The New Website **COMPETITION**
See inside for details.

The FESI Bulletin

The Magazine of FESI – **UK Forum for Engineering Structural Integrity**

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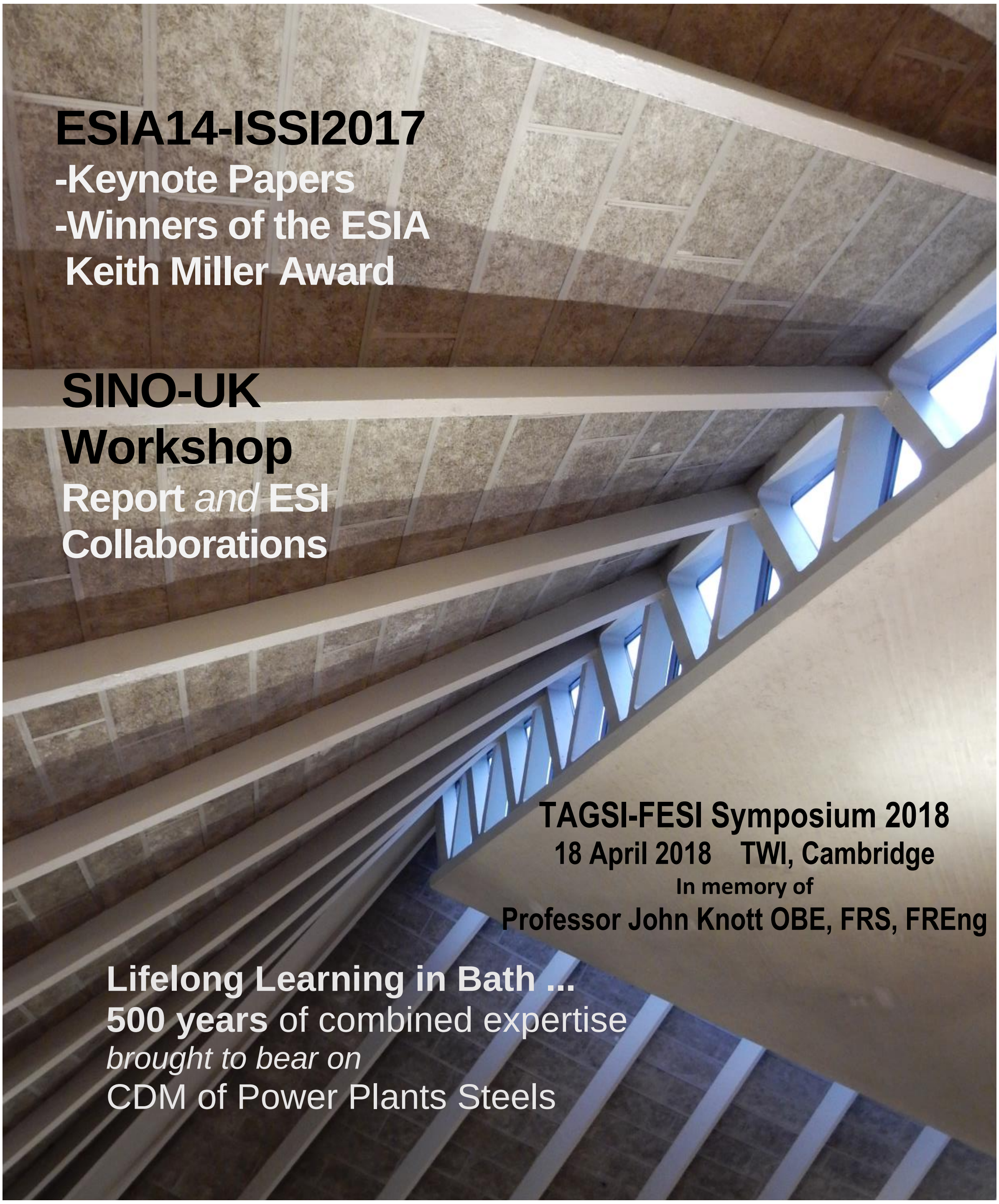

ESIA14-ISSI2017

-Keynote Papers
-Winners of the ESIA Keith Miller Award

SINO-UK Workshop

Report *and* **ESI Collaborations**

TAGSI-FESI Symposium 2018
18 April 2018 TWI, Cambridge
In memory of
Professor John Knott OBE, FRS, FREng

Lifelong Learning in Bath ...
500 years of combined expertise
brought to bear on
CDM of Power Plants Steels

Engineering Structural Integrity is ***engineering for a safer world***

It is with great sadness that I start this editorial for The FESI Bulletin with the news that our Board member, Professor John Knott, OBE, FRS, FREng, died on the evening of 5 October, after a prolonged illness.

The FESI Board and Council send their condolences to John's wife Sue and his family.

John was a giant in the engineering structural integrity and fracture communities, making many seminal contributions. We are proposing to dedicate a special issue of The FESI Bulletin to mark these contributions and his many other talents. In addition, John was the Chair of the UK Technical Advisory Group for Nuclear Structural Integrity (TAGSI) and the next joint TAGSI-FESI Symposium, Structural Integrity and Materials in Nuclear Plant, to be held on 18 April 2018, will be dedicated to his memory.

On a more upbeat note, we held a successful 14th International Conference on Engineering Structural Integrity Assessment (ESIA14) at the Manchester Conference Centre on 16 and 17 May. The ESIA series of conferences is organised biannually by FESI and, on this occasion, was held in conjunction with ISSI-2017, the Chinese Structural Integrity Consortium's (CSIC) International Symposium on Structural Integrity 2017, following an initiative by the Chairman of CSIC, Professor Shan-Tung Tu of the East China University of Science and Technology, Shanghai. It was good to welcome over 60 colleagues from the Chinese academic and industrial communities. Some 120 delegates attended across the two-day period, and contributed to a lively conference that provided the opportunity to explore ideas and developments across the engineering structural integrity spectrum. Within this issue of the Bulletin two of the keynote papers are included, together with one of the two papers awarded the Keith Miller Award for the Best Presentation by Student/Early Stage Engineers at an ESIA Conference.

ESIA14 was followed by a joint China-UK Workshop in which representatives from industry, business and academia explored specific challenges with the aim of both sharing experience and offering the potential for developing collaborations. A summary of the presentations is available from page 6 of this issue.

Over the past months, we have been progressing the new FESI website so that we are able to offer a more efficient communication service to all our members. FESI's Council consider this to be pivotal to implementing FESI's aims of which includes the communication, especially of best practice, in engineering structural integrity across the many communities: industrial, business and academic. Much time has been dedicated to ensuring this new website is both fit for purpose and will be maintained. We have selected as the image for the Home Page a picture of the three bridges that span the Firth of Forth. We are initiating an open competition associated with this selection and more detail can be found on page 4 and we would encourage you to enter.

EMAS Publishing, our publishing arm, will change its name to FESI Publishing as of 1 January 2018. The aim is to provide more visibility to this organisation, which is a wholly owned subsidiary of FESI and provides income to help support our many other activities.

Finally, I hope that you find The FESI Bulletin continues to offer a suitable mix of technical information and detail about the activities of FESI which we organise on your behalf.

Peter Flewitt
Editor-in-Chief

INSIDE THIS ISSUE

Cover image of the Design Museum: E Le May

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Application of Continuum Damage Mechanics to Power Plant Steels

Expert Workshop, Bath, 26 - 27 2017

Dr Jonathan Parker, EPRI

The concept of *lifelong learning* was tested recently when a group with over 500 years' collective experience met to discuss recent developments in, and applications of, continuum damage mechanics.

Attendees at the Continuum Damage Mechanics meeting.
Left to right: Professor Peter Flewitt, Professor Robert Ainsworth, Professor Alan Cocks, Professor David Hayhurst, Professor Peter Alberry, Professor Brian Dyson, Professor Alan Ponter, Kent Coleman, Professor Dave Dean, Dr Mike Spindler, Professor Jonathan Parker, Dr David Anderson, Dr Ian Perrin, Graham Pritchard, John Siefert and Dr Heiner Osterlin

High temperature performance of advanced alloys is complex since defects in materials developed over time, not only lead to the crack initiation and the final fracture, but also induce the material deterioration (material damage), such as decrease of strength, rigidity, toughness, stability and of residual life. Damage mechanics models have been applied to many metal alloy systems and component types and have been demonstrated to bridge structural length scales from nano- to micro- to macro-. These approaches also offer the potential to describe behaviour in simple, plain bar uniaxial tests, to complex stress states in components, to prediction of crack initiation and growth as well as weldment performance.

Discussions considered the principles and requirements that should be followed to formulate a robust and relevant creep-continuum damage mechanics constitutive model. The three key requirements which should be embodied in a suitable model were agreed:

1. **Physically Informed:**
    - Provide "physically reasonable" responses for relevant stresses and temperatures,
    - Activation energies, stress exponents and other parameters should have reasonable values,
    - State variables representing key aspects of the material response should be related to underlying physical (metallurgical) mechanisms,
    - Multiaxial forms should represent the underlying deformation and damage phenomena.
2. **Convenient Mathematics:**
    - Key features of the creep response (creep rate, rupture time, etc.) should be readily derived
    - Scalable for use in applications from simple calculations (e.g. constant stress) to complex finite element models,
    - Overall representation of the material response which can be simplified for specific cases by switching on or off features of the model.
3. **Pragmatic Approach to Data Fitting:**
    - A relevant, but minimal number of vital coefficients (consistent with physical meaning),
    - Easy-to-determine coefficients without the need to adopt complex regression,
    - Simple scaling to represent upper/lower bounds on material response by considering both strength and damage susceptibility.

In addition to discussion of a framework for model development, review presentations considered alloy specific applications of Continuum Damage Mechanics (CDM). The meeting sessions included:

1. **Metallurgical Factors** affecting high temperature performance for both Tempered Martensitic and Austenitic Stainless Steels with emphasis on:
    - Pedigree of parent metal, including documenting factors which contribute to deformation and damage,
    - Metallurgical risk factors identified relating to variability in the as-fabricated condition and which influence changes in service performance,
    - Assessment of metallurgical risk factors in multiaxial tests,
    - Characterization of damage in parent metal and cross-weld creep tests.
2. Evaluation of established **Continuum Damage Mechanics** methods and potential developments with a view to seeking a unified approach for:
    - Accommodating microstructural influences on deformation and damage,
    - Describing alloy specific susceptibilities to the initiation and growth of damage
    - Incorporation of stress state effects,
    - Assessment of validity of the selected model by considering trends in behaviour established

independently to the results used in model development.

3. **Design by Rule** compared to **Design by Analysis:**
   - Options for design-by-analysis
   - Application of design-by-analysis to susceptible component geometries
   - Complexity – balancing need and simplicity

It is apparent that the versatility of the CDM framework is particularly attractive to establishing relevant models which describe the creep behaviour of advanced steels. Particular benefits are derived for metallurgically complex steels because, for the components and loading scenarios in which they are used, there is an emerging reality that performance cannot simply be explained on the basis of strength, i.e. using deformation dominated expressions. Thus, it is apparent that creep damage susceptibility and ductility must also be understood and considered to properly mitigate the risks of fracture during service.

> "An *expert*
> is a man who has made all the mistakes which can be made
> *in a very narrow field*."
>
> Niels Bohr

FESI *Website* COMPETITION

FESI is celebrating the opening of their new website with a competition.

The FESI Council chose a photograph of the three bridges across the Firth of Forth in Scotland as one of the main images for the home page of the new website.

The bridges tell a story of success and failure in engineering structural integrity.

FESI is offering a prize of **£50** for the best brief description of this story in under 100 words. The winning description will be added to the home page.

Please send your entry, marked Website Competition, to fesi@fesi.org.uk

TAGSI/FESI Symposium 2018

Structural Integrity and Materials in Nuclear Power Plant

In Memory of
Professor John Knott OBE, FRS, FREng

18 April 2018
TWI Conference Centre
Granta Park, Cambridge, UK

Organisers

TAGSI (UK Technical Advisory Group on the Structural Integrity of High Integrity Plant) is the advisory body of industrial and academic experts that provides independent advice and peer review on structural integrity issues to the UK's nuclear industry.

Professor John Knott, Chairman from 2011, was a greatly respected, active and dedicated member of TAGSI.

http://tagsi/fesi.org.uk

FESI (UK Forum for Engineering Structural Integrity) is the membership organisation for engineering structural integrity (ESI), and disseminates best practice and new developments in ESI to academics and practitioners across industry.

www.fesi.org.uk

Major sponsor

TWI is a global leader in technology and engineering, and provides research and consultancy to its members. Respected for its expertise, professionalism, impartiality and confidentiality, TWI works with the most influential companies in all industry sectors worldwide.

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Programme

The TAGSI/FESI Symposium 2018 will offer presentations from, and an opportunity for discussion with, leading experts in the nuclear industry, and provide an overview of structural integrity issues and methodologies for current and future plant.

In TAGSI's 30th Anniversary year, the one-day event will include recent studies undertaken by the group, as well as highlighting TAGSI's role and influence over the past three decades.

To see the programme as it develops, go to www.twi-global.com/news-events/events/tagsi-fesi-symposium-2018

Registration

The registration fee for the one-day event includes:

- Lunch
- Refreshments
- Documentation
- TAGSI/FESI Symposium 2018 Workbook

To register, go to www.twi-global.com/news-events/events/tagsi-fesi-symposium-2018 (credit/debit card only)

£220 + VAT: Standard
£177 + VAT: TAGSI, FESI & ESIS members
£60 + VAT: retired persons & full-time students

Image courtesy of TWI

Sino-UK Workshop

on

ENGINEERING STRUCTURAL INTEGRITY

18 May 2017

Manchester Conference Centre, Manchester, UK

Professor Peter Flewitt introduces the Workshop

Professor Peter Flewitt chaired a Sino-UK Workshop on Engineering Structural Integrity, directly following the joint ESIA14-ISSI2017 conference.

The Workshop was convened under the auspices of FESI and CSIC (China Structural Integrity Consortium) to facilitate collaborative projects between China and UK in the field of engineering structural integrity.

The existing dynamic relationship between FESI and CSIC resulted in FESI's ESIA14 and CSIC's ISSI2017 conferences being held in conjunction in 2017. Dr Ming-Liang Zhu, representing CSIC, and John Sharples, Chief Technical Adviser, FESI, helped to arrange the meeting, which attracted more than 60 attendees.

Summaries of presentations appear below.

Sino-UK Workshop

Structural Integrity Activities: China

Dr Ming-Liang Zhu

Dr Ming-Liang Zhu of East China University of Science and Technology presented the work of East China University in the area of structural integrity, and gave an overview of funding policies in China. Dr Ming-Liang Zhu summarised the presentations from six speakers attending from China, including his own; these appear below.

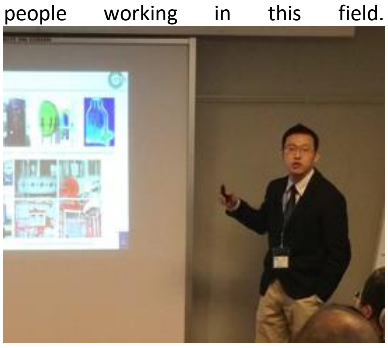
Nanjing Tech University

Professor Jianmin Gong gave a short overview of Nanjing Tech University, focusing on its history, campus, and the members of its structural integrity research group. The university has a variety of test instruments for testing and characterization, and has done a lot of

research work in the fields of pressurised equipment, including design theory based on risk for pressurised equipment, and mechanical behaviour of pressurised equipment. In structural integrity, most of their work is focused on: 1) Non-probabilistic defect assessment for pressurized equipment, 2) Fracture criterion and life prediction of fitness for service under complicated environment, and 3) Failure criterion of high temperature pressurised component with defect. The group has published work on mechanical behaviour and constitutive equation, energy and cell, and creep damage and modelling, and is supported by funding from both government and industries. Professor Jianmin Gong extended a warm invitation to attend **ISSI2018,** which will be held next year in Nanjing, China.

China Special Equipment Inspection and Research Institute

Dr Luowei Cao introduced the China Special Equipment Inspection and Research Institute (CSEI) and their work/needs in structural integrity. The CSEI is one of the most active steering bodies in China for inspection, and assessment of special equipment, such as pressure vessels, piping, boilers, elevators, and amusement devices. The organisation has a total number of 700 people working in this field.



In his presentation, Dr Luowei Cao introduced their ability for testing, analysing, assessment and inspection with sophisticated techniques, advanced software, and experienced personnel. They have a significant documentation on defect detection and damage monitoring, and are capable of evaluation of material properties by employing hydraulic bulge test and small punch technologies. The CSEI developed structural integrity assessment procedures in the case of fire damage, life prediction techniques, and structural integrity maintenance for sealing components. In recent years, they headed the initiative to apply two key projects that are supported by Chinese government, i.e., 1) a study on key technologies of risk prevention and control for pressure equipment with high parameter, 2) a study on quality inspection, evaluation and control of key static equipment in petrochemical plants. They will continue to work on this over the following 5 years. They are always seeking cooperation partners and have already had a good history of international cooperation with similar institutions around the world.

Tianjin University

Professor Xu Chen introduced Tianjin University and their work on structural integrity. Located in Tianjin, very close to Beijing, Tianjin University was founded in 1895, and is nicknamed 'the first university in China's modern history'.

Professor Xu Chen, Tianjin University's Head of the Computer Aided Reliability Engineering Lab (CARE), introduced their work on structural integrity. Their research work is mainly in 5 areas: 1) Design theory of pressure equipment, 2) Cyclic plasticity and constitutive modelling, 3) Fatigue and fracture of materials, 4) Developing fatigue test apparatus, and 5) Power electronic packaging and reliability. Their work on cyclic plastic constitutive modelling has been coded into the popular commercial software Abaqus. Their current research mainly focuses on ratcheting deformation failure mechanism and design theory of primary coolant circuit pipes of PWR, a key project funded by the National Natural Science Foundation of China, where they will finish both experiments on ratcheting of materials and piping, and complex modelling work for developing design criterion. Other researches include

safety assessment of petroleum pipeline, fatigue design of Catalyst Drain Tank in Hydrogenation. They have developed a lot of in-situ fatigue testing devices that are capable of testing using mini-samples under extremely low loading levels. They are currently collaborating with key institutions around the world in the fields of structural integrity and electronic packaging.

China General Nuclear Power Corporation

Ziping Li introduced China General Nuclear Power Corporation (CGN) and their work/needs in structural integrity**.** CGN is a leader in clean energy, with 51 subsidiaries and affiliates and 35,000 employees worldwide, focused on the development of clean energies such as nuclear power, nuclear fuel, wind power, and solar power.

CGN has over 30 years' experience in R&D and operation of nuclear power projects. At the end of April 2017, CGN's nuclear power had 20 units in operation with a total installed capacity of 21.47GW, ranking first in China and in the top five internationally. CGN, boasting a total installed capacity of 10.26 GW under construction, is the largest nuclear power constructor in the world.

CGN takes full charge of the management and organization of project design, procurement, construction and commissioning, and facilitates comprehensive management of the preliminary planning, design, financing, procurement, construction, and commissioning phases. China Nuclear Power Engineering Co. Ltd (CNPEC) is one of the core members and the first ever company specializing in nuclear power engineering management in China. CNPEC strives to be a leading NPP system integrator and special nuclear power technology provider with fully developed nuclear power construction technology.

CGN's core nuclear power technologies include HPR1000 Generation III nuclear power technology. The HPR1000 is developed in accordance with the latest safety standard with consideration of the experience of the Fukushima nuclear accident and internationally advanced design ideas. The HPR1000 has started the Generic Design Assessment (GDA) process in UK in January 2017. The reference plant for the UK HPR1000 design is CGN's Fangchenggang Plant Unit 3 in China that is under construction. CNPEC is the main driving force for UK HPR1000 GDA implementation. The demonstration of structural integrity is a key technical area for the UK GDA process.

Beihang University

Dr Dianyin Hu introduced Beihang University and their work on structural integrity. Beihang University was founded in 1952, and is the first university focusing on aeronautical and astronautical education and research in China. Dr Dianyin Hu introduced the school of energy and power engineering where one of the key research works is structure integrity.

Their research interests include: 1) Hot-section fatigue and life prediction in aero-engine, 2) Thermo Mechanical Fatigue (TMF) for a nickel-based single crystal turbine blade, 3) Crack growth behaviour for a turbine disc-blade attachment under CCF loading, 4) Probabilistic analysis and uncertainty quantification, and 5) Multiscale modelling on the composite structures and progressive damage. The school has several key labs with sufficient research facilities for aero-engine structure and strength, such as a ferris wheel CCF tester, a mechanical test system for small specimens, high temperature fatigue test machine, vibration test system, real time damage monitoring system, and a 3D strain and deformation measurement system. Their collaborators include Canada, USA, Korea, and elsewhere.

East China University of Science and Technology, and
Funding Policies in China

Dr Ming-Liang Zhu introduced East China University of Science and Technology and their work on structural integrity, and gave an overview of funding policies in China.

Located in Shanghai, East China University of Science and Technology (ECUST) has a large group of people working on engineering structural integrity. The group, headed by Prof Shan-Tung Tu, has several had achievements in recent years. They developed new theories of structural integrity, including constraint effect on fracture mechanics and its application into creep crack growth and fracture, and the investigation of fracture behaviour and mechanisms at extreme conditions. Another research area is about safety science and technology for pressurised systems, such as life prediction and design of engineering critical structures under complex loading conditions, ageing management and life extension of engineering in-service structures, and structural health monitoring technologies (on site/in-situ techniques, and damage detecting techniques at laboratory scale). In the industry 4.0 era, and the domestic *Made in China 2025* initiative, the group will continue their efforts of research in engineering structural integrity for the aerospace and nuclear power industries. This means they will have more tests and experiments on materials performance at simulated environments, more work on structural design concepts and damage monitoring techniques, and Research for Design, manufacturing, and assessment of structures in high temperature gas cooled reactors (HTGR), advanced pressurized water reactors (PWR) and fast reactor (FR).

Dr Zhu also presented several programmes that have been established in China to encourage collaborative research for Sino and UK researchers. These include the programme of China-UK Research and Innovation Bridges from the Ministry of Science & Technology, China; the programme of establishment of Uni-lab from Ministry of Education, China; and several cooperative research programs from the National Natural Science Foundation of China.

CSIC Sino-UK Workshop FESI

Coventry University MME Research Centre Strategy

Dr Bo Chen

Coventry University is implementing an ambitious new research strategy, investing over £450m in research staffing and infrastructure. The University has recruited over 300 research-active staff aligned to its newly created specialist research centres, and supported 200 funded PhD Studentships. The development of early-career researchers in establishing their own independent research career is critical to the advancement of this research strategy and we are investing in and supporting our new researchers towards this goal.

Research Groups

The following targeted research groups have been formed within the Manufacturing and Materials Engineering (MME) Research Centre at Coventry University:

- **Functional Materials** – Dr Andrew Cobley
- **Structural Integrity** – Professors Michael Fitzpatrick and Xiang Zhang
- **Magneto-Dynamics** – Sergei Molokov
- **Welding and Joining** – Professor Steve Jones
- **Metrology** – Trevor Toman
- **Materials and Mechanics** – Professor Nigel Jennett
- **Future Manufacturing** – Professor Weidong Li

Research Collaboration with Organisations and Individuals in China

- **School of Chemical Engineering and Technology** – Professor Chen, Tianjin University. Identified research topics include: (1) development of experiment-validated constitutive models for describing rachetting deformation and multi-mechanism coupling cyclic visco-plasticity and (2) in-situ fatigue and tensile-torsion testing apparatus development for electron microscopy and large-scale experimental facilities.
- **Structural Integrity Research Group** – Professor Gong, Nanjing Tech University, China, identified research topics include: (1) structural integrity and room temperature creep of titanium, and 2) study of surface strengthening, fatigue resistance and corrosion resistance of austenitic stainless steel at low temperature carburisation.
- **Beijing Key Lab of Aero-Engine Structure and Strength** – Key Researcher, Professor Hu, Beihang University, identified research topics include: (1) thermo-mechanical fatigue related structural integrity assessment for nickel-based superalloy turbine blade, and (2) multi-scale modelling of damage process on the composite structures.

Other Partnerships

Coventry University has also developed international partnerships with Australia; for example, the University is in partnership with Deakin University where 6 cotutelle PhD programmes have been launched to foster research collaboration with the clear aim of generating research impact.

Dr Bo Chen is member of the Faculty of Engineering, Environment and Computing (EEC), and sits within both the Research Centre for Manufacturing and Materials Engineering (MME) and the associated Institute for Advanced Manufacturing and Engineering (AME) – the UK's first 'Faculty on the Factory Floor', and has links with the Structural Integrity Group led by Professor Shan Tung Tu at East China University of Science and Technology.

CSIC Sino-UK Workshop FESI

Some Current Areas of UK Research in Structural Integrity

John Sharples

John Sharples presented an overview of the experimental facilities in the structural integrity division of Wood (formerly Amec Foster Wheeler). These include the high temperature water chemistry capability, the Wythenshawe AGR boiler test facility, thermo-mechanical fatigue testing and the high temperature facility alliance.

Fracture mechanics research in support of the R6 defect assessment procedures incorporates a historical perspective, as well as the basic structure and a brief overview of the procedures, and recent and ongoing tasks under the R6 development programme.

Experimental Facilities

High Temperature Water Corrosion Capability
This unique UK facility consists of 4 temperature controlled laboratories equipped with a hydrogen capability. There are versatile test rigs to best replicate plant-specific conditions at temperatures up to 360°C, 17 high temperature, pressurised water rigs with servo electric loading for crack growth testing, four interrupted load rigs for initiation testing, and four fatigue rigs using hollow specimens for simulating piping components. These test rigs enable various variables, such as materials, environment chemistry and applied loading to be investigated.

Wythenshawe AGR Boiler Test Facility
The Wythenshawe Boiler rig is owned by EDF Energy and operated by Wood. The rig is a full-scale mock-up of the main boiler passes (economiser/evaporator/super-heater) of the once-through AGR boilers. Operational feed-water faults and boiler tube chemical cleaning chemistry can be studied. The boiler tube is sectioned post-test to look for corrosion. Tests can be performed on both Serpentine and Helical AGR boilers. Over 100 Boiler Rig runs have been carried out to-date in support of the safe operation of the AGR boilers.

Thermo Mechanical Fatigue (TMF)
Wood has been involved in TMF over many years. This has been by both strain and load controlled and Radiant Lamp and Radiant Lamp Furnace heating. There are 9 test stations currently set up for TMF testing. Eight of these are for S-N data generation of featured test pieces and one-off for crack growth. In-house control software has been developed that enables real-time test monitoring, thermal cycle checking, data recording, automated test protection and 'trouble shooting' to be undertaken.

High Temperature Facility Alliance
This alliance consists of Wood, Culham Centre for Fusion Energy (CCFE), National Nuclear Laboratory (NNL), U-Battery, EDF Energy, the Universities of Bristol, Oxford and Manchester, The Open University and Imperial College London. The objectives are to establish an open high temperature materials R&D facility (located in Wood Laboratories) and to develop and deliver an exploitation plan that helps the UK play a leading role in advanced reactor technology. It has taken £2m to set up the facility and £1m matching funds from users is required over four years in order to cover operational overheads.

The facility consists of five servo-electric loading rigs for low cycle fatigue, five weight-loaded frames for measuring creep and creep crack growth, one servo hydraulic loading rig for high cycle fatigue and six fracture toughness test rigs. The test rigs can operate at 100°C at elevated pressure. They are compatible with future testing in liquid metals and are, therefore, very relevant to Generation IV reactor programmes and other reactor development projects such as the U-Battery Small Modular Reactor initiative. They are also of course relevant to the AGR fleet support and non-nuclear gas turbine support.

Fracture Mechanics Research in Support of R6 Developments
The R6 defect assessment procedures are based on a two parameter failure assessment diagram approach. One parameter describes the proximity of a flawed component to plastic collapse and the other, the proximity to linear elastic fracture mechanics fracture. The procedures stem back to as early as 1974 and the current revision, Revision 4, was first published in 2001 with updates of various sections introduced every year or so based on outcomes of the ongoing R6 Development Programme and other state-of-the-art developments in the field of fracture mechanics. The procedures consist of six chapters covering Basic Procedures, Inputs to Basic Procedures, Alternative Approaches, Compendia and Validation and Worked Examples.

The overall management of the R6 Development Programme is the responsibility of EDF Energy, and Wood has been actively involved in it for over 20 years. Other more recent participating organisations are Rolls-Royce, Frazer Nash, TWI, NRG (Netherlands), University of Manchester, NNL, Atkins, EASL and the ONR (Nuclear Regulator – as observers).

Recent and ongoing tasks include: Fracture in thin section welds; Limit load and stress intensity factor solutions for elbows; Limit loads under multi-axial loading; Treatment of secondary stresses (including elastic follow-up); Leak-before-Break; Weld residual stresses; Strain and displacement loading; Crack-tip constraint; Local approach methods; Probabilistic methods; and, Non-sharp defects.

The Universities of Bristol and Manchester and Imperial College London are also linked into R6 developments by way of feeding the results of their research studies into the programme.

John Sharples is Operations Manager (Technical) and Chief Technologist (Structural Integrity), Materials Science and Structural Integrity, Wood, and Chief Technical Advisor to FESI.

CSIC Sino-UK Workshop FESI

Cranfield University: SI and Offshore Wind Turbines

Dr Ali Mehmanparast

Cranfield University's activities with respect to the structural integrity of offshore wind turbines were introduced by Dr Ali Mehmanparast.

Offshore Wind Structural Lifecycle Industry Collaboration
The aims of the Offshore Wind Structural Lifecycle Industry Collaboration (SLIC) Joint Industry Project (JIP) and Cranfield's leading role in this project were explained.

Need for Continuous Improvement in Design and Structural integrity
The financial targets for the levelized cost of offshore wind energy in the UK and Europe were explained and the need for improving the structural design and integrity of these offshore assets were highlighted.

Cranfield-Oxford CDT in REMS
The Cranfield-Oxford joint EPSRC-funded Centre for Doctoral Training (CDT) in Renewable Energy Marine Structures (REMS) and the areas covered in this research centre (structural integrity, manufacturing and geotechnics) were presented.

Sino-UK Collaboration
Potential **collaborations** can be formed with the structural integrity group led by Professor Shan-Tung Tu at East China University of Science and Technology, Shanghai.

Dr Ali Mehmanparast is Lecturer in Structural Integrity, Centre for Offshore Renewable Energy Engineering, Cranfield University. The Centre specialises in research, design and development and techno-economic-environmental assessment of renewable energy technologies, and delivers high quality research, design and consultancy to assess and develop novel technologies particularly applied to offshore wind, wave, tidal energy.

Zentech: Engineering Structural Integrity

Dr Ramesh Chandwani

Dr Ramesh Chadwani presented Zentech International's paper, ***A 3D Crack Evolution in Weld Metal, Base Metal and the Transitional Fusion Line under a Mixed Fatigue Loading***, at ESIA14-ISSI2017. The paper, which describes some of Zentech's structural integrity capabilities, is summarised below.

A large variety of fracture resistant materials are available and employed to tolerate failure such as fatigue, creep, rupture, and so on. Yet, especially in welded structures, failure has been observed to occur in welds after a relatively low in-service life. Linear type defects in welds which are frequently detected through radiography are mostly rejected by welding codes unless the Remaining Useful Life (RUL) is precisely calculated on a case-by-case basis to justify waive or repair decisions using procedures laid out in analysis codes such as API569, BS7910 and so on. Finite Element (FE) algorithms of life prediction are authorised by codes for the case-specific life calculation of structures containing defects. However, the existing capability of predicting crack behaviour in weld and welded structures, which are the most susceptible regions to contain a defect, are limited and not well automated to be practical. These demands have led to a need for more advanced algorithms that accommodate the local effect of welding and the crack behaviour in the weld region, base metal and at the fusion line. This has been achieved by using an increasing power of computers and application of energy release rate (J-integral) for complex loading and geometries using adaptive meshing and computational mechanics techniques. The conference paper presents an example of such a capability - Zencrack Software - and explains how a weld region model can be prepared and analysed taking into account different material properties as a crack crosses a material boundary.

The example considered is a butt weld of structural steel pipe with OD = 57 mm and WT = 9.5 mm under a mixed loading of internal pressure of 0-758 bar at Low Frequency High Amplitude (LFHA) that occurs every hour and in between 644-758 bar at High Frequency Low Amplitude (HFLA) every minute. The initial crack geometry is an elliptical embedded crack and consists of a partial circumferential (0 -10 degree) Lack of Fusion defect (LOF) as noted from radiography examination. Both the pipe and weld materials have different mechanical and fracture properties and crack growth laws. The crack growth simulation is carried out until the crack opens to the external surface (leak before break).

Full details of loading, properties and 3D crack propagation analysis using Zencrack software are available in the paper, in the conference proceedings.

Zencrack: **Our Fracture Mechanics Based Software**
Zentech Software Zencrack is currently interfaced to commercially available FE Codes Abaqus, Ansys and NX-Nastran and is used by various companies in Aerospace, Mechanical, Transportation, Nuclear Power and Defence Industries for life assessment, forensic engineering and criticality analyses and studies. A number of universities and research institutions also use the software for academic research.

Zentech's Visibility in China
We have more than a 10-year presence in China, and have a consultancy and marketing arrangement with Consys Group Limited based in Shanghai. Together we have carried out a number of consultancy and training projects. Recent projects include structural assessments with Nuclear Power Institute of China (NPIC), FAD based Safety studies for Suzhou Nuclear Power Institute (SNPI), RPV fracture assessment for Shanghai Nuclear Engineering Research & Design Institute. We have also carried out a number of projects for the Commercial Aircraft Company (COMAC). All these projects have been carried out using Zencrack software. We have sold / leased copies of Zencrack software to a number of Aerospace, Transportation, Mechanical and Nuclear Power companies in China. Many academic institutions use our software for research and educational purposes. The company has links with Professor Shan-tung Tu of East China University of Science in Technology in Shanghai.

Dr Ramesh Chadwani is Managing Director of Zentech, an independent UK-based company specialising in applying advanced engineering techniques to engineering problems; their 3D crack analysis tool Zencrack is a state-of-the-art fracture mechanics capability for modelling and analysing 3-dimensional cracks, predicting their behaviour and growth under both fatigue and time-dependent loading.

Structural Integrity and Residual Stresses: TWI

Dr Guiyi Wu

Dr Guiyi Wu, TWI presented a paper at ESIA14-ISSI2017 entitled ***Effects of Residual Stresses on Engineering Critical Assessment Considering Elastic Follow-Up***. The paper is summarised below, together with Dr Guiyi Wu's exchanges with colleagues from China during the Sino-UK Workshop.

Residual stresses exist in many engineering components due to material processing, fabrication and service load history. They can be divided into membrane, bending and self-equilibrating components. The classification of these components into primary or secondary stresses depends on the level of elastic follow-up. However, it is common practice to assume that residual stresses are secondary without considering the level of elastic follow-up in the structure; it is noted that long-range residual stresses are associated with significant elastic follow-up, and therefore may be classified as primary stresses. However, there is no detail about what level of elastic follow-up is deemed to be significant, and therefore it is not clear whether a long-range residual stress should be considered to be primary, secondary or between the two. Both analytical methods and finite element modelling were performed and presented based on a three-bar structure. The level of elastic follow-up was quantified using different methods and the classification of the membrane component of residual stresses was proposed based on the elastic follow-up factor. It was demonstrated that the membrane component of residual stresses with significant level of elastic follow-up contributes to both crack driving force and plastic collapse load.

I hope that the study of residual stress in this area could contribute to the fracture/fatigue assessment standards in which more detailed guidance on elastic follow-up can be proposed.

I am personally very interested in research and application of residual stresses and their influence on structural integrity.

Xueren Wu from AVIC Beijing Institute of Aeronautical Materials presented weight function methods in the conference. After discussing with him about the application of weight function methods, he is happy to give advice and comments if needed. Weight function method is also available for accounting the contribution of residual stress to stress intensity factor of a (long) surface breaking flaw in an infinite plate in Annex Q BS 7910 standard. It would be useful if the weight functions can be made available for surface breaking flaw in pipe geometry so that the stress intensity factor arising from residual stress profile can be directly calculated.

East China University of Science and Technology also made very interesting presentations. I am looking forward to working more closely with them in the area of fracture and fatigue in low and high temperatures, possibly through NSIRC at TWI, for example.

Dr Guiyi Wu is a structural integrity specialist at TWI, Granta Park, near Cambridge. His main work in recent years has been associated with fracture mechanics and weld residual stresses.

Professor Peter Flewitt and John Sharples addressing the UK-Sino Workshop on Engineering Structural Integrity

All photos were kindly supplied by Dr Ming-liang Zhu

CSIC 中国结构完整性联盟 ESIA14 ISSI-2017 FESI

ESIA14 – FESI's 14th International Conference on Engineering Structura Integrity Assessment
in conjunction with
ISSI-2017 – CSIC's International Symposium on Structural Integrity
16 & 17 May 2017 Manchester Conference Centre, Manchester, UK

ESIA14 - FESI's 14th International Conference on Engineering Structural Integrity Assessment, and ISSI2017 - 2017 International Symposium on Structural Integrity, were held in conjunction as ESIA14-ISSI2017 in May 2017 at Manchester Conference Centre. Two Keynote papers from the conference appear below.

NUMERICAL SIMULATION OF BATTELLE PIPING SYSTEM TEST UNDER CYCLIC LOADING

Hyun-Suk Nam, Ho-Hwan Ryu, Gyo-Geun Yoon, Jong-Min Lee, Yun-Jae Kim*
Department of Mechanical Engineering, Korea University, Seoul, Korea

In this paper, an efficient numerical method using FE damage analysis is presented to simulate ductile fracture of piping systems under seismic loading. The damage model is defined based on the ductility exhaustion concept using the multi-axial fracture strain energy concept. To determine the damage model, tensile (monotonic and cyclic) test data and fracture toughness data under monotonic loading conditions are used. For validation, the proposed model is applied to simulate (1) C(T) tests under cyclic loading conditions, (2) published circumferential through-wall cracked pipe tests under cyclic loading conditions and (3) published Battelle piping system test with circumferential through-wall crack under simulated seismic loading conditions. Simulated results show overall good agreement with experimental results, providing confidence in the use of the proposed method to structural integrity assessment of cracked piping components. Effects of the piping system restraint and of compliance change due to presence of a crack in piping system on fracture behaviour are discussed.

INTRODUCTION

Recently structural integrity assessment under seismic events have been increasingly important in nuclear power plants. Seismic loading condition can be characterized by dynamic and cyclic loading. Although both loading rate and cyclic loading can affect material's tensile and 'apparent' J-resistance properties, the effect of cyclic loading mode tends to be more significant compared to that of the loading rate. For instance, it has been shown that J resistance curves are not so sensitive to the loading rate. However, in very low cycle fatigue tests simulating seismic loading conditions, 'apparent' J-resistance curves could be significantly affected by the reversal loading ratio and loading pattern, suggesting that a number of difficult tests are required for crack assessment under seismic loading condition. For this reason, it would be useful to develop a numerical tool to predict ductile fracture behaviours of piping components and systems under seismic loading conditions.

SUMMARY OF TEST RESULTS

In this section, smooth bar tensile test, fracture toughness test and piping system test were summarized, which were performed by the Battelle Institute [1]. All tests were performed at 288°C.

Material

The material tested in this experiment was A106 Gr. B carbon steel extracted from pipe with a 152mm nominal diameter.

Smooth bar tensile tests

To measure tensile properties, a smooth round bar specimen with 5.08 mm diameter and 12.7mm gauge length was extracted from A106 Gr. B. Experimental engineering stress-strain curves are shown in Fig. 1. To characterize cyclic tensile properties of A106 Gr. B, low cycle fatigue tests were performed under the strain controlled condition with 0.4% strain amplitude [1]. The stable hysteresis loop for given strain amplitude are shown in Fig. 2.

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Fracture toughness test results
The fracture toughness test under monotonic loading condition using compact tension (C(T)) specimen was performed to determine the damage model. C(T) test result under monotonic loading condition is shown in Fig. 3. Also, C(T) test under cyclic loading condition was performed to validate the damage model. Test results are shown in Fig. 4.

Pipe test results
The circumferential through-wall cracked pipe tests under cyclic loading conditions was performed to validate the determined damage model. Test results are shown in Fig. 5.

Piping system test results
Battelle piping system test with circumferential through-wall crack under simulated seismic loading conditions was also performed. Schematic of illustration of piping system test result is shown in Fig. 6. Test results is shown in Fig. 7.

DETERMINE MATERIAL PROPERTIES AND DAMAGE MODEL

Define material properties
To define cyclic material properties, the 3rd order non-linear kinematic hardening model in ABAQUS [2, 3] was adopted. Kinematic hardening coefficients were fitted from experiment results and relevant values are tabulated in Table 1. FE simulation results using these parameters were compared with experiment results as shown in Fig. 2.

TABLE 1 - Material parameters for 3rd order non-linear kinematic hardening model of A106 Gr. B.

	Isotropic hardening parameters						
	Q (MPa)				b		
A106 Gr. B	150				6		
	Kinematic hardening parameters						
	σ_o	C_1	γ_1	C_2	γ_2	C_3	γ_3
A106 Gr. B	150	110000	1000	20000	100	1000	10

Determine the damage model
The damage model is based on the multi-axial strain energy [4, 5]. The multi axial fracture strain energy, W_f, is assumed to be given in terms of stress triaxiality by the following from,

$$W_f = A\exp(-C\frac{\sigma_m}{\sigma_e}) + B \tag{1}$$

where A, B and C are material constants which can be determined by smooth and notch bar tensile test results under monotonic loading condition. Using monotonic tensile test results, the material constants were determined as below,

$$A = 2980\ ; B = 1.82\ ; C = 70 \tag{2}$$

Based on this locus, incremental damage due to plastic deformation, $\Delta\omega$, can be calculated using the following equation,

$$\Delta\omega = \frac{\Delta W_p}{W_f} \tag{3}$$

When the accumulated damage becomes critical ductile failure is assumed locally and incremental crack growth is simulated simply by sharply reducing all stress components at the gauss point. FE simulation is carried out using the multi-axial fracture strain energy model. The proper value of critical accumulated value is chosen to fit the crack initiation toughness as shown in Fig. 3. Determined critical accumulated value is 0.4 at element size=0.6mm.

VALIDATION OF DETERMINED DAMAGE MODEL

Fracture toughness prediction under LCF loading condition
Using determined damage model in previous section, C(T) tests under LCF loading condition were simulated as shown in Fig. 4. Predicted results show good agreement with experiment results for each stress ratio condition.

Ductile crack growth simulation of circumferential cracked pipe under LCF loading condition and piping system with circumferential cracked pipe
The circumferential through-wall cracked pipe tests under cyclic loading conditions was also simulated. In Fig. 5, predicted results agree overall well with experimental data in all Figures. Also, pipe system test results were simulated in Fig. 6. In Fig. 6, simulated results predict a proper crack initiation time.

CONCLUSION

The multi-axial fracture strain energy model is used to conduct the simulation for LCF loading condition. To determine the damage model, C(T) test under monotonic loading condition was used. This model was extended that theory that the fracture strain depends strongly on the triaxial stress states. Incremental damage is defined by the ratio of incremental plastic strain energy and fracture strain energy. To validate the damage model, C(T) test, cracked pipe test, piping system test were simulated. Predicted results show a good agreement with experimental data.

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FIGURES

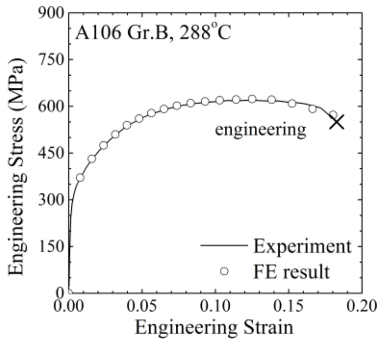


FIGURE: 1 – Comparison of experimental engineering stress-strain data with simulated results.

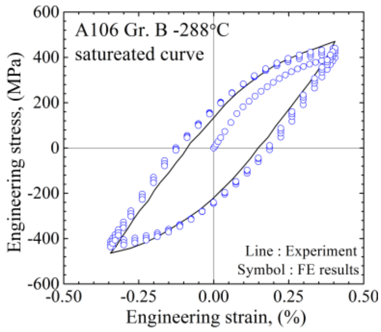


FIGURE: 2 – Comparison of experimental stable hysteresis loops with simulated results for A106 Gr. B.

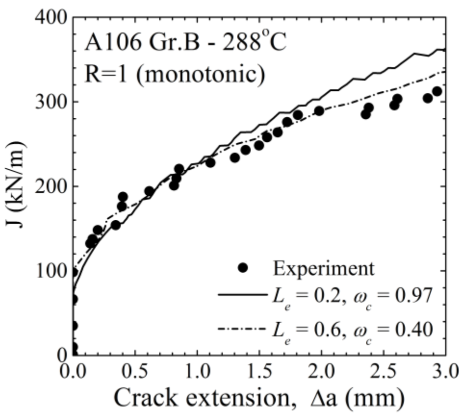
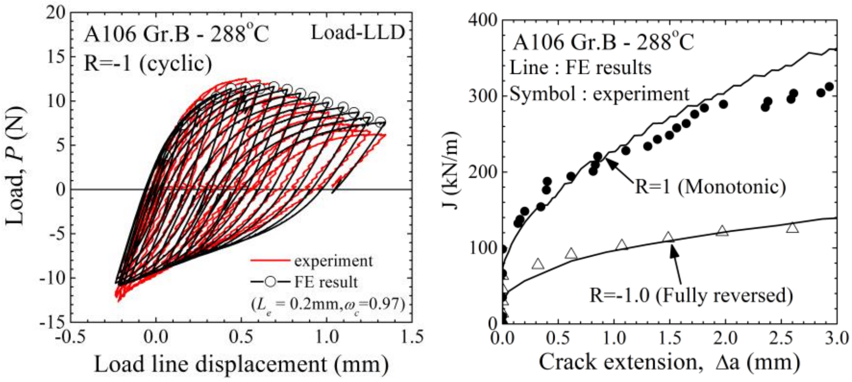
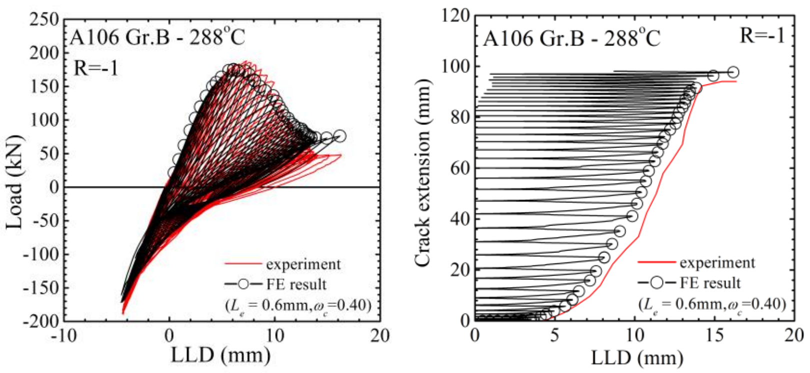


FIGURE: 3 – Comparison of experimental monotonic J-R curve with simulated results for different L_e values.



(a) (b)

FIGURE: 4 – Comparison of C(T) test data under LCF loading condition with simulated results for A106 Gr. B (a) Load-LLD, (b) J-R curves



(a) (b)

FIGURE: 5 – Comparison of pipe test data under LCF loading condition (R=-1) with simulated results for A106 Gr. B: (a) load-LLD curve, (b) crack extension (Δa)-LLD curve

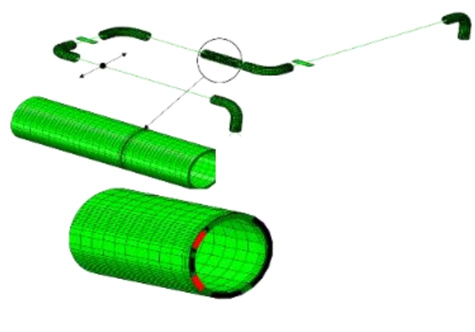


FIGURE: 6 - Schematic of illustration of piping system test

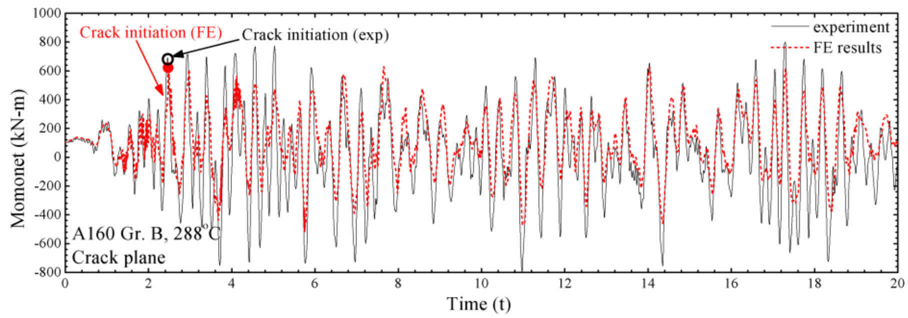


FIGURE: 7 – Comparison of piping system test data with simulated results

STRUCTURAL INTEGRITY ISSUES ASSOCIATED WITH POLYMERIC-MATRIX FIBRE-COMPOSITES AND ADHESIVE JOINTS UNDER CYCLIC FATIGUE LOADINGS

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The present paper examines crack growth in a range of structural adhesive joints under cyclic-fatigue loadings. It is shown that cyclic-fatigue crack-growth in such materials can be modelled by a form of the Hartman and Schijve crack-growth equation which aims to give a unique and linear 'master' representation for the fatigue data points that have been experimentally obtained. This relationship is shown to capture the experimental data representing the effects of test conditions, such as the R-ratio ($=\sigma_{min}/\sigma_{max}$) present in the fatigue cycle and test temperature. It also captures the typical scatter often seen in such tests, especially at low values of the fatigue crack-growth rate. Furthermore, the methodology is shown to be applicable to, and to unify, the results from Mode I (opening tensile), Mode II (in-plane shear) and Mixed-Mode I/II fatigue tests. Finally, it is used to predict successfully the rate of fatigue crack-growth in two adhesively-bonded repair-type joints where naturally-occurring disbonds have initiated and grown.

NOMENCLATURE

a	crack length
A	constant in the Hartman-Schijve crack-growth equation
da/dN	rate of crack growth per cycle
D	constant in the Hartman-Schijve crack-growth equation
G	energy release-rate (ERR)
G_{max}	maximum value of the applied energy release-rate in the fatigue cycle
G_{min}	minimum value of the applied energy release-rate in the fatigue cycle
ΔG	range of the applied energy release-rate in the fatigue cycle, as defined below
ΔG	$= G_{max} - G_{min}$
$\Delta\sqrt{G}$	range of the applied energy release-rate in the fatigue cycle, as defined below
$\Delta\sqrt{G}$	$= \sqrt{G_{max}} - \sqrt{G_{min}}$
$\Delta\sqrt{G_{th}}$	value of $\Delta\sqrt{G_I}$ at a value of da/dN of 10^{-10} m/cycle
$\Delta\sqrt{G_{thr}}$	range of the fatigue threshold value of $\Delta\sqrt{G_I}$, as defined below
$\Delta\sqrt{G_{thr}}$	$= \sqrt{G_{thr.max}} - \sqrt{G_{thr.min}}$
m	exponent
n	exponent in the Hartman-Schijve crack-growth equation
N	number of fatigue cycles
R	displacement ratio $(=\delta_{min}/\delta_{max})$
δ_{max}	maximum displacement applied during the fatigue test
δ_{min}	minimum displacement applied during the fatigue test

INTRODUCTION

Adhesively-bonded components and bonded repairs are widely used throughout the aerospace industry (Kinloch, 1983). However, given the central role that damage-tolerance assessment and analysis plays in the design and certification of modern aerospace structures and bonded repairs (Miedlar et al. 2003), it is imperative to understand their cyclic-fatigue behaviour. Further, it is important to have a sound, and validated, means for accounting for the effects of test conditions, such as the *R*-ratio, test temperature and type of loading, and the inherent variability, and hence scatter, seen in the fatigue performance of structural adhesives.

The above comments have recently been reinforced by the recent approach from the US Federal Aviation Administration (FAA 2009). Until recently, certification of adhesively-bonded aircraft structures was based on a 'no growth' design philosophy. However, in 2009 the FAA introduced a slow growth approach to certify composite and adhesively-bonded structures and adhesively-bonded repairs. The precise wording given in FAA Advisory Circular 20-107B is:

> *"The traditional slow growth approach may be appropriate for certain damage types found in composites if the growth rate can be shown to be slow, stable and predictable. Slow growth characterization should yield conservative and reliable results. As part of the slow growth approach, an inspection program should be developed consisting of the frequency, extent, and methods of inspection for inclusion in the maintenance plan."*

Unfortunately, a lack of understanding of, and an inability to predict, the disbond growth, especially for disbonds that arise from small naturally-occurring material discontinuities, is an obstacle that hampers the use of this approach.

The measurement and predictive methods developed so far (e.g. Ripling et al. 1963, Jethwa and Kinloch 1997, Curley et al. 2000, Pascoe et al. 2013, Azari et al. 2014) have been largely based upon the principles of linear-elastic fracture-mechanics (LEFM). Nevertheless, the use of fracture-mechanics methods for design and life-prediction studies for structural adhesives still represent relatively new areas of research and have yet to be widely adopted by design engineers (Kinloch and Young 1983). Current fracture-mechanics approaches to crack growth in structural adhesive joints are based on variants of the Paris crack-growth equation, where the rate of crack growth per cycle, da/dN, is assumed to be linearly related to either $(G_{max})^m$ or $(\Delta G)^m$. Here G_{max} is the maximum value of the applied energy release-rate in the fatigue cycle and ΔG is the range of the applied energy release-rate in the fatigue cycle $(=(G_{max} - G_{min}))$. However, several major problems have been found to arise with this approach of using either ΔG or G_{max} as the 'crack driving force (CDF)'.

First, unfortunately, the value of the exponent, m, in this relationship tends to be relatively large for structural adhesives (and fibre-composite materials). Secondly, fatigue crack growth may be initiated from relatively small naturally-occurring material discontinuities, and be more rapid than predicted from experimental data obtained from relatively 'long-crack' tests. Thirdly, how to account for typical scatter that is observed in the experimental fatigue tests is a challenge. Fourthly, how to account for, and model, the effects of the particular test conditions, such as the R-ratio employed, the test temperature and the mode of loading, has yet to be resolved. The present paper (Kinloch et al. 2016) presents a study of the use of the Hartman-Schijve approach, which is a variant of the 'Nasgro' method, to model and predict fatigue crack-growth in structural adhesives in order to overcome the aforementioned problems.

THEORETICAL BACKGROUND

More recently, work has shown (Rans et al. 2011, Jones et al. 2012, Jones et al. 2014, Jones et al. 2014a, Jones et al. 2015, Jones et al. 2016, Ishbir et al. 2014, Simon et al. 2017) that, to describe the Mode I cyclic-fatigue behaviour of adhesive joints and polymeric fibre-composites, the term $\Delta\sqrt{G_I}$ should be employed as the CDF. Thus, the form of the Hartman and Schijve equation (Hartman and Schijve 1970) becomes, for Mode I (tensile-opening) loading,

$$\frac{da}{dN} = D\left[\frac{\Delta\sqrt{G_I} - \Delta\sqrt{G_{Ithr}}}{\sqrt{\{1 - \sqrt{G_{Imax}}/\sqrt{A}\}}}\right]^n \quad (1)$$

where D, n and A are constants and where the term $\Delta\sqrt{G_I}$ is defined by,

$$\Delta\sqrt{G_I} = \sqrt{G_{Imax}} - \sqrt{G_{Imin}} \quad (2)$$

$$\Delta\sqrt{G_{Ithr}} = \sqrt{G_{Ithr.max}} - \sqrt{G_{Ithr.min}} \quad (3)$$

and the subscript '*thr*' in Equations (1) and (3) refers to the values at threshold, such that $\Delta\sqrt{G_{Ithr}}$ represents the range of the fatigue threshold value as defined by Eqn. (3). Now, for structural adhesives, it is often found from experimental tests (Jethwa and Kinloch 1997, Curley et al. 2000, Kinloch et al. 2000, Ashcroft and Shaw 2002, Azari et al., 2010) that a clearly defined threshold value exists, below which little fatigue crack-growth occurs. In this case, the value of the threshold $\Delta\sqrt{G_{Ithr}}$ is taken to be the experimentally-determined value. If this is not the case, then the concepts described in the ASTM standard (ASTM 2013), which are widely used by the metals community, may be employed. This standard defines a threshold value which, in the above terminology, may be taken to be the value of $\Delta\sqrt{G_I}$ at a value of *da/dN* of 10^{-10} m/cycle. This is termed $\Delta\sqrt{G_{Ith}}$ and hence, by rearrangement of Eqn. (1), the value of $\Delta\sqrt{G_{Ithr}}$ is given by,

$$\Delta\sqrt{G_{Ithr}} = \Delta\sqrt{G_{Ith}} - \sqrt{\{1 - \sqrt{G_{Imax}}/\sqrt{A}\}}\left[\frac{10^{-10}}{D}\right]^{1/n} \quad (4)$$

Considering the parameters in the above equations then the value of $\Delta\sqrt{G_{Ithr}}$ is experimentally measured for those adhesives where a clearly defined threshold value exists, below which little fatigue crack growth occurs. If this is not the case, then it is calculated via Eqn. (4) above. As previously discussed (Jones, 2014a), the value of A is the quasi-static adhesive fracture energy, or a parameter chosen so as to fit the experimentally-measured *da/dN* versus ΔG_I (or G_{Imax}) data. Finally, it should be noted that adhesive joints can also undergo fatigue crack-growth under Mode II (in-plane shear) loading and Mixed-Mode I/II loading, and then the energy release-rate, G, carries the appropriate subscript.

RESULTS

As an example, the experimental Mode I and Mode II data (Ripling et al. 1988, Russell 1988) for a structural epoxy-film adhesive (i.e. FM-300K from Cytec, USA) are shown plotted in Fig. 1 according to Eqn. (1). Here log (*da/dN*) through the adhesive layer is plotted against log $\left[\frac{\Delta\sqrt{G} - \Delta\sqrt{G_{thr}}}{\sqrt{\{1 - \sqrt{G_{max}}/\sqrt{A}\}}}\right]$, where the corresponding Mode I and Mode II values are employed as appropriate. The values of A and $\Delta\sqrt{G_{thr}}$ have been calculated, as described above, from the individual experimental data. It should be noted that, for each mode of loading, the values for the constants D and n in Eqn. (1) have been taken to be the same for all the tests, as shown in Tables 1 and 2. Now, Fig. 1 reveals that, for both Mode I and Mode II loading, the various effects of mode of loading, R-ratio and temperature-dependence essentially collapse onto a single 'master' linear plot when Eqn. (1) is employed to represent the fatigue data. Further, the slope, n, of the 'master' linear relationship has a relatively low value of about two, and the associated scatter of the data is also relatively low.

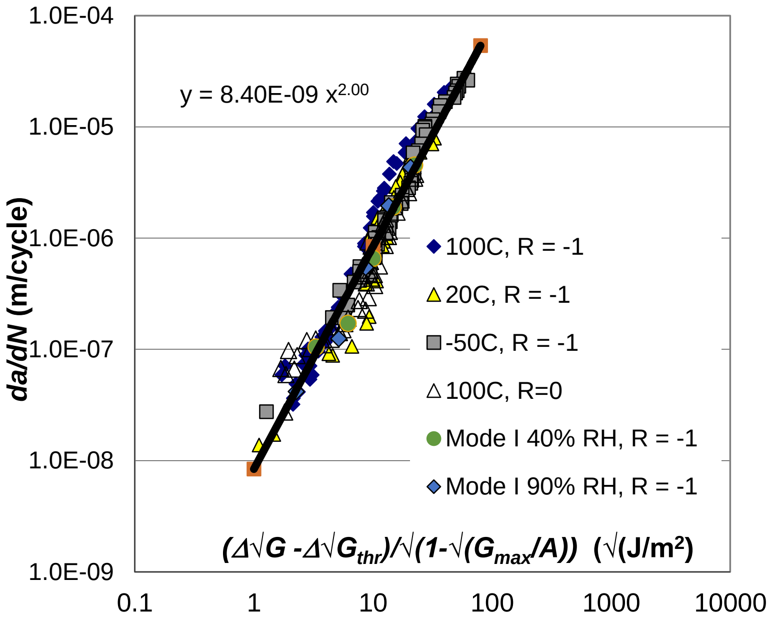

Figure: - 1 The Hartman-Schijve representation of the Mode I and Mode II fatigue behaviour for the epoxy-film adhesive 'FM300K'.

TABLE 1. Values of the parameters employed in the Hartman and Schijve Eqn. (1) for Mode I crack growth in the 'FM300K' adhesive.

Test	*D* (m/cycle)	*n*	*A* (J/m^2)	$\Delta\sqrt{G_{Ithr}}$ (√(J/m^2))
40% RH	8.40 x 10^{-9}	2.00	630	9.8
80-90% RH	8.40 x 10^{-9}	2.00	630	10.5

TABLE 2. Values of the parameters employed in the Hartman and Schijve Eqn. (1) for Mode II crack growth in the 'FM300K' adhesive.

Test	*D* (m/cycle)	*n*	*A* (J/m^2)	$\Delta\sqrt{G_{IIthr}}$ (√(J/m^2))
100^{o}C & R = -1	8.40 x 10^{-9}	2.00	975	12.5
20^{o}C & R = -1	8.40 x 10^{-9}	2.00	1200	14.1
-50^{o}C & R = -1	8.40 x 10^{-9}	2.00	1500	15.5
100^{o}C & R = 0	8.40 x 10^{-9}	2.00	2700	10.0

Now, these results may be coupled with a finite-element analysis (Hu et al. 2016) of an adhesively-bonded component or structure (using the appropriate adhesive) and so be used to model and predict the rate of fatigue crack-growth in the adhesive layer. In the present paper, two examples have been selected which consist of different designs of adhesively-bonded joints where naturally-occurring disbonds have been allowed to initiate and grow under cyclic-fatigue loading in: (i) a symmetrical double over-lap adhesively-bonded specimen (Cheuk et al. 2005) and (ii) an asymmetrical adhesively-bonded doubler joint (Pascoe et al. 2013a). Both designs are typical of adhesively-bonded repairs. It has been found that, in both cases, the use of the Hartman-Schijve equation, coupled with the finite-element analysis, gives rise to computed crack length, a, versus number, *N*, of fatigue-cycle histories that are in very good agreement with the experimental measurements, as shown for example in Fig. 2.

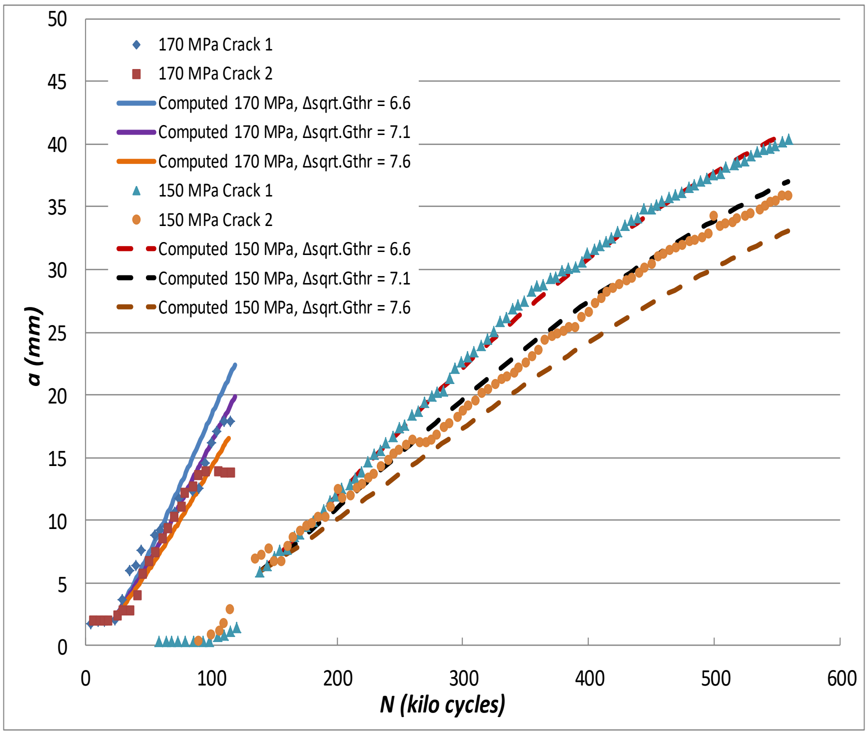

FIGURE: - 2 The measured (Pascoe et al. 2013a) and predicted crack growth, a, histories for the initial naturally-occurring defects growing in the adhesive layer under cyclic-fatigue loading in the asymmetrical double over-lap adhesively-bonded specimens. (The values of $\Delta\sqrt{G_{Ithr}}$ ($\sqrt{}$(J/m^2)) used represent the mean and the standard deviation values, which were measured experimentally. Results are shown for both the 150 MPa and the 170 MPa maximum fatigue stress levels that were employed.)

CONCLUSIONS

The exciting potential for the Hartman-Schijve approach, which is a variant of the 'Nasgro' method, to unify many aspects of the cyclic-fatigue crack-growth behaviour that have been observed in structural adhesive joints have been described. In particular:

- A 'master' linear representation has been observed for each adhesive studied when such data are replotted according to the Hartman-Schijve approach, i.e. Eqn. (1).
- The variability, and hence the scatter, which was observed in the typical plot of log *da/dN* versus log ΔG_I (or G_{Imax}) from testing replicate specimens, has been captured by varying only the fatigue threshold term, $\Delta\sqrt{G_{Ithr}}$, in the Hartman-Schijve equation; with the value of $\Delta\sqrt{G_{Ithr}}$ being ascertained either via direct measurement or as calculated from Eqn. (4). Indeed, the degree of scatter associated with the Hartman-Schijve 'master' linear relationships was always found to be relatively low, as observed by the relatively high values of the correlation coefficients that were deduced.
- Having ascertained the constants in the Hartman-Schijve equation, it has been found that the complete curve for the experimentally-measured results (i.e. typically of the form *da/dN* versus G_{max} or ΔG) could be computed with a relatively high degree of accuracy.
- The Hartman-Schijve approach may account for both *R*-ratio and test temperature effects, again yielding a unique 'master' linear relationship which captures these effects.
- The Hartman-Schijve approach was found to be applicable to Mode I, Mode II and Mixed-Mode I/II types of fatigue loading. Indeed, it has been demonstrated that both the Mode I and the Mode II fatigue behavior for an adhesive may be conveniently described by a single, unique, 'master' linear relationship via the Hartman-Schijve approach.
- Finally, the Hartman-Schijve approach has been used to predict the crack-growth histories under cyclic-fatigue loading in two adhesively-bonded repair-type joints, where naturally-occurring disbonds were allowed to initiate and grow. The agreement with the experimental results was very good, and the typical scatter that is observed in the experimental fatigue tests was also captured.

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FESI Congratulates the Winners of the Keith Miller Prize

for the Best Student Presentation or Paper at an ESIA Conference

A prize in honour of the late Professor Keith Miller, a world-leading expert in ESI, is awarded for the best paper or presentation given by a student at an ESIA conference. At ESIA14-ISSI2017 the Keith Miller Prize was awarded to two students:

De-Qiang Wang, East China University of Science & Technology, *In-situ observation and numerical modelling of crack-inclusion interaction behaviour under cyclic loading*

Geena Raitt, Imperial College London, *The Effect of a Low Constraint Geometry on Fracture Parameters for a Nuclear Reactor Pressure Vessel (RPV) Steel*

De-Qiang Wang's paper appears below. Geena Raitt's paper will appear in 2018.

IN-SITU OBSERVATION AND NUMERICAL MODELLING OF CRACK-INCLUSION INTERACTION BEHAVIOUR UNDER CYCLIC LOADING

De-Qiang Wang, Ming-Liang Zhu*, Fu-Zhen Xuan, Shan-Tung Tu

Key Laboratory of Pressure Systems and Safety, Ministry of Education, School of Mechanical and Power Engineering, East China University of Science and Technology, Shanghai 200237, China

The interaction between cracks or micro-defects has been well investigated and incorporated in several engineering structural integrity assessment codes and standards. However, the interaction between a fatigue crack and an inclusion is often assumed similar to the case of crack-crack, and little research work has reported the exact influence. In this study, in-situ experimental observation of a fatigue crack and an inclusion in a low alloy steel under cyclic loading was conducted to figure out how the inclusion would affect the fatigue crack growth behaviour. Digital image correlation technique and finite element modelling were used to characterise the variation of strain distribution and plastic zone when the growing fatigue crack approaches the inclusion. It was found that the interaction effect of fatigue crack and inclusion appeared when the distance between them was less than 10μm, as evidenced by increased fatigue crack growth rate and decreased plastic zone size. After coalescence of the crack and inclusion, cyclic strain was accumulated around the inclusion and a new crack was then initiated when the strain reached about 3.5%.

Keywords: In-situ fatigue; crack growth; inclusion; finite element modelling; digital image correlation; strain accumulation

INTRODUCTION

Metallic materials or composite materials always contain defects in different types and sizes. Micro-defects, including pores and inclusions, play an important role in fatigue initiation in high cycle and very high cycle fatigue (VHCF) regime [1, 2]. On the other hand, defects could have a retardation effect during fatigue crack propagation [3], based on which some crack growth retardation methods were proposed [4].

The interaction between micro-defects has been well investigated and incorporated in several engineering structural integrity assessment codes and standards [5]. However, the interaction between a fatigue crack and an inclusion is often assumed similar to the case of crack-crack, and little research work has been reported the exact influence. Most of research work up to now related to crack-inclusion interaction were based on theoretical and numerical simulation [6, 7], focusing on the equations of stress intensity factor. Little work reported the crack-inclusion interaction by experimental method, due to difficulty in either limited access of experimental apparatus or having both crack and inclusion at the same time. The traditional deformation measurement methods, e.g. extensometer, strain gage, are not as useful as the full field deformation measurements. Savalia et al. [8] obtained the surface deformations in the vicinity of a crack-inclusion using moiré interferometry in composite materials and the de-bonding process between the inclusion–matrix pair was successfully mapped by recording crack opening displacements. Recently, Hao et al. [9] investigated the effect of the inclusion on the angular deflection fields, and the stress intensity factor at the crack tip was analysed by digital gradient sensing method. However, the existing experiments mentioned above are under quasi-static loading conditions. The crack-inclusion interaction effect under fatigue loading is rarely investigated.

In this work, in-situ experimental observations of a fatigue crack and an inclusion in a low alloy steel under cyclic loading was conducted to figure out how the inclusion would affect the fatigue crack growth behaviour. Digital image correlation technique and finite element methods were used to characterise the variation of strain distribution and plastic zone size before and after the coalescence of crack and inclusion.

MATERIAL AND EXPERIMENTAL METHOD

Materials and Microstructures

The material investigated was cut from the heat affected zone of a welded joint of a Ni–Cr–Mo–V steel, which was welded by the submerged arc welding (SAW) technique. Prior to welding, the base metal has undergone quenching and tempering processes. After welding, a post weld heat treatment (PWHT) was carried at 620°C for 10 h. Moreover, the welds were subjected to an artificial aging at 350°C for 3000h to simulate the long-time service condition. The chemical composition (in wt.%) of the material mainly consists of: C 0.25, Mn 0.29, Ni 3.56, Cr 1.71, Mo 0.38, V 0.09 and Fe as the balance. The yield stress and ultimate stress are 835.5 MPa and 938 MPa, respectively. The heat affected zone consists of three zones: fully quenched-tempered zone (FQTZ), partially quenched-tempered zone (PQTZ) and tempered zone (TZ) [10]. In this work, the crack was placed in the PQTZ which was found to be the weakest fatigue performance zone in our previous work [11]. Fig. 1 shows microstructures of PQTZ which mainly consists of martensites and bainites.

Specimen preparation

Standard CT specimen with a /W ratio of 0.5 and a thickness B of 16mm were firstly prepared and then pre-cracked using high frequency fatigue testing machine. The initial notch tip was placed in the PQTZ. The stress intensity factor range ΔK during the pre-cracking process was decreased from 15 MPa·m$^{1/2}$ to 13.5 MPa·m$^{1/2}$ during which the fatigue crack extended for about 1.5 mm. The pre-crack process was terminated when the total pre-crack length reached 3 mm. Several miniature specimens with a gauge cross-section of 0.5×2.5 mm^2 and a gauge length of 8 mm were then cut from the CT specimen by Electrical Discharge Machining (EDM) technique. The specimen for in-situ SEM fatigue test was thus prepared with a pre-crack length of 0.63 mm. The shapes and dimensions of the standard CT specimen and a small size fatigue specimen are shown in Fig 2.

A round inclusion is embedded in the matrix in front of crack tip, as shown in Fig. 3. The diameter of this inclusion is about 4.7μm and the initial distance from crack tip to inclusion centre is about 25.4 μm. Interrupted test was conducted to take images for correlation in DIC and crack growth rate measurement.

In-situ fatigue test

The well-prepared specimen was mounted on the micro-tensile tester (Deben) and put into the scanning electron microscopy. The initial stress intensity factor range and stress ratio were set as 14.5 MPa·m1/2 and 0.5, respectively. The test was interrupted every 50-200 cycles to take images for correlation and crack growth rate measurement. The resolution of each image is 1024×768 pixels, and the magnification was 5000X. The test was terminated when the crack propagated through the inclusion and the CGR returned to the initial level.

Strain measurement

Digital image correlation technique was employed to calculate the full-field strain distribution, including crack tip and inclusion, based on the commercial software (VIC-2D 2009, Correlated Solutions). Image taken at un-deformed condition was set as reference image, and deformed images were targeted ones. Suitable parameters such as subset size and step size were determined by error analysis in our previous work [12] and selected to be 25 pixels and 5 pixels, respectively, to have a relatively good resolution for strain measurement.

RESULTS AND DISCUSSION

Crack growth rate measurement

Crack growth rate was measured per 200 cycles and plotted against the ratio of crack growth length a to initial distance between crack tip and inclusion centre a0, as shown in Fig. 4. It should be noted that the distance calculated here is the average value of start and ended distances in each step. According to the variation of FCG rate, the entire curve can be divided into four zones: non-interactive effect zone, interactive effect zone, crack re-initiation zone and recovery zone. It can be seen that the crack growth rate was at the average level in the non-effective zone. Then, it increased gradually with the distance between crack and inclusion decreasing until the coalescence of crack and inclusion. After that, the FCGR decreased sharply due to the crack re-initiation. After the crack re-initiation, the crack growth rate gradually recovered to the previous level.

Crack growth morphology

Fig. 5 shows the crack growth morphologies before the coalescence of crack and inclusion and corresponding strain distribution based on DIC measurement. All the SEM images shown here are taken at maximum load. The crack extended in a zigzag way. When the distance between crack tip and inclusion was about 10μm, the crack deflected to the inclusion, indicating the effect of inclusion on crack growth behaviour. The strain distribution near crack tip is varied with the distance Δd between crack tip and inclusion. When Δd=10μm, the crack tip plastic zone is classical bean-shaped, and little deformation occurred around the inclusion. However, the plastic strain decreased considerably when Δd=2 μm, indicating that the inclusion had a strong effect on crack tip deformation.

Strain calculation by finite element method

A simple linear elastic model was built to calculate the of strain variation with distance between crack tip and inclusion. Mesh refinement was conducted around crack tip and inclusion. The plastic zone was determined as area where stress is larger than yield stress. The results were shown in Fig. 6. It can be seen that the plastic zone size keeps constant, while the highly concentrated stress zone decreases with the increasing of crack length, which to some extent is in accordance to experimental results.

Strain accumulation and crack re-initiation

After the coalescence of crack and inclusion, it took about 200 cycles for crack re-initiation. Four images were taken, and the corresponding strain maps were obtained by DIC, as shown in Fig. 7. The interval of every adjacent image was 50 cycles. It is obvious that the strain accumulated with the increase of number of cycles. The strain values at the crack initiation site was extracted and plotted with the number of cycles, as shown in Fig. 8. It is observed that the critical strain for crack initiation from the inclusion is estimated to be around 3.5%. It should be noted that the strain calculated here is not an absolute value but a relative one as the stress ratio was 0.5. The curve plotted here just indicated the strain accumulation process.

CONCLUSIONS

In this study, in-situ SEM technique and Digital Image Correlation (DIC) were combined to study the interactive effect between fatigue crack and inclusion for the first time to our knowledge. Crack growth rate and morphology were observed by SEM and the full field strain was mapped by DIC. The main conclusions are summarized as follows:

- According to the variation of FCG rate, the crack inclusion interaction process can be divided into four zones: non-interactive effect zone, interactive effect zone, crack re-initiation zone and recovery zone.
- The interaction effect of fatigue crack and inclusion appeared when ratio of crack growth length to initial distance between crack and inclusion a/a0=0.48, as evidenced by increased fatigue crack growth rate and decreased plastic zone size.
- Inclusion has a retardation effect on fatigue crack growth as crack re-initiation takes hundreds of cycles. The critical strain measured for crack re-initiation in this condition was about 3.5%.

ACKNOWLEDGEMENT

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FIGURES

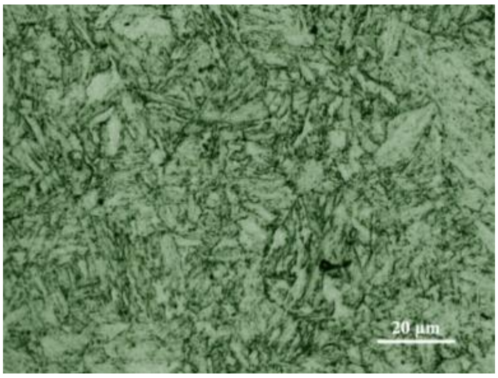

FIGURE: 1 - The microstructure of partially quenched-tempered zone

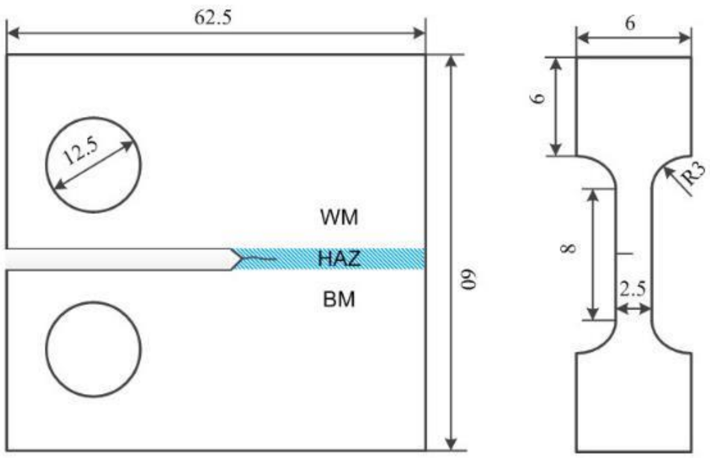

FIGURE: 2 - The shape and dimensions of standard CT specimen (left) and miniature fatigue specimen (right)

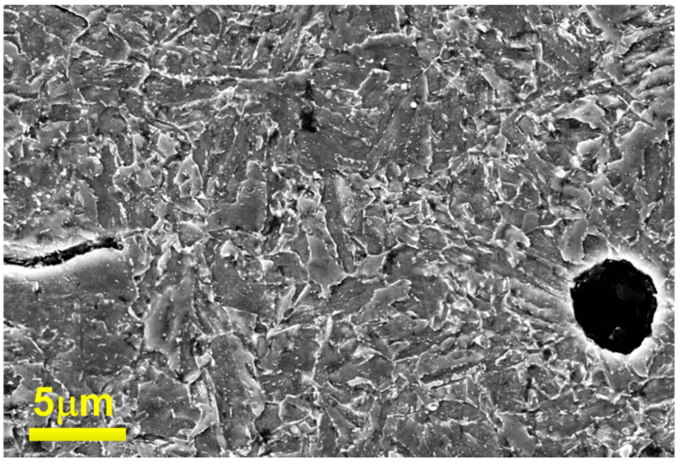

FIGURE: 3 - The initial positions of crack tip and inclusion

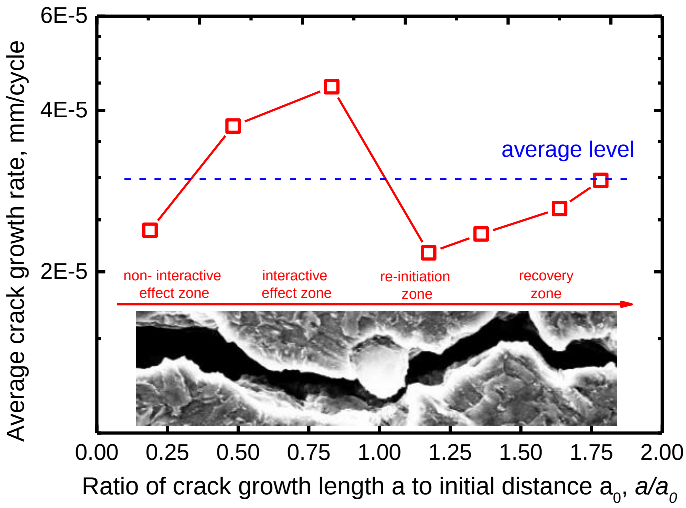

FIGURE: 4 - The crack growth rate variation with ratio of crack growth length to initial distance between crack and inclusion

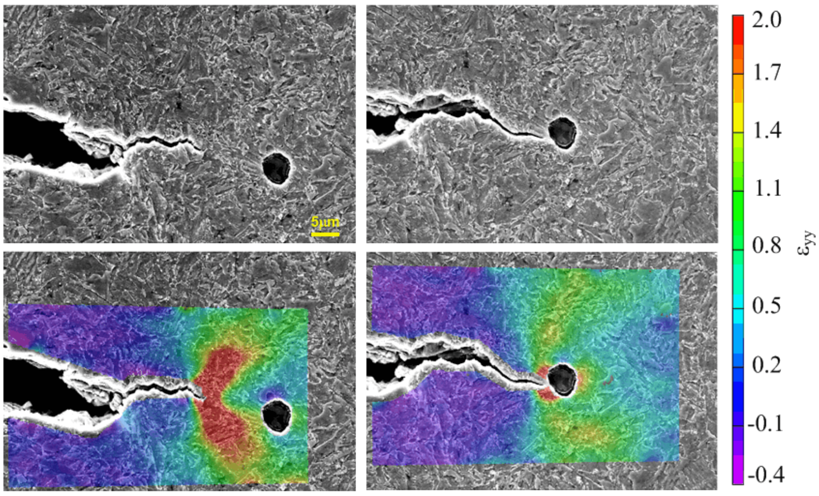

FIGURE: 5 - The crack growth morphology and corresponding strain map before the coalescence of crack and inclusion

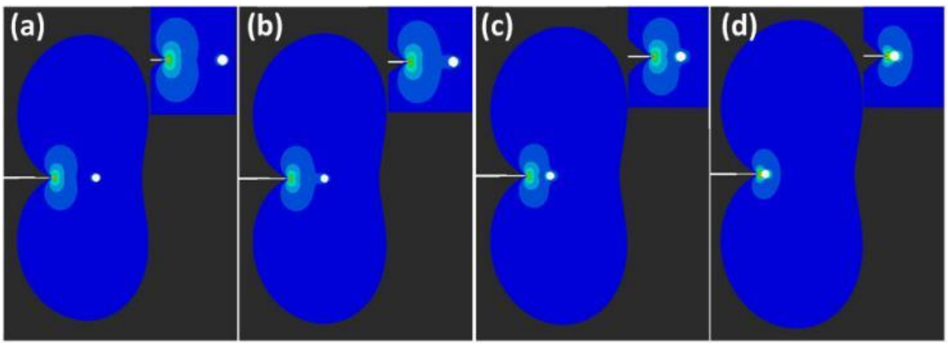

FIGURE: 6 – The crack tip strain variation with different distance between crack and inclusion (a/a_0=0, 0.19, 0.48, 0.83 for (a), (b), (c), (d), respectively; the inserted images are magnified views of stress distribution around crack tip)

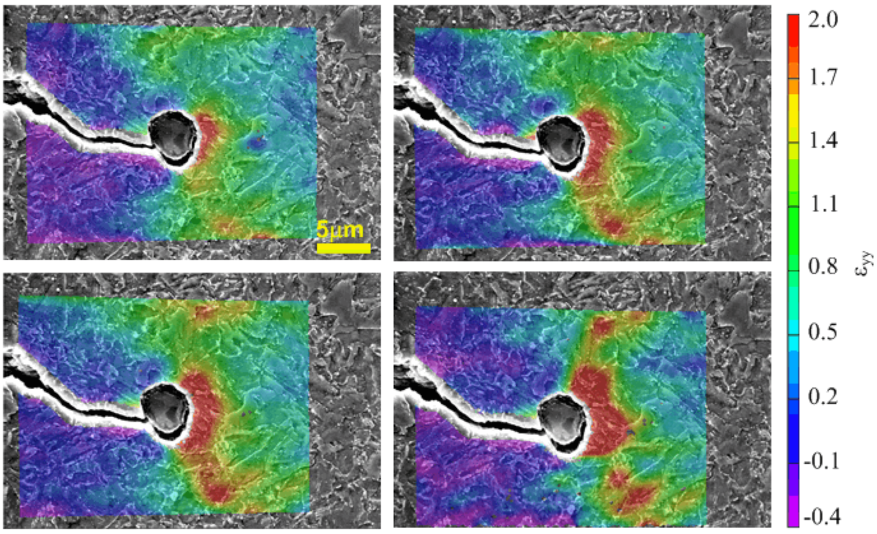

FIGURE: 7 - The maps of strain evolution around the inclusion during the crack re-initiation period

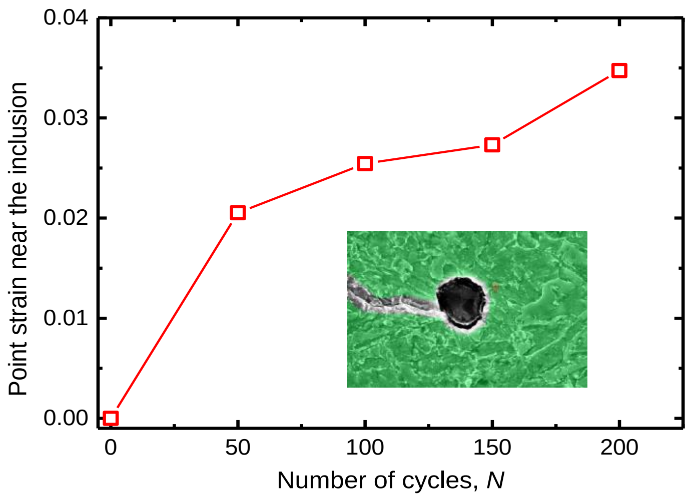

FIGURE: 8 - The strain evolution around the inclusion during the crack re-initiation period

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FESI thanks Dr Ming-liang Zhu for capturing ESIA14-ISSI2017 in photographs.

Professor Shan-Tung Tu, Chairman, CSIC

ESIA14-ISSI2017 is opened in Manchester on 16 May 2017

Dr Brian Tomkins, Chairman, FESI

ESIA14-ISSI2017 delegates

Professor Tu and Dr Tomkins with delegates at a refreshment break

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Key responsibilities:

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Role requirements:

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- Previous experience of engineering consultancy would advantageous.
- Be able to gain security clearance required for working on civil nuclear and on naval nuclear tasks and programmes.

Core Materials Consultant, Ref: 19609

Our Structural Performance Team, based at our Birchwood Park office near Warrington in Cheshire, comprises a broad range of multi-disciplinary technical experts spanning metallurgy, materials science, corrosion science, structural integrity analysis, structural and mechanical engineering and advanced manufacturing processes.

We currently have an opportunity for a Core Materials Consultant to join our team, providing a key role in this vital national defence programme, including supporting the Continuous At Sea Deterrent. Specifically, this role is associated to the core materials of nuclear naval plant and is an opportunity to support the UK submarine programme in relation to structural integrity to support in-service operation, manufacture, plant-life extension and next generation concept design.

Key responsibilities:

Provide independent safety, engineering and technical advice to the Ministry of Defence on core materials associated to nuclear propulsion and design.

- Perform a review of nuclear safety cases in line with regulatory requirements.
- Have active involvement in appropriate safety review groups and meetings.
- Interaction with related in core material Research & Technology programmes.
- Interface with key stakeholders, internal and external.

Role requirements:

We are seeking applicants who can apply theoretical concepts, together with practical skills and knowledge, to challenging

- Professional Institution accredited Degree or Post Graduate qualification in a scientific or engineering discipline.
- Experience/familiarity associated to structural integrity and the manufacture, construction and operation of nuclear plant components and their underlying safety cases, including materials behaviour in hostile in-reactor environments.
- An ability to understand, deliberate and assimilate structural integrity safety case arguments, clearly and concisely, based upon knowledge.
- Strong communication skills both written and oral.
- A willingness to work on defence related tasks.
- Essential that the post holder is or can be Security Cleared.

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To apply for these roles please go to **https://www.woodplc.com/careers** and follow the links for roles that were formerly with Amec Foster Wheeler.

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April 24 - 26

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All registrations include attendance at the three-day events, plus a digital membership to the interactive ARDC Europe community. Additional benefits include:

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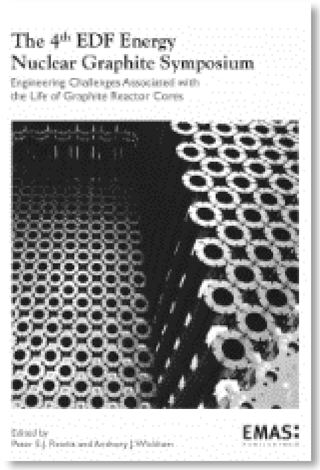

Selected Papers from the 4th EDF Energy Nuclear Graphite Symposium

ENGINEERING CHALLENGES ASSOCIATED WITH THE LIFE OF GRAPHITE CORES

May 6th–9th 2014, The National College, Nottingham, UK

Edited by: P.E.J. Flewitt and A.J. Wickham

Contents:
- Foreword, J. Reed, Head of AGR Graphite Core Safety Case and Lifetime, EDF Energy
- Assessment
- Engineering Models
-
- Inspection and Monitoring
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- IMechE member rates for all events jointly organised by IMechE and FESI
- A certificate of attendance that counts towards CPD targets

To find out more about FESI's CPD and training events, email john.sharples@fesi.org.uk

2017			
Design Engineering November Lecture	20 November	London	imperial.ac.uk
Seminar: Durability, Reliability and Fatigue	21 November	Rotherham	hbmprenscia.com/amct
Kuwait Corrosion Conference	21 November	Kuwait	twi-global.com
Forensic Engineering: Technical Lecture	21 November	Leamington Spa	events.imeche.org
Mining for Wimps	22 November	London	imperial.ac.uk
Technology Day: Introduction to Reliability Engineering, Fatigue and Vibration	22 November	Rotherham	hbmprenscia.com/amct
Pipelines: Cost Reduction and Integrity Management – Oil & Gas Technical Group	22 November	Aberdeen	twi-global.com
IMEE – Innovation I Materials for Extreme Environments	22-24 November	Huddersfield	npl.co.uk
TC11 Meeting	23 November	Swansea	structuralintegrity.eu
Stainless Steel World Conference & Expo 2017	28 November	Maastricht	twi-global.com
Training Course: The Role of Structural Integrity in Plant Operation and Life Extension	28 November	Warrington	fesi.org.uk
Nuclear Ventilation 2017 Conference	28-29 November	Manchester	events.imeche.org
Fatigue Design 2017	29-30 November	Senlis, France	gruppofrattura.it
Imperial Fringe: Walking in the Air	5 December	London	imperial.ac.uk
Joining Dissimilar Metals for Applications in Heavy Engineering	6 December	TWI	twi-global.com
Internal Combustion Engines Conference	6-7 December	Birmingham	events.imeche.org
Behaviour Change: Achieving Health & Safety Culture Excellence	6-7 December	London	hsl.gov.uk
DSEAR Compliance for Managers and Supervisors	12 December	Buxton	hsl.gov.uk
Laser Welding in Manufacturing	13 December	TWI	twi-global.com
2018			
TC8 Meeting	14-15 January	Paris	structuralintegrity.eu
COMAH Technical Aspects of COMAH Safety Reports	23-24 January	HSL, Buxton	hsl.gov.uk
DSEAR Controlling Dust Explosion Risks	24 January	HSL, Buxton	hsl.gov.uk
COMAH Onshore Major Hazards: New Knowledge on Flammable Hazards	27 February	HSL, Buxton	hsl.gov.uk
TC1 Meeting	12-13 April	Prague	structuralintegrity.eu
TAGSI-FESI Symposium 2018 – Structural Integrity and Materials in Nuclear Power Plant	18 April	TWI, Cambridge	Enquiries: becki.parratt@twi.co.uk
2018 EU ARDC – Applied Reliability and Durability Conference	24-26 April	Copenhagen	ardconference.com
TC9 Meeting	10-11 May	Torino	structuralintegrity.eu
Pressure Vessel and Piping Conference	15-20 July	Prague	asme.org/events/pvp
ERPI Expert Workshop on Creep Continuum Damage Models for Structural Mechanics (with ASME)	19-20 July	Prague	asme.org/events/pvp
ECF22: 22nd European Conference on Fracture	26-31 August	Belgrade	ecf22.rs
IMEKO XXII World Congress	3-6 September	Belfast	npl.co.uk
TC15 Meeting	4-6 September	Trondheim	structuralintegrity.eu
ISSI2018	t/b/a	China	fesi.org.uk
2019			
ICMFF12 – 12TH International Conference on Multiaxial Fatigue and Fracture	24-26 June	Bordeaux	Enquiries: ICMFF2019@adera.fr

To be included on the emailing list for The FESI Bulletin, email brian.daniels@fesi.co.uk