Institution: The Open University (OU)	
Unit of Assessment: B12 Engineering	
Title of case study: Contour Method Stress Mapping Improves Manufacture, Lifetime and Safety of Products and Structures	
Period when the underpinning research was undertaken: 2002-2020	
Details of staff conducting the underpinning research from the submitting unit:	

Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Prof Lyndon Edwards	Professor	1993 - 2011
Prof Michael Edward Fitzpatrick	Professor	1996 - 2016
Prof P John Bouchard	Professor	2008 - present
Dr Salih Gungor	Senior Lecturer	2000 - present
Dr Jan Kowal	Senior Lecturer	2000 - present
Dr Foroogh Hosseinzadeh	Senior Lecturer	2009 - present

Period when the claimed impact occurred: 2013-2020

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact

Manufacturing processes introduce internal (residual) stresses causing unwanted distortion and shortening the life of structures. The Open University has developed novel variants of the Contour Method of residual stress determination and applied it to map stresses in over 150 components for industrial clients. The measurements have changed manufacturing processes, validated numerical modelling, improved fracture control and contributed to industrial assessment procedures across aerospace, nuclear, medical and additive manufacture sectors. Our research has catalysed a UK start-up, a Centre of Excellence for Advanced Materials in China, and commitment to a National Stress Engineering Centre at Harwell.

2. Underpinning research

Most manufacturing processes introduce hidden internal stresses in products and structures. These "residual stresses" cause distortion and can shorten the useful life of structures. Conversely beneficial residual stresses can be introduced to control manufacturing processes and improve product performance. The research challenge is how to quantify and control residual stresses in highly complex manufactured parts.

The Contour Method of residual stress determination involves cutting a body containing stress at a cross-section of interest. The surfaces created by the cut deform as the residual stresses relax during the cut. The "contour" of the newly created distorted surfaces is then measured and an elastic finite element stress analysis used to back-calculate the cross-sectional distribution of undisturbed residual stresses acting normal to the plane of the cut.

The Contour Method has been implemented and extended by OU researchers following its publication in 2000. **Edwards, Fitzpatrick and Gungor**, for instance, applied the technique in conjunction with other approaches to welded plate joints made from aerospace aluminium alloys and in 2008, our research team **[O1]** implemented a novel multi-axial contour method to measure the full residual stress tensor in a plasma arc weld.

Bouchard and Hosseinzadeh pioneered application of the Contour Method to complex geometry engineering structures via a 4 year "*Advanced Contour Measurement Technology Research Programme*" (2009-13) funded by the East Midlands Development Agency, Rolls-Royce and the OU. They published original work **[O2]** that quantifies factors contributing to cutting artefacts and identifies approaches to mitigate them. An early breakthrough involved applying the Contour Method to map hoop residual stresses in a welded pipe based upon the novel idea of using a diametral cut parallel to the pipe axis **[O3]**. This paper also describes the first application of a hybrid measurement technique (Contour Method coupled with X-ray diffraction) for a welded pipe, mapping three direct components of the residual stress tensor.

These innovations have allowed residual stresses to be measured in multiple directions in cylindrical structures of complex geometry (for example valves and turbine discs).

The practical significance of OU research underpinning the Contour Method was set out by Hosseinzadeh, Kowal, and **Bouchard** in 2014 **[O4]**. This publication described the state of understanding of the technique through addressing three fundamental questions: how to cut components, how to measure surface deformation and how to analyse the measured data. The significance of introducing plasticity error during cutting is addressed by Hosseinzadeh **[O5]** and effective strategies for presented for mitigating such errors. In 2017, OU research staff developed a new method for dealing with asymmetric stiffness of cut parts that has been applied to complex geometry industrial parts and incorporated in our recent publication describing a new Incremental Contour Method, iCM **[O6]**.

OU research staff have supervised 9 PhD researchers who have contributed to Contour Method technology since 2000. These include research on the Rosette Method, near surface stresses, managing plasticity, applications to T-butt welds, piping welds, measuring shear stress using the fracture surface approach, length-scale refinement, asymmetric cuts and the bulge correction.

3. References to the research

O1. Kartal, M.E., Liljedahl, C.D.M., **Gungor**, **S**., **Edwards, L**., and **Fitzpatrick, M.E**. Determination of the profile of the complete residual stress tensor in a VPPA weld using the multi-axial contour method, *Acta Materialia*, vol. 56, Iss 16, 2008, pp 4417-4428. https://doi.org/10.1016/j.actamat.2008.05.007

O2. **Hosseinzadeh, F**., and **Bouchard, P.J**. (2013) Controlling the Cut in Contour Residual Stress Measurements of Electron Beam Welded Ti-6Al-4V Alloy Plates, *Experimental mechanics*, 53, 829-839. https://doi.org/10.1007/s11340-012-9686-1

O3. **Hosseinzadeh, F**., and **Bouchard, P.J**. (2013) Mapping Multiple Components of the Residual Stress Tensor in a Large P91 Steel Pipe Girth Weld Using a Single Contour Cut. *Experimental Mechanics*; 53: 171-181. https://doi.org/10.1007/s11340-012-9627-z

O4. **Hosseinzadeh, F**., **Kowal, J**., and **Bouchard, P.J**. (2014) Towards Good Practice Guidelines for the Contour Method of Residual Stress Measurement, *Journal of Engineering* https://doi.org/10.1049/joe.2014.0134

O5. **Hosseinzadeh, F**., Traore, Y., **Bouchard, P.J**., and Muransky, O. (2016) Mitigating Cutting-Induced Plasticity in the Contour Method, Part I: Experimental*, International Journal of Solids and Structures*, 94-95 pp. 247–253. https://doi.org/10.1016/j.ijsolstr.2015.12.034

O6. Achouri, A., **Hosseinzadeh, F**., **Bouchard, P.J**., Paddea, S., and Muransky, O. (2021) The Incremental Contour Method using Asymmetric Stiffness Cuts, *Materials & Design, Vol*. 197, 109268. Available online 28th October 2020. https://doi.org/10.1016/j.matdes.2020.109268

Other authors are OU PhD students or post-doctoral researchers, apart from O. Muransky at the University of New South Wales.

4. Details of the impact

OU Contour Method research has impacted manufacturing, the lifetime performance of components, safety, professional practice, commerce and the economy. Pathways to impact comprise collaboration with businesses, global sharing of knowledge and expertise through published work and conferences, providing advanced measurement services to industry, catalysing other providers of Contour Method measurements, hosting training seminars and contributing to the development of improved Structural Integrity Assessment Procedures.

Enhanced safe lifetime performance

In nuclear power **EDF Energy [C1]** state that "*Open University's research in developing the Contour Method of residual stress determination and applying it to map residual stresses in* *complex welded structures has helped ensure safe and reliable operation of EDF Energy power stations. These outputs have also provided EDF Energy with valuable benchmark data that have been incorporated in R6, which is one of the key procedures that EDF Energy uses to assess the integrity of their UK nuclear assets*". For example, the OU applied Contour Method in tandem with the slitting technique and revealed high levels of residual stress in Compact Tension tests specimens that explained unexpectedly high crack growth rates observed in the creep crack growth tests. EDF Energy **[C1]** further state that "*this work is now a key reference underpinning EDF Energy advice on creep crack growth rates in Type 316H HAZ materials*" and that "*this advice has been used in safety case assessments for key high- temperature components in the UK's Advanced Gas Cooled Reactors, reducing unexpected down time and enhancing the safety and cost-effectiveness of nuclear power plant*".

Improved codes and standards for the nuclear energy sector

The R6 Procedure for the Assessment of Structures Containing Defects **[C2,** pp.6-7**]**, developed by the UK nuclear industry and used worldwide, sets out a fracture mechanics-based methodology for assessing the safety of critical plant (i.e. to guard against catastrophic failure). Three new sections dealing with residual stress have been added to the R6 procedure over the past decade: Section III.15 (Calculation of Residual Stress in Weldments); Section V.5 (Validation Sheets for the Calculation of Residual Stress in Weldments); and Section V.6 (Worked Example of the Calculation of Residual Stress). The OU has contributed to these new sections through membership of R6 Panel subgroups (Weld Modelling Guidelines and Benchmarks, Weld Residual Stress Profiles) and by providing maps of residual stress reference data for benchmark test components that have been measured by the Contour Method, see **[C1]**.

Improved manufacture

OU research has advanced the capabilities of the Contour Method of residual stress determination, raised its Technology Readiness Level (TRL) and applied it to map stresses in more than 150 components since August 2013 via industry measurement contracts worth over GBP1,500,000. Many of these measured residual stress maps have changed manufacturing processes, validated numerical modelling, optimised fatigue lifetime and improved fracture control across manufacturing, aerospace, nuclear, offshore and medical sectors. Some examples are set out below.

Rolls-Royce [C3] has contracted the OU to carry out more than 20 Contour Method work packages with a total cost of ~ GBP500,000 from August 2013-20 **[C3]**. Typical examples include mapping stresses in Trent 1000 turbine discs to confirm the accuracy of manufacturing process models; in rotary friction joints for optimising welding processes, in double helical gears to quantify the impact of different manufacturing processes, in test components manufactured by Selective Laser Melting in order to validate process models, and in additively manufactured parts. Rolls-Royce **[C3]** specifically state that the measurements performed by OU *"have reduced costs, improved manufacturing processes, validating process models and supported safety cases for nuclear power plants. The benefit to Rolls-Royce is significant as evidenced by the volume of measurements, their diversity of application, and the relevance to the different business units within Rolls-Royce.*"

Airbus Defence and Space [C4] is responsible for the design of propellant tanks used for both telecommunication and scientific based space missions. These high energy, hazardous propellant tanks are safety critical during the propellant loading phase and are subject to fracture control requirements. Airbus commissioned the OU to measure the residual stress levels introduced by the planetary end-cap electron beam weld of their latest spherical tank design, for the next generation Eurostar spacecraft platform (ENEO). The Contour method results confirmed and validated analytical predictions of weld induced residual stress that have been subsequently used to demonstrate the fracture tolerance of the latest tank design to potential manufacturing defects. Airbus **[C4]** state that "*this contribution to the necessary fracture control programme has been reviewed and accepted by customers and the European Space Agency"* and finally note that "*the qualification tank has now successfully passed its pressure cycling requirements and […] its burst pressure requirement.*"

DePuy is part of the Johnson & Johnson Family of Companies and offers a comprehensive portfolio of orthopaedic products**.** The Staff Material Engineer **[C5]** confirmed "*the impact of the Open University's research and implementation of the contour method residual stress measurements on our femoral knee implant components and on improving the efficiency of our manufacturing processes*". Femoral knee implants are one component of a total-knee-replacement where residual stresses play a key role. Dimensional distortion of femoral knee implants during manufacture (leading to rejection) is a direct consequence of residual stresses being induced or pre-existing residual stresses re-distributing. A series of contour method measurements were conducted on femoral knee implants by the OU which showed that the shot- blasting manufacturing process significantly alters the bulk residual stress of the femoral from its as-cast condition. These '*resulted in optimized manufacturing routes, increased quality assurance when it comes to checking changes at the blasting step due to possible impact/dimensional changes at machining and improved product quality*" **[C5]**.

CETIM [C6] is a Technical Centre for Mechanical Industry based in France with a EUR150M overall business volume. Over the past 7 years, Cetim has commissioned Contour Method measurement work from the OU for 13 projects at a total cost of GBP120,000. For example, contour method measurements (using the OU multiple-cut, multiple-method variants) were conducted on a 2m diameter gear for the offshore industry (wind turbines) in order to validate the use of a carburizing method for increased strength and wear resistance through introducing beneficial compressive residual stresses near the tooth of the wheel.

Impact on other organisations and companies supporting industry

OU Contour Mapping research underpins the development of further centres designed to apply the findings to support industrial and manufacturing improvements. In 2017 OU researchers set up Stress-Space Ltd (www.stress-space.com). The company is growing with GBP232,000 revenue in 2019/20, and delivers residual services to business largely based on published OU research (as set out in Section 2). For example, its Contour method stress measurements on transmission drive chain parts for an aerospace prime *"revealed the limitations of the initial design (fatigue hot spot) and was used to assess the merits of an improved design with a new manufacturing route in order to eliminate the risk of failure during service operation*" **[C7]**. The merits of Stress-Space Ltd's Business Case for Growth (founded on application of OU Contour method research), resulted in its selection to participate in the prestigious ESA BIC UK Incubation Programme in 2019 attracting research funds exceeding GBP150,000 **[C7]**.

The Centre of Excellence for Advanced Materials (www.Ceamat.com) in Dongguan, China has adopted the OU's Contour method technology to create a new GBP10,000,000 Stress Measurement Facility. Director of the Stress Measurement Facility **[C8]**, who was an OU researcher from 2013 – 2018 noted: "*Our organisation and the stress analysis department in particular has greatly benefited from the various educational lectures you provided, the contour method seminar you organised and advice you provided on equipment purchase and setting our research priorities […] it is our ambition to bring this technology to the Chinese market and achieve similar and wider benefits."*

OU Contour Method research has catalysed **[C9]** an ambitious collaborative plan to establish a National Stress Engineering Centre (N-SEC) at Harwell which will "*co-locate several complementary measurement techniques, including the Contour method, with the neutron capabilities at ISIS* [STFC Facility] *Together with a new neutron instrument, e-MAP, the combined capabilities would really be unique in the world"*. N-SEC has grown from an ISIS-OU collaboration to a consortium that now includes several UK universities and Research and Technology Organisations and is supported by a number of industries. ISIS has invested of order GBP500,000 in developing the concept and the building and instrument design. N-SEC, referred to as I-SEC in the UKRI Infrastructure Roadmap **[C10,** p.58**]**, has been selected by STFC, with support from its Industry and Business Partnership Board, as one of four proposals that STFC submitted to the new UKRI Infrastructure Advisory Committee and that application for GBP23,000,000 is currently awaiting a decision **[C9]**.

5. Sources to corroborate the impact

C1. Testimonial, EDF Energy High Temperature Specialist, EDF Energy.
C2. Extracts from EDF Energy Nuclear Generation Ltd**.** R6 Revision 4 Amendment 12. *Assessment of Structures Containing Defects*, Gloucester, UK, 2019.
C3. Testimonial, Technical Specialist Materials, Rolls-Royce.
C4. Testimonial, ADS Propulsion Structural Integrity Technical Authority, Airbus Defence and Space.
C5. Testimonial, Staff Materials Engineer, Materials & Surface Technology (MST), De Puy Synthes, Ireland.
C6. Testimonial, residual stress and fatigue analyses R&D Manager, Research Department, CETIM.
C7. Testimonial, Operational Director, Stress-Space Ltd.
C8. Testimonial, Dean, Dongguan Centre of Excellence for Advanced Materials (CEAM).
C9. Testimonial, Director, ISIS Neutron and Muon Source, STFC.
C10. UKRI Infrastructure Roadmap (2019) Theme 3: Catalysing productive and clean growth - Manufacturing futures. International Stress Engineering Centre, p. 58.