

Institution: Imperial College London
Unit of Assessment: 12 Aeronautical, Mechanical, Chemical and Manufacturing Engineering
Title of case study: 1. Standards for the Application of Materials in Industry
<p>1. Summary of the impact (indicative maximum 100 words)</p> <p>Impact on industry, academia and government institutions from engineering materials research in the Mechanical Engineering department has been delivered through it directly leading to UK, USA and International Standards and Codes relating to three themes:</p> <ul style="list-style-type: none"> • Predicting and assessing the service life of high-temperature components. • Determining the fracture resistance of plastics, composites and adhesives. • Predicting the catastrophic failure of plastic pipelines. <p>The results of the research of staff in this unit have led directly to UK, US and International Standards and Codes: ASTM Standards E1457-07 (2012) and E2760-10 (2012); R5 EDF Energy Code of Practice (2012); BS 7910 (2013); ISO 25217 (2009); ISO CD 15114 (2011) and ISO 13477 (2008). These documents all cite peer-reviewed publications by staff from this unit. These Standards and Codes are now the basis of fracture-mechanics methodologies used by leading engineering companies like Airbus, EDF, E.ON, GKN, Rolls-Royce and Vestas, whose commercial success depends upon technological leadership. In this way our research has led to savings by UK industry of many millions of pounds, as detailed in Section 4.</p>
<p>2. Underpinning research</p> <p>This case study covers research by Professors Kinloch and Nikbin, Readers Blackman and Leever (all staff members from 1993-present) and Davies (lecturer 2011-present) in the Mechanical Engineering department.</p> <p><u>The Design and Service-Life Assessment of High-Temperature Components</u></p> <p>The work of Davies and Nikbin on the remaining life of high-temperature components is embedded in many Standards and Codes. Their research has led to:</p> <ul style="list-style-type: none"> • The development of the fracture-mechanics parameter C^* for elevated temperatures. • Innovative analytical and numerical models to predict crack initiation and growth. <p>Previous ASTM Standards for creep crack-growth (CCG) were limited to the use of the high-constraint compact-tension specimen. Davies and Nikbin developed experimental CCG testing methods on alternative specimen designs with a range of constraint levels [1] that allow a more accurate representation across a range of in-service conditions. The development of improved assessment and predictive methods of failure in components is an extremely urgent research area that is being continually developed to be able to be one step ahead of Nuclear Safety issues in the UK's ageing AGR fleet. As an example, Nikbin's paper [2], which won the 'Best Paper Award' in the ASME conference in San Diego (1998), describes the validation of the methodologies and paved the way for increased support from EDF for this work. The resulting methodologies are used in many Standards and Codes including ASTM Standards E1457-07 (2012) and E2760-10 (2012), R5 EDF Energy Code of Practice (2012) and BS 7910 (2013).</p> <p><u>The Fracture Resistance of Plastics, Composites and Adhesives</u></p> <p>Blackman and Kinloch's work underpins the Standards to determine fracture toughness under a variety of service conditions. Their innovative development of highly accurate, strain-energy release-rate methods based on analytical beam theories [3], led directly to ISO 25217 (2009). Earlier ASTM Standards, based on a simple-beam model, were over-conservative and limited in scope. Blackman and Kinloch's 'corrected beam' model accounted for the effects of beam-root rotation and transverse shear. These are crucial factors when fracture-testing adhesives and fibre-composite plastics which are now widely used as structural materials. Their new procedures incorporated built-in cross-checks to ensure the validity of the test and analytical procedures. Blackman also developed crack-length independent testing and analysis schemes for mode II (shear) fracture in adhesive joints and in fibre-composites [4]. His research showed that unacceptably variable results from the originally-proposed mode II test were caused by (a) specimen clamping conditions and (b) complex micro-cracking ahead of the mode II crack tip. By</p>

Impact case study (REF3b)

developing new experimental calibration and adopting a novel 'effective crack length' approach, Blackman greatly improved the accuracy of the mode II test. Both developments are embodied in ISO CD 15114 (2011).

The Failure of Plastic Pipes

Catastrophic failures by Rapid Crack Propagation (RCP) appeared soon after polymers were first used for pressurised gas and water pipelines. The high crack-speed and the hundreds of metres of RCP needed for the decompression process to stabilise, make this failure extremely dangerous. Leever's key research [5] which underpins Standards to avoid RCP shows how suppressing the pipe decompression process makes a meaningful laboratory-scale RCP test method feasible. The 'S4 Test', which Leever invented, was standardised in ISO 13477, and has become the industry Standard for design against RCP. Deeper understanding of material properties which resist fracture came with Leever's 'adiabatic decohesion' model. This attributes RCP to a highly localised polymer-melting process: hugely significant because plastic pipe materials owe most of their fracture resistance to a layer at the free surface, where test temperature control is most difficult. Leever [6] showed how the earlier ISO 13477 Standard test method had to be improved if the temperature sensitivity of this layer was not to exert an over-optimistic influence on the test results. The changes he proposed were implemented in ISO 13477 (2008).

3. References to the research * References that best indicate quality of underpinning research.

- * [1] C.M. Davies, F. Mueller, K.M. Nikbin, N.P. O'Dowd, G.A. Webster, "Analysis of creep crack initiation and growth in different geometries for 316H and carbon manganese steels". ASTM STP 1480, Journal of ASTM International, Vol 3, pp. 115-134, (2006) DOI: 10.1520/STP45508S
- * [2] K.M. Nikbin, "Comparison Between Crack Growth in Fracture Mechanics Specimens and Feature Component Tests Carried Out in a Low-Alloy Steel". ASME Journal of Pressure Vessel Technology, Vol 122, pp. 40-44, (1999) DOI: 10.1115/1.556147 (**'Best Paper Award' at the ASME Conference, San Diego, USA, July, 1998.**)
- [3] B.R.K. Blackman, A.J. Kinloch, M. Paraschi, W.S. Teo, "Measuring the mode I adhesive fracture energy, GIC, of structural adhesive joints: The results of an international round-robin", International Journal of Adhesion & Adhesives, Vol 23, Issue 4, pp. 293-305, (2003) DOI: 10.1016/S0143-7496(03)00047-2
- * [4] B.R.K. Blackman, A.J. Brunner, J.G. Williams, "Mode II fracture testing of composites: a new look at an old problem", Engineering Fracture Mechanics, Vol 73, Issue 16, pp. 2443-2455, (2006) DOI: 10.1016/j.engfracmech.2006.05.022
- [5] C.J. Greenshields, P.S. Leever, "Correlation between full scale and small scale steady state (S4) tests for rapid crack propagation in plastic gas pipe" Plastic, Rubber & Composites, Macromol. Engineering, Vol 28, pp. 20-25, (1999) DOI: 10.1179/146580199322913287
- [6] P.S. Leever, S. Hillmansen, L.D.F. Moreno, "Specimen temperature conditioning and drift before an S4 pipe fracture test". Polymer Testing, Vol 23, pp. 727-735, (2004) DOI: 10.1016/j.polymertesting.2004.01.003

4. Details of the impact

The pivotal contribution of our research to UK, US and International Standards and Codes is evident from their direct citations to our research papers. The authors have played major roles on committees overseeing the publication of relevant Standards and Codes. Nikbin is Chairman of the ASTM and VAMAS committees on 'The Role of Residual Stress in Weldments', a Member of the ESIS Technical Committee TC11 on 'High Temperature Mechanical Testing' and Chairman of the British Standards Institute Committee for BS7910. Davies is a Member of the 'UK Technical Advisory Group for Structural Integrity' Committee NT-22 Sub-Group on 'Fracture and Residual Stress'. Blackman is the Technical Secretary and Kinloch a Member of the ESIS Technical Committee TC4 on 'Fracture of Polymers, Composites and Adhesives'.

The Standards and Codes on the Design and Service-Life Assessment of High-Temperature Components: ASTM Standards E1457-07 (2012) and E2760-10 (2012), R5 EDF Energy Code of Practice (2012) and BS 7910 (2013)

Our Standards and Codes are used at EDF Energy's AGR nuclear plants on a daily basis, for routine safety checks on high-temperature components prone to cracking. The cost of lost output is roughly \$1M per day for a typical 1,000 MWe AGR plant. In 2010, 10 GWe of electricity was generated in UK AGR plants. The cost of refurbishing these old plants in order to run beyond their design life is estimated at £200-300M per GWe. The cost of new-build could be as much as £5,000M per GWe. The details of the savings conferred by the use of our Standards are confidential to EDF. However, even at a nominal 1-5% of the annual savings from extending plant life and reducing plant downtime, our contribution is millions of pounds annually. The sale of the Standards and Codes to Industry also generates UK revenue: on average two hundred licenses worldwide at £10,000 per annum is £2M as confirmed by a High Temperature Specialist in the Assessment Technology Group of EDF Energy [A].

The wide international acceptance of the Standards and Codes makes the UK a global leader in methodologies for high-temperature safety in the nuclear industry. For example, our Standards and Codes have been directly adopted by ASME in the US, as well as by nuclear safety bodies in Japan and Korea [A]. Indeed, High Temperature Specialist in the Assessment Technology Group of EDF Energy [A] has stated that: *"Professor Nikbin and his colleagues have significantly influenced key developments in R5 assessment procedures, which are used to assess the integrity of components in the UK's Advanced Gas Cooled Reactors (AGRs) which operate in the creep range. Of particular note are their important contributions in driving improvements in predictive modelling of the creep crack growth process and in developing an improved understanding of the role of residual stresses in the incubation and growth of cracks under creep conditions. Furthermore their significant contributions in the field of creep crack growth testing and high temperature assessment methods have led directly to improvements in international standards, including ASTM E1457, ASTM E2670 and BS 7910."*

The Standards on the Fracture Resistance of Plastics, Composites and Adhesives: ISO 25217 (2009), ISO CD 15114 (2011).

The research underpinning these Standards has made fracture-mechanics techniques accessible to industrial users, bridging the theoretical-experimental divide. At Airbus, our fracture-mechanics Standards are now routinely employed for materials qualification, calculation of design allowables and process control. The need for light, optimised, airframes and adhesively-bonded connections has heightened interest in fracture-mechanics techniques. The proportion of composite materials in aircraft has grown dramatically to reach 53% in the A350XWB. The cost benefits of weight savings are impressive. Every kilogram shed means not only substantial fuel-cost savings but also CO₂ emission reductions of over 16 tonnes per year. The Head of Structural Engineering Methods at Airbus [B] has stated: *"The design of advanced composite structures relies, at some stage, on the assessment of fracture mechanics parameters. Fracture mechanics standards are key in ensuring that co-cured/co-bonded components are at a specific performance level. Also, the control quality of incoming materials or manufactured elements relies on process control specimens, again derived from the same fracture mechanics standards. The excellent research on fracture mechanics by Blackman and Kinloch at Imperial College has been crucial in the development and publication of the ISO Standards on cracking in composites and structural adhesives. These Standards are used extensively by Airbus in these areas and have led to significant savings from improved design and smarter production and repair methods."*

GKN and Rolls Royce rely on our Standards when using adhesive-bonding techniques for aero-engine components like metal-composite fan blades. Our fracture-mechanics Standards were essential to determining the optimum surface pretreatment techniques for bonding titanium-alloy and fibre-reinforced plastic composites. Indeed, a Rolls Royce adhesive Specialist [C] has stated: *"In addition, the results from the Imperial College bonding research work have been read across to support innovation and improvements in manufacturing methods for Rolls Royce engine fan-casing components. It is estimated annual savings of up to £5M could be achieved through improved in-service behaviour."*

Vestas uses our Standards extensively to obtain fracture-mechanics data for designing adhesively-

bonded, fibre-composite wind-turbine blades. Each standard procedure gives an immediate cost saving. The contribution of fracture Standards cannot be isolated, but a failed prototype blade would cost £100k and a failed production blade would incur costs of many millions of pounds, as confirmed by Technology R&D Leader, Vestas [D].

The Standards on the Failure of Plastic Pipes: ISO 13477 (2008).

Leevers' research has underpinned advances in plastic pipe materials, processes and applications. Indeed a Senior Consultant at Plastic Pipes [E] has stated: *“The framework of international standards built around Leevers' ISO 13477 'S4' test has been essential to maintaining technological progress while maintaining absolute confidence in keeping RCP safely at bay.”* Savings can be estimated from experience in the US, where ISO 13477 is not applied and the costs of RCP failures in water pipe have been high: ten outstanding court suits for RCP during proof testing cite costs in the millions of dollars. The synergy of good Standards and sustained underpinning research accelerates innovation and [E] has also stated: *“Uponor's ProFuse pipe product posed a special RCP challenge due to its multilayer structure; our collaborative research programme using Imperial's ISO 13477 methodology was crucial in meeting the necessary industrial standards.”* Further, [E] has analysed the cost benefits of Leevers' basic research on the control of skin stiffness and adhesion to avoid any embrittling effect. They include savings of £100-300k in costly full-scale field tests, time savings of months in identifying the performance envelope, increased revenue yielded by getting a £20M p.a. product line to market more quickly, and the *“major financial benefit to the business gained by association with Imperial's reputation”*.

5. Sources to corroborate the impact

List of Standards and Codes produced from the research outlined in section 2 - all of which reference the published work of the Imperial researchers:

- [7] M. Koçak, et al., "FITNET, Fitness-for-Service (FFS) (2008) Procedure", Revision MK8, Vol. I-II, Editors, 2008. Available at http://www.hzg.de/imperia/md/content/gkss/institut_fuer_werkstoffforschung/wmf/best_paper_award_cesol-madrid_7-9_oct_08.pdf. Also available [here](#)
- [8] ASTM "Standard Test Method for Measurement of Creep Crack Growth Times in Metals" (2007) http://enterprise.astm.org/filtrexx40.cgi?+REDLINE_PAGES/E1457.htm. Archived [here](#).
- [9] ASTM "Standard Test Method for Creep-Fatigue Crack Growth Testing" DOI: 10.1520/ E2760-10 (2012) http://enterprise.astm.org/filtrexx40.cgi?+REDLINE_PAGES/E2760.htm. Archived [here](#).
- [10] R5 EDF Energy Code of Practice: "Assessment Procedure for the High Temperature Response of Structures" (2012) Procedure R5 Issue 3, British Energy Generation Ltd., Gloucester. Available to panel on request
- [11] BSI "Guidance on Methods for Assessing the Acceptability of Flaws in Metallic Structures". BS 7910 (2013) ISBN(s):9780580601088, 0580459659
- [12] ISO "Adhesives: Determination of the mode I adhesive fracture energy G_{IC} of structural adhesive joints using double cantilever beam and tapered double cantilever beam specimens". ISO 25217 (2009) http://www.iso.org/iso/catalogue_detail.htm?csnumber=42797.
- [13] ISO "Fibre-reinforced plastic composites: The determination of the Mode II fracture resistance, G_{IIC} , for unidirectionally reinforced materials using the calibrated end loaded split (C-ELS) test and an effective crack length approach". ISO DIS 15114 (2011) http://www.iso.org/iso/catalogue_detail.htm?csnumber=55357.
- [14] ISO "Thermoplastics pipes for the conveyance of fluids. Determination of resistance to rapid crack propagation (RCP). The small-scale steady-state test ('S4 Test')" ISO 13477 (2008) http://www.iso.org/iso/catalogue_detail.htm?csnumber=39858

Industrialists who can validate our claims of the impact of the standards:

- [A] High Temperature Specialist, EDF Energy
- [B] Head of Structural Strength Methods, Airbus
- [C] Adhesives Specialist, Rolls Royce plc.
- [D] Technology R&D Leader, Vestas
- [E] Senior Consultant, Plastic Pipes