Institution: The Open University

Unit of Assessment: B13 Electrical and Electronic Engineering, Metallurgy and Materials

Title of case study: Aircraft structures: Life extension and damage tolerant design

1. Summary of the impact

We have optimised aerospace structural designs and assessment methods through development and application of hybrid residual stress characterisation techniques. Our research results on bonded crack retarders have redirected industry development programmes on hybrid metal laminate material systems and been used to evaluate reinforced structural concepts for US Air Force wing and fuselage applications. Methods to assess and mitigate maintenance-induced damage have been developed and implemented based on our research. Our contour measurement technology has been transferred to the US Air Force, which now has the capability to perform measurements in-house and support work with both NASA and the US Navy.

2. Underpinning research

1995–97: Edwards (Lecturer / Senior Lecturer) led MoD-funded research on the study of residual stresses by adapting the Sachs layer removal technique to research fatigue crack growth from cold-worked holes in airframes [3.1].

2000–04: Edwards (Reader / Professor) and **Fitzpatrick** (Senior Lecturer / Reader; joined the OU 1995) worked on the assessment of welding techniques for the fabrication of aerospace structures as part of the EPSRC-funded WELDES programme, in collaboration with Airbus, Alcoa and QinetiQ. Weld residual stress measurement [3.2] and modelling [3.3] contributed to our understanding of long fatigue crack growth in both Metal Inert Gas (MIG) and Variable Polarity Plasma Arc (VPPA) welded aluminium, crack closure effects on stress intensity factors and the prediction of fatigue lifetime for skin-stringer panels.

2001–08: Edwards (Reader / Professor), **Fitzpatrick** (Senior Lecturer / Reader) and **Gungor** (Lecturer, joined the OU 2002) pioneered the application of the contour method [3.2] and validated the novel contour 'rosette' method for the determination of the complete stress tensor in a component. This research used the contour method technique in conjunction with other approaches to provide accurate and, most importantly, validated measurements of the residual stresses that were used in models for the fatigue crack growth rates and damage tolerance of welded joints in aerospace aluminium alloys. Hybrid approaches to residual stress measurement using synchrotron X-rays for high spatial resolution were complemented by neutron measurements of strain in critical areas identified by full field contour measurements.

2006–09: Edwards (Professor; left the OU 2011) and **Fitzpatrick** (Reader) worked on the development of bonded crack retarders for the retardation of fatigue cracks in welded aerospace structures, funded by Airbus UK. Following earlier work on residual stresses in welded aircraft structures, bonded crack retarders were shown to be a powerful structural solution for improving damage tolerance in integral aircraft structures [3.4].

2006–09: Fitzpatrick (Reader / Professor) studied the residual stresses around scribe mark damage in fuselage alloys following fatigue cracking in some airframes [3.5, 3.6], funded by Airbus. Nano-indentation, previously shown to be sensitive to residual stress, was validated by synchrotron X-rays for application to small-scale stress fields.

2009–13: Fitzpatrick (Professor) and **Moffatt** (Lecturer) modelled the life benefit and stability of bonded crack retarders for improved damage tolerance of new and existing airframes in partnership with Airbus.

2009 to present: Fitzpatrick (Professor) researched laser shock peening for damage repair and life enhancement of aerospace materials [3.6], funded by Airbus and the US Air Force, with support from Alcoa.

3. References to the research

3.1 **Journal article.** Özdemir, A. T. and Edwards, L. (1996) 'Measurement of the three-dimensional residual stress distribution around split-sleeve cold-expanded fastener holes', *Journal of Strain Analysis for Engineering Design*, vol. 31, pp. 413–421, DOI: 10.1243/03093247V316413

3.2 **Journal article**. Zhang, Y., Ganguly, S., Edwards, L. and Fitzpatrick, M. E. (2004) 'Cross-sectional mapping of residual stresses in a VPPA weld using the contour method', *Acta Materialia*, vol. 52, pp. 5225–5232, DOI: 10.1016/j.actamat.2004.07.045

3.3 **Journal article**. Tan, J. M-L., Fitzpatrick, M. E., and Edwards, L. (2007)'Stress Intensity Factors for Through-Thickness Cracks in a Wide Plate: Derivation and Application to Arbitrary Residual Stress Fields.' *Engineering Fracture Mechanics* 74(13): 2030-54. DOI: 10.1016/j.engfracmech.2006.10.017

3.4 **Journal article.** Liljedahl, C. D. M., Fitzpatrick, M. E. and Edwards, L. (2008) 'Residual stresses in structures reinforced with adhesively bonded straps designed to retard fatigue crack growth', *Composite Structures*, vol. 86, pp. 344–355, DOI: 10.1016/j.compstruct.2007.10.033

3.5 **Journal article.** Khan, M. K., Fitzpatrick, M. E., Hainsworth, S. V., Evans, A. D. and Edwards, L. (2011) 'Application of synchrotron X-ray diffraction and nanoindentation for the determination of residual stress fields around scratches', *Acta Mater*., vol. 59, pp. 7508–7520, DOI: 10.1016/j.actamat.2011.08.034 **Listed in REF2.**

3.6 **Journal article.** Dorman, M., Toparli, M. B., Smyth, N., Cini, A. Fitzpatrick, M. E. and Irving, P. E. (2012) 'Effect of laser shock peening on residual stress and fatigue life of clad 2024 aluminium sheet containing scribe defects', *Materials Science and Engineering A,* vol. 548, pp. 142–151, DOI: 10.1016/j.msea.2012.04.002

4. Details of the impact

Our research has informed the damage-tolerant design and lifing of aircraft structures in the presence of residual stresses and a recently-identified source of fatigue initiation caused during airframe maintenance.

We have developed the contour method of residual stress measurement, since 2002, into a validated industrial tool for measuring residual stresses in complex engineering components, and integrated it with non-destructive stress measurement techniques capable of resolving fine spatial detail. We have applied our comprehensive toolkit of stress analysis techniques to aircraft structures in collaboration with the MoD, the US Air Force Research Laboratory, Airbus, BAE Systems, Bombardier, and Alcoa. In 2013 we set up a business unit at the OU providing a contour method measurement service for industry.

Our research into the development, application and validation of the contour method is now enabling its uptake in industry:

> *'The OU had the unique capability to measure large field residual stresses with the accuracy and repeatability required for safety critical structures. We were convinced by the validation evidence provided by their research that the contour technology was at a stage suitable for transfer into our work on airframes and associated components. … As a direct result of collaboration with Professor Fitzpatrick and his staff, along with focused training and technical support provided by the research team at the OU, AFRL/RQ now has an organic means by which to evaluate the stress state of laser peened test coupons and structures. … We are currently using our on-site contouring for several internal research programs and also to support collaborative research with both NASA and the US Navy.'* [5.1].

Our research has also demonstrated accurate prediction of fatigue crack growth for damage tolerant design of integral forged structures that do not have the natural crack arrest characteristics of conventionally riveted designs. In particular, our research into the design of bonded crack retarders since 2005 through various projects for life enhancement of new and existing aircraft structures has enabled Alcoa to:

'[establish] *collaborations with producers of advanced fibers and adhesive systems to evaluate and develop material systems to further improve the design concepts evaluated in past and current collaborations with The Open University ... the results from the bonded crack retarder projects [have been implemented] in several United States Air Force Research Laboratory funded projects to evaluate selectively reinforced and hybrid laminate aerospace structural concepts for wing and fuselage application*' [5.2].

'*Research in two key areas has resulted in an improved understanding of the mechanisms by which adhesively bonded selective reinforcement may be exploited … Aided by The Open University's contributions, Airbus has achieved TRL3* [Technology Readiness Level 3] *for bonded crack retarders applied to wing structures, and expects to achieve TRL4 in mid-2014. This represents a sizable investment to date, and has firmly established selective reinforcement as a candidate for aircraft wings.*' [5.3].

Following the discovery of unanticipated fatigue cracks from maintenance-induced scribe marks in some airframes from the 1990s onwards, and an instruction from the regulator to investigate the problem, we developed a new method from 2006–9 to determine residual stress at a very small length-scale.

'*The OU group was able to supply us with detailed mapping of the residual stress and hardening associated with different types of scratch damage. Their work was a significant advance in the methodology that was available to us, and was distinctive because although the determination of the residual stress around such small-scale features is extremely challenging, they provided cross-validation of their measurements by developing the nanoindentation method to determine the scratch residual stresses, and compare the results with synchrotron X-ray data. The overall work programme revealed the complexity of the interaction of the hardening from the tool and the residual stress generated. … A key outcome was that this work informed the conclusion by the regulator to base the accept-or-repair decision on scratch depth criteria.*' [5.4].

The scribe marks work led to the investigation from 2008 of laser shock peening as a possible repair strategy (now patented by Airbus) which has now broadened to a programme looking at laser peening for life enhancement and improved damage tolerance.

'*We funded the OU to study residual stress generation from laser shock peening as a candidate technique* [for repair]. *An early result caused us to change the direction of the programme rapidly. The OU mapping of the laser peen stress field at much higher spatial resolution than we had ever seen previously led us to investigate different peen methods from different providers. Again, the OU's use of multiple, cross-validated techniques, was vital, particularly when the data generated contradicted that provided by the OEMs! The OU's work on the contour method of stress measurement, and the research to extend the method to new capability for measuring near-surface stresses, was very important to underpin this work.*

'A key outcome to-date of this work is that the laser peen technology has formally progressed through the Airbus Technology Readiness Level review system, with the OU making a direct input to that process.' [5.4].

5. Sources to corroborate the impact

5.1 Letter from Program Manager, Aerospace Systems Directorate, Air Force Research Laboratory, dated 23 October 2013.

5.2 'Impact of Open University research on Airbus wing structures', Letter from Technology Manager – Aerospace, Alcoa Technology, dated 30 September 2013.

5.3 Letter from Technology Product Leader (Metallic Wing R&T), Airbus Operations Limited, dated 1 October 2013.

5.4 Letter from R&T Project Manager, Airbus Airframe Architecture and Integration, Airbus Operations GmbH, dated 11 October 2013.