the micromechanisms of damage due to tensile loading. Both inter- and intralaminar damage was observed. Bridging was seen in both the 0˚ splits and transverse ply cracks with the bridging points forming in resin-rich regions in the plies. In the 0˚ splits crack pinning occured in the resin-rich regions but this was not observed in the transverse ply cracks. Several transverse ply cracks may form in a single ply, however crack shielding was observed to inhibit the growth of transverse ply cracks, within close proximity, through the samples. Debonded toughening particles and fibres were associated with the initial stages of delamination.

In addition to the above papers regarding the computed tomography scans, results from the computed laminograpy have now been processed to the point where we can confirm the key aspiration of the laminography: specifically, that micromechanisms of damage at the fibre and ply level can be observed *in situ* in very much larger coupons that allowable by CT. Figure 1 highlights this finding, where intralaminar cracks (transverse ply) and an area of delamination have been clearly segmented from a volume of material at the tip of the notch in a coupon of ~80 x 80mm in-plane dimensions. We identify this as a highly original and important result, allowing assessment of material behaviour at a scale of direct engineering relevance.

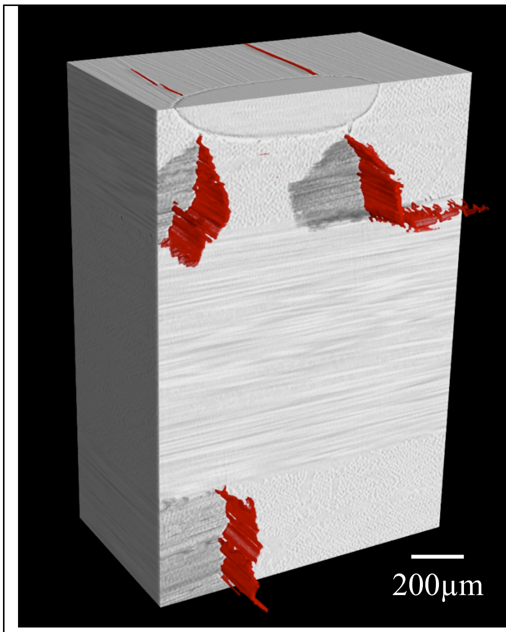

Fig. 1 Laminograph volume of notch tip damage in CFRP panel loaded *in situ*: cracks are segmented in red with the surrounding material partially withdrawn to show relationship the ply structure.