10th

fatigue design

International Conference

29 & 30 November 2023 • **France**

ABSTRACT BOOK

Partners: Nordic Countries

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X-Raybot mini

IN DEVELOPMENT
2023

Compact diffractometer

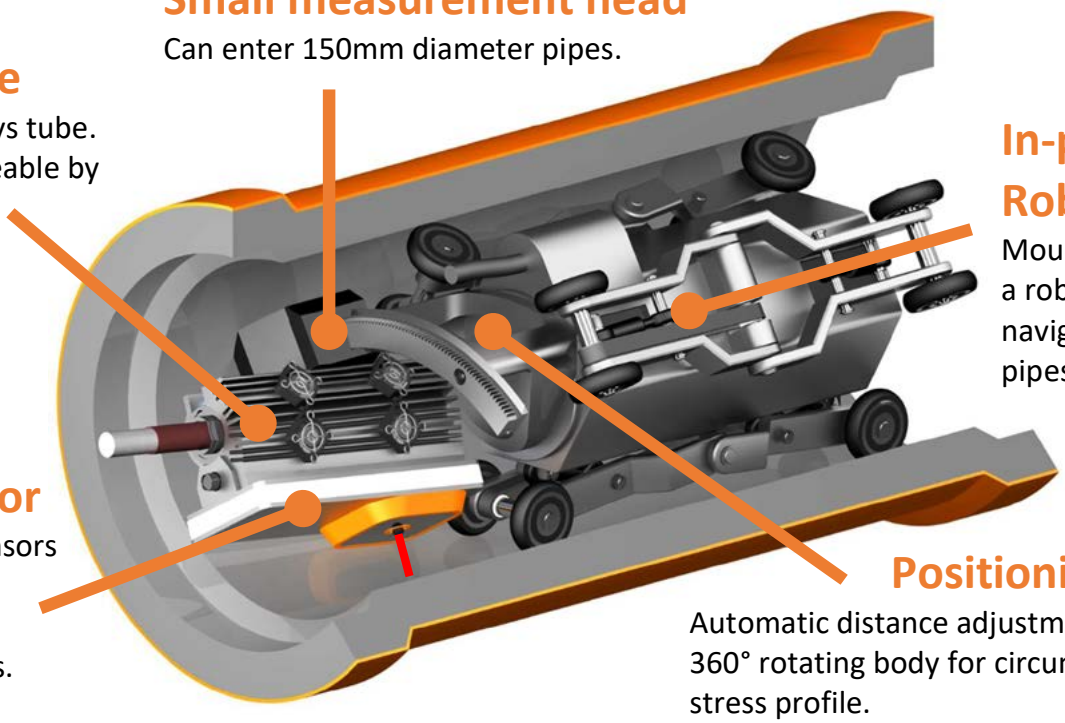
Complete stress tensor components evaluation.

Small measurement head

Can enter 150mm diameter pipes.

X Ray Tube

Air cooled X-rays tube. Easily exchangeable by the user.



In-pipe Robot

Mountable on a robot to navigate in pipes.

2D Detector

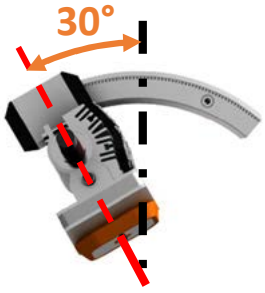
4 Silicon 2D sensors permitting to acquire the diffraction rings.

Positioning

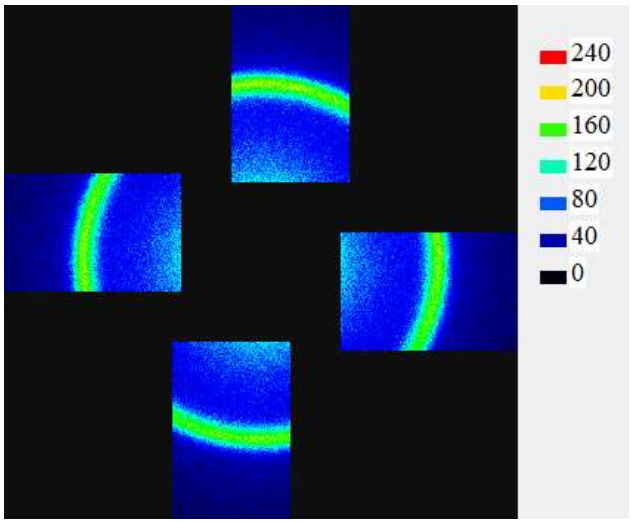
Automatic distance adjustment. 360° rotating body for circumferential stress profile.

SOFTWARE

- ✓ Multiple exposures with the tilting of the measurement head from -30° to 30°, to evaluate the complete stress tensor components.



- ✓ Robust error bars evaluation according to the Guide of Uncertainties in Measurements (GUM).
- ✓ Each diffraction pattern is fully fitted through a non-linear best fit method that permits to account for overlapped peaks.



Example of raw counts on a single exposure

Contact :

MRX France 06 82 34 38 66 www.mrxrays.com info@mrxrays.com

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Fabien Lefebvre

Introduction Message

On behalf of the Fatigue Design 2023 International Scientific Committee and Organizing Committee, we would like to welcome you all to the 10th edition of Fatigue Design 2023 taking place at CETIM, Senlis, France on November 29 & 30 2023.

This anniversary edition provides an opportunity to reflect on the origins of this conference, which has been held biennially since 2005. Indeed, the current relevance of this conference prompts us to reevaluate its title, which unites two terms that have historically been overlooked: 'Fatigue' and 'Design'. In the realm of Mechanics, 'Fatigue' refers to 'Fatigue Resistance', which denotes a material's ability to endure damage and, more broadly, a component or mechanical structure's capacity to withstand repeated loads during service.

With the contemporary demands for weight reduction, enhanced performance, and the assessment of remaining service life, mechanical stress levels have increased, and the risk of fatigue failure has become a critical concern in the design of mechanical components. Consequently, in recent years, the concept of 'Fatigue Design' has supplanted that of 'Fatigue Verification' post-design.

Organized by CETIM and his partners, the 10th Fatigue Design 2023 International Conference aims to present the most innovative approaches, scientific and technological advances in design methodologies, testing methods and tools to evaluate and extend the fatigue lifetime of the industrial equipment. The papers are mostly focusing on the industrial applications.

The Nordic Countries have been designated as the 'partner country' for Fatigue Design 2023, particularly in the context of cutting-edge research on fatigue and fracture mechanics in Northern Europe. Over 30% of the conference speakers hail from the Northern European region.

This edition will place a special emphasis on Fatigue Life Extension and Residual Life Assessment, featuring four keynotes on these subjects and multiple dedicated sessions.

Building on the introduction of Big Data and Artificial Intelligence concepts in the previous edition, these themes will continue to be part of the conference. Additionally, a new topic related to fatigue in transmission systems will be introduced as a new point of discussion.

The following scientific and technical topics are covered:

- additive manufacturing,
- big data and Artificial Intelligence,
- complex loading
- composite and elastomers,
- contact fatigue and fatigue in transmission system
- damage tolerance and fatigue life,
- experimental and numerical design and validation methods,
- fatigue of assemblies (mechanical, welded, adhesive-bonding, multimaterial...),
- reliability-based approaches and probabilistic methods,
- influence of manufacturing process in fatigue analysis (effect of microstructure, welding, stress relief techniques...),
- vibration fatigue behaviour.

The presentations will focus on the latest development and most recent experimental, numerical simulation techniques and the associated engineering tools applied to the large domain of the industrial applications.

The 10th edition of Fatigue Design International conference is being organized in close collaboration with the proceedings' publisher, Elsevier, and will be made available online through Structural Integrity Procedia on ScienceDirect, ensuring global accessibility for better dissemination and maximum exposure. The selection and peer review of the papers have been conducted in cooperation with the International Scientific and Organizing Committees.

"Fatigue Design" has evolved into the leading conference for addressing industrial concerns related to the fatigue design of structures and components, serving as a pivotal intersection between industry and academia. With 104 oral presentations, approximately 50% of which are presented by industry experts, this edition will feature 20 new oral presentations, along with a new dedicated room for the conference.

We anticipate that speakers and delegates will engage in fruitful exchanges and discussions on technical and scientific developments and issues throughout the conference. Poster sessions and exhibition booths provide additional opportunities for fostering interactions between scientists, industry professionals, PhD students, and solution providers. Additionally, the digital platform will enable the participation of individuals who are unable to attend in person, further promoting the conference and its contributions on a global scale.

I extend my sincere gratitude to the dedicated members of the International Scientific and Organizing Committees for their invaluable scientific guidance in the selection and review of papers. I also express my appreciation to the authors, delegates, exhibitors, and sponsors for their meaningful contributions. Special thanks go to the SF2M Fatigue commission and our colleagues at CETIM for their tireless efforts in organizing and ensuring the success of this conference.

I wish you all a most pleasant stay in Senlis and hope that you will enjoy the conference.

Fabien Lefebvre

CETIM Scientific Advisor
Chairman Organizing Committee Fatigue Design 2023

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Exhibitors

3R	**Eikosim**	**Mecatest**	**Rumul**
BETA CAE	**HBK**	**Misulab**	**Steplab**
CETIM	**Hexagon**	**MRX**	**UTC Compiegne**
Easi-Stress	**Intes**	**MTS**	

Poster Award 2023

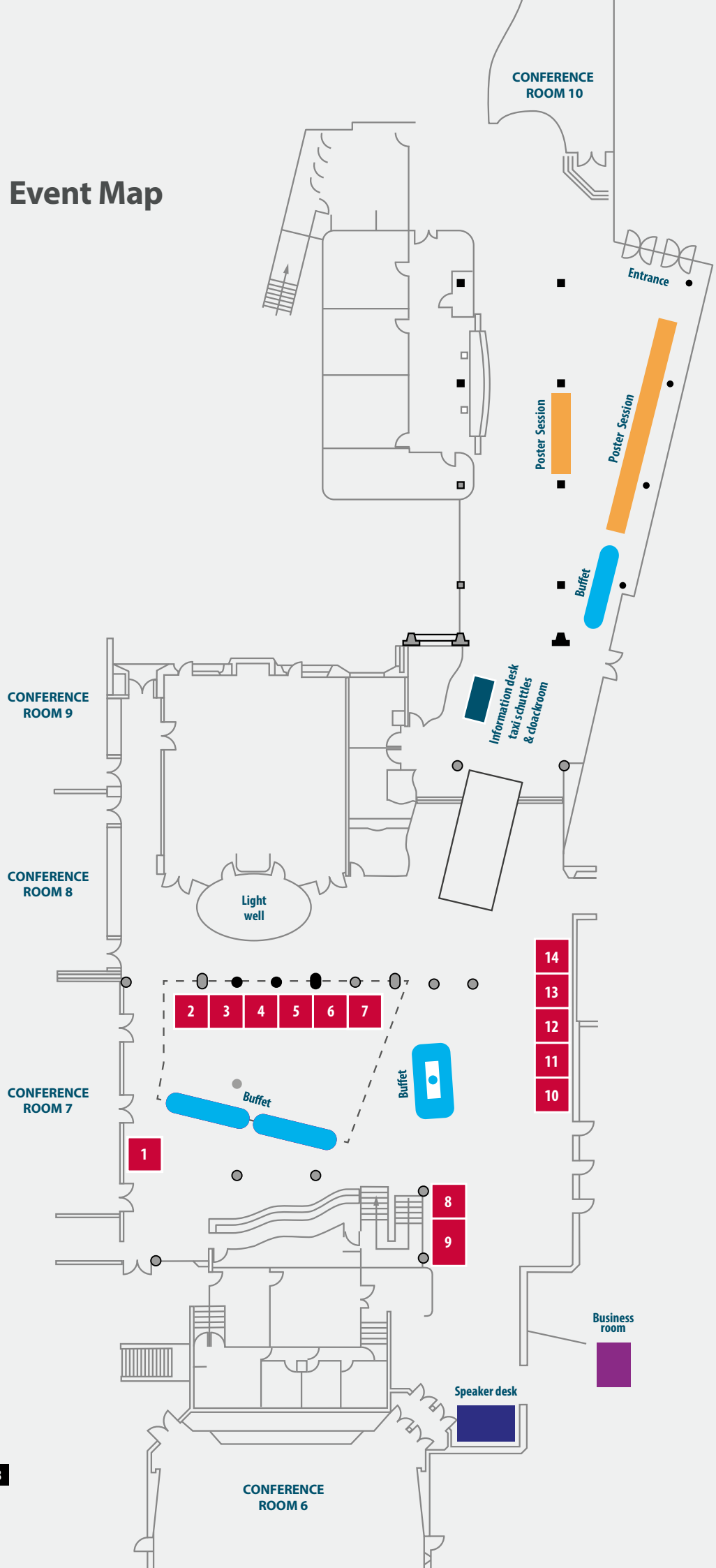
The poster session of the 10th edition of the Fatigue Design conference includes more than 20 posters. This session will offer the opportunities for the technical exchanges between the scientists, industry participants, PhD students.

To acknowledge and promote outstanding research and to encourage the young researchers/ scientists and PhD students, an award for the best poster has been set.

The best poster will be chosen by the Poster Award Committee members with scientific and technical criteria. The Poster Award winner will receive a Certificate of Recognition and an I-Pad©.

During the 9th Fatigue Design 2021 conference, the Poster Award has been dedicated to Melody Le Falher from the LTDS, Ecole Centrale de Lyon, Lyon, France and Safran Transmission Systems, Colombes, France for her work on *"Fretting fatigue of lug-bush connection members with interference fit: comparison between a multiaxial fatigue stress analysis and "tribological" Ruiz surface stress approach".*

Event Map



EXHIBITORS:

1. STEPLAB
2. RUMUL
3. INTES
4. EASI-STRESS
5. HEXAGON
6. Mecatest
7. 3R
8. MRX
9. CETIM + Misulab
10. HBK
11. BETA CAE Systems
12. UTC Compiegne
13. Eikosim
14. MTS

Content

Plenary Session

S01 Additive Manufacturing

S02 Big Data and Artificial Intelligence

S03 Complex Loadings

S04 Composites, Elastomers and Adhesive Bonding

S05 Contact Fatigue and Fatigue Transmission System

S06 Damage Tolerance and Fatigue Life

S07 Experimental and Numerical Design and Validation Methods

S08 Fatigue and Manufacturing Process (Effect of Microstructure, Welding, Residual Stresses,…)

S09 Fatigue of Assemblies (Mechanical, Welded, Adhesive-bonding, Multimaterials,…)

S10 Fatigue Under Severe Environmental Conditions

S11 Non-linear Behavior and Cumulative Damage

S12 Reliability–based Approaches and Probabilistic Methods

S13 Vibration Fatigue

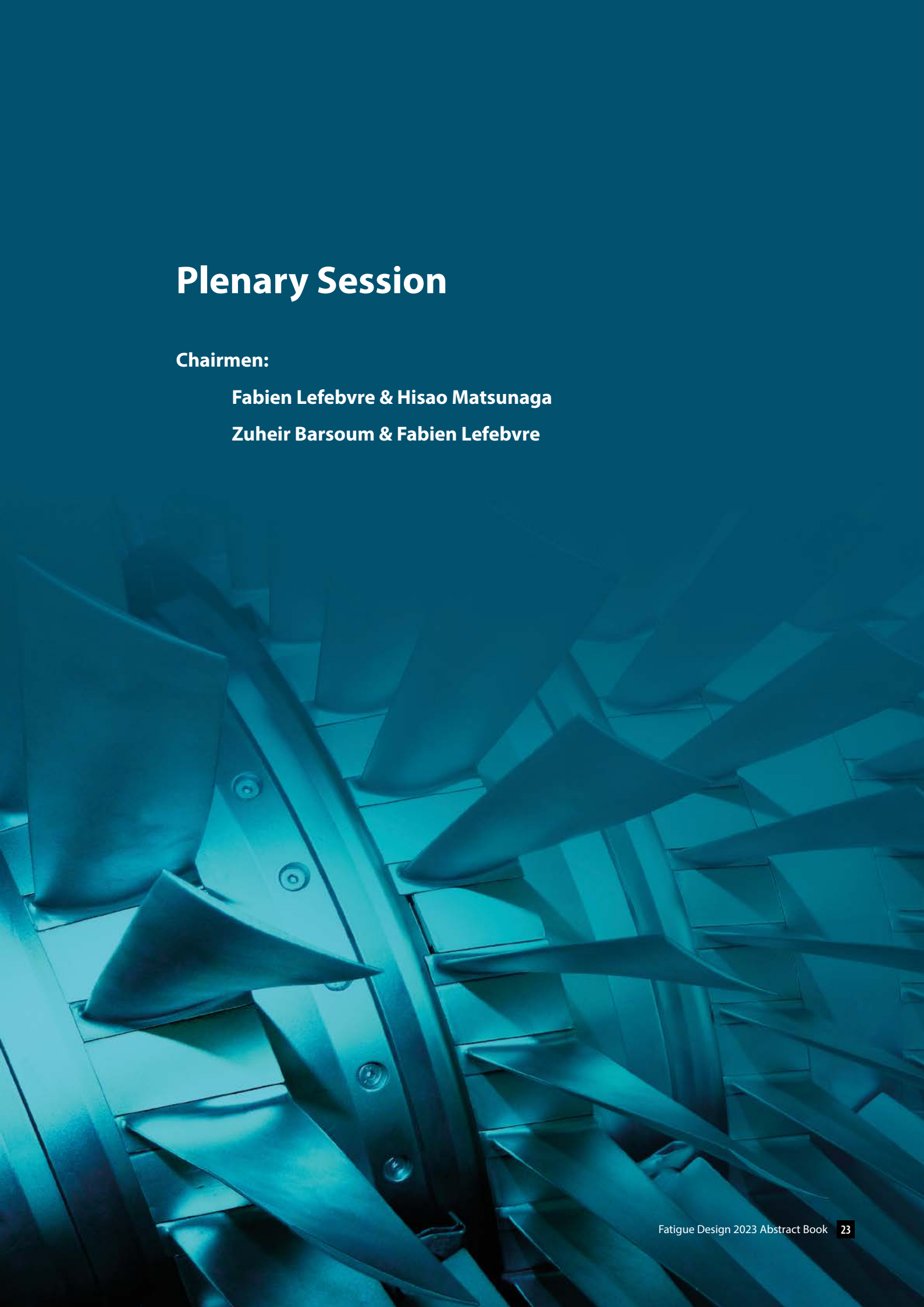
Poster Session

Plenary Session

Chairmen:

Fabien Lefebvre & Hisao Matsunaga

Zuheir Barsoum & Fabien Lefebvre



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FATIGUE DESIGN 2023

FD23-6

Application of a ΔJ approach for thermal fatigue crack growth assessment on the large scale yielding pacific experiment

Stéphan Courtin[1], Nicolas Dutruel[1], Gaëlle Leopold Jean-Marie[2], Stéphane Chapuliot[2]

[1]EDF R&D, ERMES, Palaiseau, France. [2]EDF R&D, MMC, Moret-sur-Loing et Orvanne, France

Austenitic stainless steel large nuclear components, with high thicknesses, may experience cyclic large scale yielding due to mechanical and thermal loadings during their service life. International codes and standards only provide inadequate and very conservative methods for dealing with the fatigue crack growth associated with this situation. Non-codified alternatives, such as ΔJ approaches reported in References [1] and [2], then appear to be good candidates for predicting fatigue crack growth beyond small scale yielding.

This paper aims to apply a ΔJ approach on the PACIFIC experiment permitting thermal fatigue crack propagation in large scale yielding conditions [3]. Numerical protocol and modelling assumptions will be detailed. Thanks to sensitivity analyses, a particular focus will be given on the choice of the cyclic elastic-plastic stress-strain curve. Comparisons between numerical results and experimental fatigue crack growth data will be finally provided and discussed.

[1] J. Li, O. Ancelet, A. Double and S. Chapuliot, Evaluation of fatigue crack propagation by ΔJ approach, in Proceedings of the ASME 2019 Pressure Vessels & Piping Conference

[2] K. Hojo and S. Kumagai, Fatigue crack growth prediction of a pipe with a circumferential surface flaw using ΔJ and reference stress method, in Proceedings of the ASME 2022 Pressure Vessels & Piping Conference

[3] G. Leopold, F. Curtit and S. Courtin, Thermal fatigue crack propagation in large scale yielding (LSY) conditions: PACIFIC experiment on a 316L quasi-structure, in Proceedings of the ASME 2017 Pressure Vessels & Piping Conference

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FATIGUE DESIGN 2023

FD23-8

Generalized modelling approach to predict short and long fatigue crack propagation behaviors

Ayhan Ince

Concordia University, Montreal, Canada

Many fatigue crack growth prediction models have been developed to consider both short crack and long crack behaviors by accounting for the stress intensity range-based crack driving forces or crack closure-based concepts. Despite some successes, all of those fatigue crack growth models lacked mechanically comprehensive approach to fully address the complex behavior of short cracks, thus it led to very limited applications. Based on the recent systematic study performed in the author's group, a new generalized two-parameter driving force model has been developed to account for crack growth driving forces and corresponding crack growth thresholds to predict both short crack and long crack propagation behaviors. Fatigue crack growth rates predicted by the proposed model are compared with fatigue crack growth and life data set of short and long cracks for various stress levels at R-ratios of 0.1 and 0.5 for the titanium alloy, Ti-6Al-4V. The model predicted results are also compared to short and long crack propagation data set of the aluminum alloy, 2024-T3 for various stress levels at R-ratios of 0.0 and 0.5. The predicted results show good agreement with experimental crack growth data set for these alloys. Based on the comparison of crack growth predictions and fatigue life results with experimental data set, the proposed model demonstrates good predictive capability to account for multiple critical driving force parameters to accurately simulate crack growth behaviors in both short and long crack regimes.

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FATIGUE DESIGN 2023

FD23-75

Possibilities with high frequency mechanical impact (HFMI) treatment in fatigue life extension of welded structures

Zuheir Barsoum[1], Yuki Banno[2,1], Martin Edgren[3,1], Torbjörn Narström[4,1]

[1]KTH Royal Institute of Technology, Stockholm, Sweden. [2]Gifu University, Gifu, Japan
[3]Dekra Industries, Stockholm, Sweden. [4]SSAB, Oxelösund, Sweden

In 2016, the International Institute of Welding (IIW) published a recommendation/guideline for HFMI treatment of welded structures including proper treatment procedures, quality control and amount fatigue strength improvement that can be claimed for steel grades 235 – 960 MPa in yield strength, where up to 8 fatigue strength (FAT) improvement can be achieved for High Strength Steel welds. Post weld treatment with HFMI techniques have shown outstanding fatigue life improvement for welded structures and similar recommendations as those in IIW are finding their way into other international standards, e.g. the Eurocodes.

Recently, HFMI techniques have been used in several research projects for life extension of welded steel bridge details, e.g. in Sweden and Japan, with successful results and a clear rehabilitation. The studies within these research programs have focused on; implementation of digitalized weld quality assurance for determining the weld quality pre-and post-weld improvement, development of framework for NDT and DT in order to determine crack size for pre-fatigued welded details to determine the benefits of life extension with HFMI techniques, development of finite element framework for simulation of HFMI process, damage tolerance and fracture mechanical analysis for evaluating experimental results. Results from these research programs give recommendations for acceptable crack size prior life extension using HFMI techniques where IIW recommendations also can be applied for pre-fatigued details.

The current study will give an overview of these research activities and preliminary results with regards to life extension of welded steel details using HFMI techniques.

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FATIGUE DESIGN 2023

FD23-143

Responsible fatigue design of components under multiaxial loading

Jan Papuga

Czech Technical University in Prague, Prague, Czech Republic

These days, some multiaxial fatigue solution is commonly embedded in most publicly available fatigue solvers. The lecture discusses the known facts within the domain of multiaxial fatigue estimation, and the level they are experimentally proven to be validated. The individual steps of the analysis are analyzed. These are: load path deconstruction to individual cycles, their analysis and segmentation to amplitude and mean components of stresses/strains, their merging into the damage parameters and the characteristic features of various types of damage parameters. These are only some of the prerequisites to a statement of the damage level induced by the evaluated loading, and to an adequate assessment of the remaining useful life, requesting the usage of the damage accumulation method validated in the domain of multiaxial loading. The lecture discusses the scope of validation these prerequisites were subjected to, so that the second step – remaining life calculation or even its extension - could be taken responsibly enough. Though engineering could be called the craft of mastering multitude of incalculable factors, the lecture is concluded by a call for a corrective collaborative action that could improve the status quo and shed more light on the quality of the calculation process.

S01
Additive Manufacturing

Chairmen:

Yves Nadot & Christophe Reynaud

Moritz Braun & Christophe Grosjean

Francesca Curà & Louis Rech

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FATIGUE DESIGN 2023

FD23-2

Local fatigue assessment of butt-welded joints between additively manufactured 316L stainless steel parts

Moritz Braun[1], Jan Schubnell[2]

[1]Hamburg University of Technology, Hamburg, Germany
[2]Fraunhofer Institute for Mechanics of Materials, Freiburg, Germany

Additive manufacturing (AM) has seen a rapid increase in application for many applications in recent years; nevertheless, there are still technical limitation with respect to widespread industrial applications. One important aspect is the relative limited building volume of the laser powder bed fusion (LPBF) process. Thus, the joining of AM parts makes it possible to increase the volume of AM structures; however, there are currently only a few investigations on the fatigue strength of welded AM parts. In this study, local fatigue assessment methods are applied to assess the fatigue strength of butt-welded joints of 316L AM steel plates made by gas metal arc welding. To account, for the different weld seam position relative to the LBPF building process, joints were produced with weld seams parallel and vertical to the layer orientation of AM plates. For fatigue assessment, local concepts based on the micro-structural support effect hypothesis are selected. This includes the stress averaging, the critical distance, and the IBESS approach.

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FATIGUE DESIGN 2023

FD23-3

Infrared imaging surface roughness criticality assement of wire arc additive manufactered specimens

Mathilde Renault[1,2], Lorenzo Bercelli[2], Bruno Levieil[2], Julien Beaudet[2], Cédric Doudard[2], Sylvain Calloch[2]

[1]Naval Group, Bouguenais, France. [2]IRDL, Brest, France

Wire Arc Additive Manufacturing is an additive manufacturing process with a high rate of material deposition capable of producing near-net shape parts. This process involves the reduction of production costs (material and lead times) and considers innovative designs. However, the deposition technique induces heterogeneities in the material, in particular the presence of porosity and a degraded surface finish. The surface condition has a first-order influence on the fatigue life of unmachined parts due to the stress concentrations induced by the presence of the valley. Various finishing treatments can be considered to reduce the criticality of the surface finish influence over crack initiation and propagation : conventional ones such as hammer, laser or shot peening and some specially developed for Addiditive Manufacturing (AM) processes such as in-situ cooling device or hot-rolling system. The multitude of AM parameters and the different finishing surface post-treatments entail many configurations that will modify fatigue properties. For this reason, rapid fatigue evaluation methods are an asset for process evaluation.

Thermo-elastic Stress Analysis (TSA) is a non-contact technique for measuring the distribution of stress in the surface of a component subject to cyclic loading by using a sensitive infrared camera. The analysis of the thermo-elastic coupling amplitude maps allows the detection of initiation and monitoring of crack propagation. A four-point bending fatigue test protocol is conducted on CuAl9 WAAM specimens. The identification of crack kinetics then allows the assessment of a probabilistic model based on linear elastic fracture.

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FATIGUE DESIGN 2023

FD23-5

Fatigue strength assessment of additive manufactured components considering local quality and geometry using the theory of critical distances and 4R method

Kalle Lipiäinen, Shahriar Afkhami, Antti Ahola, Timo Björk

LUT University, Lappeenranta, Finland

Laser based powder bed fusion (L-PBF) manufactured components are typically used in weight-critical cyclically loaded applications. Building orientation and parameters have a substantial influence on the fatigue performance. A multiparametric method, namely the 4R method, was applied for evaluating the fatigue test data of high-strength L-PBF specimens, including a consideration of local quality. The analysis considering local quality with fractography identified and measured quality characteristics is demonstrated with unnotched and notched specimens with additional stress concentration factor (SCF). The results suggest that the local quality, influenced by the building characteristics, can be assessed when local stresses are obtained from finite element analysis considering the theory of critical distances (TCD). The fatigue strength assessment of notched components benefits from the consideration of local cyclic behavior with the 4R method by improving the accuracy of assessments. As a result of this study, a multiparametric method for fatigue strength assessment approach with a master FAT curve was proposed for additively manufactured components.

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FATIGUE DESIGN 2023

FD23-51

Influence of post-processing treatments on the fatigue behavior of additively manufactured metallic materials

Alexis Renaud[1], David Marechal[1], Jason Rolet[1], Sandy Blanc[2], Loïc Exbrayat[3], Joffrey Tardelli[1]

[1]IRT-M2P, Metz, France. [2]Safran Additive Manufacturing Campus, Le Haillan, France
[3]Safran Tech, Magny-Les-Hameaux, France

The fatigue behavior of additively manufactured (AM) parts is strongly affected by manufacturing parameters. In the case of laser powder bed fusion (LPBF) processes, the characteristics of the powder and of the laser beam lead to specific properties and microstructures. The surface of AM parts is characterized by a very high roughness, a high number of macroscopic pores compared to the bulk, and by the presence of partially melted particles and residual powder trapped into the roughness profile. These elements have significant impact on the fatigue behavior of the parts.

Several post-processing treatments can improve the surface quality of AM parts and decrease their roughness. These processes can be chemical (chemical polishing), electrochemical (electrolytic polishing or plasma electrolytic polishing), physical (laser finishing) or mechanical (tribological processes, machining). They all affect the metallic surface in different ways and may impact the final properties such as the fatigue resistance.

In the scope of the After-ALM and the NEMO projects, the above-listed treatments were applied on 316L stainless steel and Inconel 718 alloys manufactured by LPBF. The resulting surface morphologies and microstructures were characterized, and the fatigue behavior of the treated materials was evaluated using rotating bending tests according to aeronautical standards. The fracture surfaces were investigated to understand the initiation mechanisms for the different post-processing treatments. Comparison of the effect of roughness and internal stresses were undertaken to separate the influence of these two effects.

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FATIGUE DESIGN 2023

FD23-52

Fatigue behaviour of wire arc additively manufactured sheet material

Cheng Huang[1], Lingzhen Li[2,3], Niels Pichler[2,3], Elyas Ghafoori[2,3,4], Leroy Gardner[1]

[1]Imperial College London, London, United Kingdom. [2]Empa, Dübendorf, Switzerland
[3]ETH Zürich, Zürich, Switzerland. [4]Leibniz University of Hannover, Hanover, Germany

Wire arc additive manufacturing (WAAM) is a metal 3D printing technique that is well recognised in the construction sector for its high efficiency, cost-effectiveness and flexibility in build scales. However, there remains a lack of fundamental data on the structural performance of WAAM elements, especially regarding their fatigue behaviour. A comprehensive experimental study into the fatigue behaviour of WAAM steel plates has therefore been undertaken and is reported herein. Following geometric, mechanical and microstructural characterisation, a series of WAAM coupons was tested under uniaxial high-cycle fatigue loading. A total of 75 fatigue tests on both as-built and machined coupons, covering various stress ranges and stress ratios, have been conducted. The fatigue test results were analysed using constant life diagrams (CLDs) and S-N (stress-life) diagrams. The CLDs revealed that the fatigue strength of the as-built WAAM steel was relatively insensitive to the different stress ratios. The S-N diagrams showed that the surface undulations resulted in a reduction of about 35% in the fatigue endurance limit for the as-built WAAM material relative to the machined material, and a reduction of about 60% in the fatigue life under the same load level. The as-built and machined WAAM coupons were shown to exhibit similar fatigue behaviour to conventional steel butt welds and structural steel S355, respectively. Preliminary S-N curves were also proposed for the WAAM steel.

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FATIGUE DESIGN 2023

FD23-65

Fatigue durability of inconel 718 obtained by additive layer manufacturing route

Cesar-Moises Sanchez-Camargo[1], Yves Nadot[1], Jonathan Cormier[1], Fabien Lefebvre[2], Robin Hauteville[2], Wen Hao Kan[3], Louis Ngai Sum Chiu[3], Chen Li[3], Aijun Huang[3]

[1]Institut P', Futuroscope, France. [2]CETIM, Senlis, France. [3]MCAM, Monash, Australia

A Laser Powder Bed Fusion Inconel 718 produced with intentionally non optimized parameters is investigated to elucidate the role of defects and microstructure on the High Cycle Fatigue life. Samples coming from three build orientations and three heat treatments are tested at room temperature and at 650 °C under R = 0.1 load ratio. Results show that the printing orientation has a minor effect on fatigue life at both room and high temperatures. Most samples failed from Lack of Fusion type defects (ranging from 200 µm to 600 µm) and each defect size is carefully analyzed by using SEM observations. It can be observed that surface defect leads to transgranular fracture surface when sub-surface initiation leads to rather crystallographic type fracture surface. By producing S-N curve on Hot Isostatic Pressure condition, it is shown that the relative influence of defect on the S-N curve is much higher at 20°C compared to 650°C. Kitagawa diagram are plotted for both temperatures in order to quantify the influence of defect size on the fatigue limit. Natural cracks are observed at the surface in order to discuss the relative part of initiation life in the whole fatigue life.

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FATIGUE DESIGN 2023

FD23-76

Self-heating testing of additively manufactured Ti-6Al-4V with different microstructures and porosity levels

Grégoire Brot[1,2], Imade Koutiri[2], Vincent Bonnand[1], Véronique Favier[2], Nicolas Ranc[2], Corinne Dupuy[2], Fabien Lefebvre[3], Robin Hauteville[3]

[1]DMAS, ONERA, Université Paris Saclay, Châtillon, France. [2]PIMM, Arts et Metiers Institute of Technology, CNRS, Cnam, HESAM University, Paris, France. [3]CETIM, Senlis, France

Accelerated characterization of high-cycle fatigue properties is necessary in order to enable the optimization of parameter of additive manufacturing processes such as LPBF (Laser Powder Bed Fusion). Therefore, two accelerated characterization methods are applied and compared on Ti-6Al-4V samples produced using LPBF process. The first method uses ultrasonic fatigue machine and the second one determines the fatigue limit using self-heating testing. To study the interactions between the material and the accelerated testing methods, fatigue tests are carried out on different grades of Ti-6Al-4V-LPBF differing by their microstructure or their porosity. Three grades have the same microstructure but different porosity levels and three grades have different microstructures with the same porosity. It was found that both material features highly influenced the VHCF properties of LPBF-Ti-6Al-4V revealing the sensitivity of accelerated 20 kHz fatigue tests to these features.

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FD23-90

Ti-6Al-4V L-PBF chemically etched components: from the surface micro-geometric characteristics to the fatigue strength

David Mellé[1,2], Etienne Pessard[1], Franck Morel[1], Daniel Bellett[1], René Billardon[3]

[1]LAMPA, HESAM University, Arts et Métiers Campus d'Angers, Angers, France
[2]Safran Tech, Materials and Processes department, Magny les Hameaux, France
[3]Safran Transmission Systems, Colombes, France

Producing structurally loaded components by additive manufacturing processes is still a challenge that is partly due to the high surface roughness that is generally obtained. This is true despite increasing efforts in the development of finishing processes to improve the surface state.

Different studies concerning the fatigue strength of additively produced Ti-6Al-4V components, especially by laser powder bed fusion, are available in the scientific literature. The crack initiation mechanisms encountered, including after finishing processes, are also well documented. However, in order to correctly design highly loaded components, it is important to be able to identify the critical porosity, or critical surface feature, in the population of surface features.

Fatigue tests have been conducted on plane bending coupons with a rectangular section in the high cycle fatigue domain. The complete scanning of the tested surface, before and after testing, made it possible to both identify the population of surface micro-geometric features and determine the critical porosity in this population. Classical approaches (especially Kitagawa-Takahashi diagram) have been applied. Several parameters have been compared to determine the ideal parameter to evaluate the criticity of the surface features and to predict the most critical one. Even though the Murakami √area parameter establishes a consistent link between critical porosity and the fatigue strength, it is more ambiguous concerning the identification of the killer porosity from the population.

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FATIGUE DESIGN 2023

FD23-91

Numerical estimation of fatigue life scatter in micro-sized electron beam melted parts using machine learning technique

Yixuan Hou, Reza Talemi

KU Leuven, Gent, Belgium

Through the combination of voids and micro-sized parts, additively manufactured metal lattice structures have significant advantages in weight reduction, thermal insulation, high specific strength, and energy damping, showing great potential in the aerospace, biomedical, and transportation industries. However, the surface defects, produced by the multiple phenomena during the additive manufacturing process, are the main origins of premature crack initiation and lead to early fatigue failure under cyclic loading. A thorough understanding of the fatigue behaviour for addittively manufactured micro-sized parts requires extensive full-scale fatigue testing, which is costly and time-consuming. This study focuses on estimating the fatigue life scatter of electron beam melting manufactured Ti-6Al-4V micro-sized parts using a combination of machine learning and finite element modelling. To this end, a generative adversarial network is trained to generate 2D surface profiles of the EBM-manufactured Ti-6Al-4V micro-sized parts based on X-ray tomography. Next, the regenerated 2D surface profiles are randomly used to construct 2D Finite Element models to detect the critical notches and get the stress gradients at the hot spot. Finally, Continuous Damage Mechanics and Theory of Critical Distance are implemented to estimate the fatigue lifetime. This way, hundreds of simulations are performed using regenerated surface profiles. The obtained results show that using both a generative adversarial network and finite element simulation makes it possible to numerically reproduce the scattered fatigue data, which is the inherent characteristic of additively manufactured materials.

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FD23-108

Multiaxial fatigue analysis of additively manufactured hollow specimens from AlSi10Mg

Jan Papuga[1], Luis Reis[2], Martin Matušů[1], Pedro Costa[2], Jan Šimota[1], Jakub Rosenthal[3], Francisco João Bumba Paca[4]

[1]Czech Technical University in Prague, Prague, Czech Republic
[2]Instituto Superior Técnico - University of Lisbon, Lisbon, Portugal. [3]OTH Amberg-Weiden, Amberg, Germany
[4]Instituto Superior Técnico, University of Lisbon, Lisbon, Portugal

The paper presents experimental results and results of different fatigue strength assessment methods carried out on hollow specimens from AlSi10Mg with a specific design featuring an internal cavity and a cylindrical outer surface. The selected test geometry combines the design freedom of additive manufacturing with the suitability for surface temperature / thermographic measurements. Compared to classic cylindrical hollow specimens, increasing the inner diameter of the active part lessens the stress gradient in the torsion loading case, while keeping the outer dimensions still acceptably small for layer-by-layer or Laser Powder Bed Fusion technology. The surface in the tested section was left as-built, while the heat treatment recommended by the AM machine manufacturer was applied. Four loading cases were tested in the high cycle fatigue area under load-controlled configuration – push-pull, torsion, and combined loading of in-phase and out-of-phase tension-torsion. All loading cases featured fully reversed loading cycles. The results show that these specimens reach substantially higher lifetimes (or fatigue strengths) if the coacting load channels are out of phase compared to the case, in which the same stress amplitudes are applied in phase. The fatigue strength estimation performed using several multiaxial fatigue strength criteria shows that only some of the methods follow the same behavior.

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FD23-119

Numerical and experimental investigations of wire arc additively manufactured components made of 3Dprint AM35 grade

Xiongfeng Ruan[1], Burak Karabulut[1], Jelena Dobric[2], Barbara Rossi[1,3]

[1]KU Leuven, Sint-Katelijne-Waver, Belgium. [2]University of Belgrade, Belgrade, Serbia
[3]University of Oxford, Oxford, United Kingdom

Today, wire arc additive manufacturing (WAAM) can be used to fabricate critical structural steel components. It allows to fabricate highly optimized shapes achieving very high levels of material's capacity utilization. But there are certain scientific challenges linked to this manufacturing technique that need to be explored and the fatigue resistance of WAAM components is one of them. In this research, the behaviour of wire arc additively manufactured unalloyed S355 carbon steel elements is investigated analytically and experimentally. The sample was manufactured by cold metal transfer (CMT) welding process using the grade 3Dprint AM 35 (S355) following a welding procedure optimised to limit the welding-induced imperfections. A series of microstructural and mechanical investigations were carried out including: (i) hardness tests, (ii) static tensile tests, and (iii) cyclic fatigue tests in both longitudinal and transverse direction. The obtained results are then compared with existing research on similar details containing both unwelded base plates and WAAM components. This collated database of more than 700 reference test results is then used to assess the applicability of the current design guidelines to predict the fatigue life of WAAM components. Finally, proposals are made for the detail categories and the reliability of these proposals is then supported by the use Weibull models, commonly used in survival analysis.

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FATIGUE DESIGN 2023

FD23-125

Effect of re-lasing on the fatigue properties of 316L stainless steel produced by laser powder bed fusion

Foued Abroug[1], Yunran Ma[1], Morgane Mokhtari[1], Lionel Arnaud[1], Anis Hor[2], Clément Keller[1]

[1]*Laboratoire Génie de Production (LGP), Université de Toulouse, INP-ENIT, Tarbes, France*
[2]*Institut Clément Ader (ICA), Université de Toulouse, CNRS, ISAE-SUPAERO, Toulouse, France*

Despite the great success of the metal additive manufacturing process by Laser Fusion on Powder Bed (L-PBF), this technique still lacks maturity in several areas. Among its major challenges, the low fatigue strength of the L-PBF parts [3] caused, among other things, by two main types of defects. Firstly, a high surface roughness, mainly linked to the phenomenon of partial powder melting on the part surface [1]. Secondly, internal defects are created during the building process and are randomly distributed in the material [2]. The present study aims to investigate the effect of a second lasing [4][5] on the improvements of the characteristics of L-PBF parts. Based on preliminary experiments, two relasing strategies were selected. A high cycle fatigue campaign was subsequently carried out with a stress ratio of R=-1 on samples with or without relasing, in the as-built state or after polishing. Specimens printed in Net-Shape showed even after relasing and polishing, a much lower fatigue strength than those machined in the bulk after additive manufacturing [6]. In addition, preliminary results show that the tested relasing conditions has a slight beneficial effect on the quasi-static and fatigue strength of the 316L obtained by L-PBF.

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S02

Big Data and Artificial Intelligence

Chairmen:

Xavier Hermite & Frédéric Kihm

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FD23-41

Increasing the reliability of industrial overhead cranes by structural health monitoring

Jeroen Van Wittenberghe, Vitor Soares Rabelo Adriano, Okan Yilmaz, Filip Van den Abeele

OCAS NV - ArcelorMittal Global R&D Gent, Zelzate, Belgium

Overhead cranes are subjected to significant cyclic loads and stresses during their operation, which can lead to fatigue cracking and other forms of damage. Their correct and safe operation is critical while lifting and handling loads. Therefore, industrial cranes are subjected to periodic inspections and maintenance. However, inspections only give information on the condition of a crane at a certain moment and focus on propagating damage which makes it difficult to determine the remaining lifetime of the structure. In this paper a Structural Health Monitoring (SHM) system is presented that is based on load monitoring. The SHM system involves the use of strain sensors combined with the operational crane data to continuously monitor the crane loading and response of the structure. This continuous data stream is analysed by a model optimised using machine learning to determine the fatigue life consumption and detect anomalies. This model is based on a digital twin of the overhead crane to determine the critical areas and critical welds of the crane. The output of the SHM system assists maintenance personnel to identify and address potential problems at critical areas before they result in costly failures or accidents. In addition, SHM can help extending the service life of overhead cranes, reducing the need for costly replacements and helping to ensure the continued safety and efficiency of industrial operations. The results are presented of a pilot project implementing the SHM system on two small capacity cranes (12.5 ton).

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FD23-73

Impact of daily and seasonal temperature variation on rolling contact fatigue damage in the rail

Olivier Vo Van[1], Vincent Laurent[2,3]

[1]SNCF SA, Saint-Denis, France. [2]Eurobios, Cachan, France. [3]Université Paris-Saclay, Gif-sur-Yvette, France

Rolling contact fatigue is the most frequent degradation mode observed on the rail. Many mechanical studies have revealed the main physical sizes that generate the crack initiation, which are all linked with the track geometry, the dynamic of the wheel and contact conditions. Except for extreme climate, exogenous phenomena such as ambient temperature have not been analysed. The main reason is that temperature variations induce stress cycles in the rail that are under the endurance limit of the material. Therefore, most fatigue life estimation methods do not consider these cycles.

In this paper, 6 years of daily temperature measurement over all the French railway network are used and integrated in a machine learning model developed for computing residual lifespan of each rail segment before crack initiation by rolling contact fatigue. Temperatures are aggregated using the continuum damage mechanics model developed by Lemaitre and Chaboche that gives the possibility to let low amplitude cycles to contribute to fatigue damage. Classification models are then implemented, and importance variables are finally quantified. Results show that daily temperature variations have more impact than seasonal variations and that its contribution to fatigue is significant.

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FATIGUE DESIGN 2023

FD23-89

Determination of stress concentration factors of welded joints from 3D-surface scans by artificial neural networks

Öner Aydogan, Matthias Jung, Jan Schubnell

Fraunhofer Institute of Mechanics of Materials, Freiburg, Germany

The surface geometry and the stress concentration of welded joints shows a large variation and is individual for each joint at each position. This is one reason for the conservative fatigue assessment of welded joints. In the past the determination of stress concentration factors (SCF) by Finite Element (FE) simulation was based on the idealized surface geometry of the welded, defined by weld toe radius and flank angle, or other geometrical parameters. In this work a new approach is presented to directly determine SCFs of welded joints based on the real shape of the surface from 3D-surface scans. For this, different types of artificial neuronal networks (ANN) are used. As input parameter for the ANN single 2D-cuts evaluated from 3D-scans were used. The ANN was trained SCFs determined from FE-simulation based on the real weld geometry and idealized weld geometry (approximated by weld toe radius and flank angle). The developed SCF solution was compared to commonly used SCF solution based on idealized weld geometry. The error of the proposed solution based on the real weld geometry was quite smaller compared to solutions based on the idealized geometry.

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FD23-100

Uncertainty quantification of the crack propagation behavior in welded stiffened panels using a hybrid system integrating artificial neural networks and finite element analysis

Mohammad Tamimi[1], Mohamed Soliman[2]

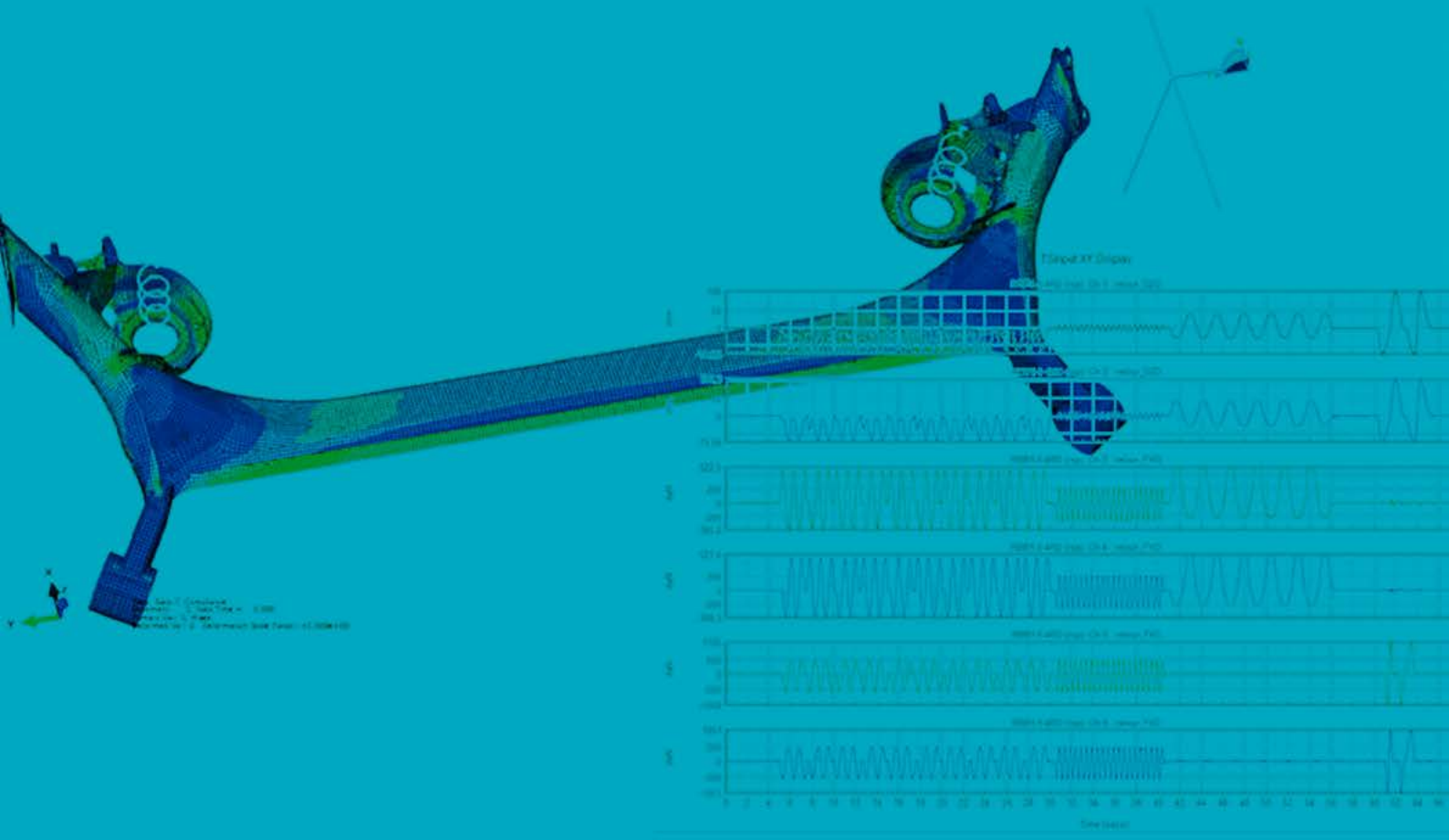
[1]Yarmouk University, Irbid, Jordan.[2]Oklahoma State University, Stillwater, USA

Predicting the crack propagation behavior in welded stiffened panels, which are often used in marine, civil, and aerospace structures, has been challenging. The presence of welded stiffeners creates complex stress conditions that need to be properly considered while predicting the crack growth. Another challenge is the presence of significant uncertainties, the variability in the mechanical properties of materials and geometric parameters are among the main contributors to these uncertainties. In this context, accurate quantification of uncertainties associated with these parameters is crucial for the accurate prediction of the fatigue service life and for ensuring structural integrity and operational reliability throughout the service life. This paper conducts a sensitivity analysis to evaluate the effect of relevant input parameters, covering geometric and mechanical properties, on crack propagation behavior. The geometric parameters include the main panel thickness and stiffener characteristics while the mechanical properties cover the crack propagation regression parameters, modulus of elasticity, and yield strength. Furthermore, the effect of the geometric uncertainties on the fatigue reliability of these panels is also quantified. A 3-D finite element analysis, an artificial neural network, and an elastic-plastic crack growth model are integrated to predict crack propagation under cyclic loading. The sensitivity and reliability assessment approach is illustrated on stiffened panels with T- and L-shape stiffeners subjected to axial tensile fatigue loading. The proposed approach is validated using experimental test data reported in literature.

S03
Complex Loadings

Chairmen:

Mohamed Bennebach & Jan Papuga



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FATIGUE DESIGN 2023

FD23-61

Prediction of mechanical response due to creep-fatigue loading using unified mechanics theory in nickel-based superalloy

Saurabh Mangal[1], Sri Krishna Sudhamsu Kambhammettu[2], C Lakshmana Rao[1]

[1]*Indian Institute of Technology, Madras, Chennai, India.* [2]*National Institute of Technology, Jamshedpur, India*

Components of aero-engine turbines are made with nickel-based superalloy, are subjected to complex thermo-mechanical loads. Creep-fatigue sequence of loading is one of the primary sequences of loading encountered in these engines, which will lead to failure in their components. The dominant mechanism due to creep-fatigue interaction (CFI) in nickel-based superalloys is multiple crack initiation and their propagation at high temperatures. Contemporary efforts to predict the mechanical response due to a combination of creep and fatigue loading, such as linear damage summation, use a procedure of combining damage estimations by creep and fatigue, in an arbitrary manner. The major drawbacks of these approaches are in terms of the extensive experiments required to estimate the model parameters and the limited predictive capability of these models. The combination of effects of creep and fatigue, as postulated in these models, are empirical and they do not seem to have any basis on the physics of deformation and failure in the materials. Such arbitrariness in combining the effects of creep and fatigue damages can be eliminated if the developed models are based on the mechanisms responsible for deformation and failure in these materials and the effects of these mechanisms are combined in some logical way. To address these issues, a thermodynamic-based unified mechanics theory (UMT) is proposed to capture the change in entropy due to creep and fatigue individually. An UMT-based model is used to monitor the degradation in the material due to a combination of these two types of loading, i.e., creep and fatigue, in nickel-based superalloys. The energy dissipated due to the hysteresis loop of CFI loading has been used to quantify entropy generation due to fatigue. The stress relaxation during hold time has been modelled using Norton's law of creep. The entropy generated and calibrated by these two loadings is combined using the framework of UMT, to predict the total damage in the material due to a combination of these two types of loadings. The predictions of the model are later combined with typical experiments conducted on these materials.

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FD23-98

Probabilistic structural integrity assessment of a floating offshore wind turbine under variable amplitude loading

Baran Yeter, Feargal Brennan

University of Strathclyde, Department of Naval Architecture, Ocean and Marine Engineering, Glasgow, United Kingdom

The objective of the present study is to assess the fatigue reliability of a spar-type floating offshore wind turbine based on fracture mechanics. Although floating offshore wind turbines (FOWT) have been historically much more expensive than their fixed bottom peers, the levelised cost of energy of FOWT has decreased dramatically due to increasing wind turbine size, higher capacity factors, innovative designs, and optimal operational strategies. However, there is still much to be done to bring the cost down, especially from the operational and maintenance (O&M) standpoint. In this regard, a damage-tolerant approach is a strong alternative to a safe-life design approach that leads to overdesigning. The present study illustrates a probabilistic framework for structural integrity assessment of a spar-type FOWT, which can be used to design a cost-effective inspection and maintenance planning. The structural integrity assessment is carried out for a fatigue-critical structural detail with an initial crack subjected to variable amplitude loading. The cycle-by-cycle crack growth is simulated using the modified Paris' law, which allows accounting for the overload-induced retardation on the crack propagation. Furthermore, the factors influencing crack growth are subjected to a great deal of uncertainty. These uncertainties include initial crack size, loading spectrum, load interactions, and material fracture characteristics. To deal with the probabilistic nature of the crack propagation, Monte Carlo Simulation is carried out to estimate the probability of failure. Finally, a sensitivity analysis is performed to determine the degree of significance of the random variables.

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FD23-111

Assessing fatigue in materials with small defects: A new multiaxial model based on principal stress amplitude

Lucas Carneiro Araujo, José Alexander Araújo

University of Brasília, Brasilia, Brazil

A new multiaxial fatigue model for materials containing small defects proposed by the authors is presented, which one can be considered as a modification of the SWT model. This new model relates the fatigue limit of the material obtained from the parameter with values associated with the principal stresses generated by the loads. These values are the amplitude of principal stresses and the maximum principal stress observed. For the new model, an amplitude value associated with the principal stresses is defined by using the Maximum Variance Method. This amplitude only can be easily obtained under uniaxial loading conditions, but its calculation for torsion, proportional and non-proportional multiaxial loadings is not trivial, because not only the value but also the direction of the principal stresses varies instant to instant. Therefore, the calculation of the principal stress amplitude posed a challenge not yet addressed by other authors. The multiaxial fatigue model was evaluated with experimental data from AISI 4140 steel, with several different loading conditions, such as traction-compression, torsion and combined loadings with different ratio between shear and normal stresses amplitudes, in-phase and 90° out of phase. In addition, specimens were tested in two conditions: (i) smooth specimens, considering the effect of non-metallic inclusions, and (ii) specimens where a superficial micro hole with a straight bottom was machined with 550 µm in diameter and depth. Comparing the experimental data with the prediction of the new model it was observed that the predictions are slightly conservative with average error not exceeding 15%.

S04

Composites, Elastomers and Adhesive Bonding

Chairmen

Victorien Gautheron & Laurent Gornet

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FATIGUE DESIGN 2023

FD23-22

Fatigue behaviour of cord rubber composite materials in air spring bellows of rail vehicles

Julian Torggler[1], Christian Buzzi[1], Martin Leitner[1], Tobias Faethe[2], Heiko Müller[3]

[1]Graz University of Technology, Graz, Austria. [2]Siemens Mobility GmbH, Graz, Austria
[3]Gummi-Metall-Technik GmbH, Bühl, Germany

Bogies of rail vehicles for passenger coaches and traction units commonly contain air spring systems as secondary spring stages. In the development and design of spring stages, it is necessary to ensure precise knowledge about the material properties and fatigue behaviour of the air spring bellows.

The aim of this work is to systematically investigate the damage mechanisms evaluated at air spring bellows on sample level and to analyse the fatigue strength of the base material under different load conditions. A validated numerical model of the component is used as basis for deriving the local stresses of the composite. A specimen geometry is developed by means of numerical analysis, which ensures the transferability of the local load states to the specimen geometry. The determination of the stresses in the small sample is carried out by a simplified numerical model. To validate the local stresses, surface strain measurements have been carried out.

The specially developed small sample is biaxially loaded and different layups are examined at varying load levels. The fatigue test results reveal that under comparable load conditions, the fibre angle exhibits a clear influence on the fatigue strength. Furthermore, the effect of the peak load at a constant base load is also remarkable based on the conducted experiments. With the help of the presented methodology utilizing the developed representative small sample and testing procedure, a time- and cost-efficient fatigue design of cord rubber composite materials in air spring bellows of rail vehicles is facilitated.

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FD23-32

Fatigue behaviour of 25% wt. short glass fibre reinforced recycled polypropylene filled with mineral filler in presence of notches

Andrea Resente[1], Dr Mauro Ricotta[1], Ms Fiorella Trivillin[2], Prof Giovanni Meneghetti[1]

[1]Department of Industrial Engineering, University of Padova, Padova, Italy
[2]Group Technology Organization, Electrolux Italy S.P.A, Porcia, Italy

An experimental investigation of the fatigue behaviour of notched and unnotched specimens made of 25% wt. short glass fibre reinforced recycled Polypropylene filled with mineral filler is presented.

To this end, plain and double-edge notched specimens (with notch radius ranging from 0.25 mm to 10 mm) were produced by injection moulding and tested under tension-tension fatigue, highlighting the effect of the notch root radius and the notch geometry. During the fatigue test, the damage evolution was monitored using a traveling microscope to define the number of cycles spent for the fatigue crack nucleation. The fracture surfaces were careful analysed both at the macroscopic and microscopic level, discussing the analogies existing between plain and notched specimens.

The fatigue tests were reanalysed in terms of net stress amplitude defining the traditional stress-life curves, each of them fitted on data derived for a given specimen geometry. Then, an energy-based approach was proposed for the assessment of fatigue life spent for the crack nucleation. The model is conceptually based on the actual damage evolution observed both during the fatigue tests and reported in the technical literature: the initiation of a macro crack results from the accumulation of damage in the matrix. Thus, the strain energy density evaluated in the matrix and averaged on a structural volume embracing the notch tip was adopted as fatigue damage index to correlate in a single scatter band the fatigue data of unnotched and notched specimens.

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FATIGUE DESIGN 2023

FD23-92

Spar cap/shear web debonding under fatigue loading studied on the DTU 12.6m wind turbine blade

Philipp Ulrich Haselbach, Peter Berring, Sergei Semenov

Technical University of Denmark, Roskilde, Denmark

Understanding fatigue damage initiation and propagation of composite wind turbine blades is an essential step towards the design of reliable prognostic health management systems (PHM) and to improve lifetime predictions. This study presents a numerical and experimental investigation of the debonding process in the spar cap/shear web region of a full-scale composite wind turbine blade under fatigue loading.

For this purpose, numerical simulations have been performed to design and specify the size and locations of artificial defects to provoke steady, controllable damage growth in the adhesive bondline between the rear shear web and cap region of the DTU 12.6m wind turbine blade under fatigue loading. Subsequently, these artificial defects are embedded into the manufacturing process of the composite wind turbine blade with the help of slip foils and partially perforated slip foils to create regions with no bonding, 30% and 50% bonding of the contact surfaces of the adhesive joint, respectively.

The numerical predictions and experimental results of the damage growth in the adhesive joint are compared. The observations demonstrate the complexity of damage growth of composite structures under fatigue loading and the necessity of accurate numerical prediction tools for reliable prognostic health management systems.

S05

Contact Fatigue and Fatigue Transmission System

Chairmen:

Yan Ming Chen & Pascal Daguier

Christophe Reynaud & Luc Amar

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FATIGUE DESIGN 2023

FD23-57

In-situ image based crack measurement methodology for gear single tooth bending fatigue testing

Isaac Hong, Haelie Egbert, Ahmet Kahraman

The Ohio State University, Columbus, USA

Geared powertrains are one of the most common forms of mechanical power transmission found in aerospace, automotive and industrial sectors.

Gear failure is costly in downtime, direct financial cost, and even safety/human life perspective.

Fatigue failures are among the most frequent causes of gear failure and include both contact fatigue related failures and bending stress related fatigue failures.

Bending failures are catastrophic as they can result in almost instantaneous loss of torque transmission capability.

Modeling and prediction of this failure is therefore necessary from both a crack propagation view and a cumulative damage perspective, as crack propagation can be a direct measure of fatigue damage.

Current crack propagation model validation relies on post-mortem analysis of the crack path to match against model results. In this study and optical image-based technique using high speed imaging technology is developed to measure cycle to cycle crack propagation rates during a gear single tooth bending test.

An image processing algorithm is developed to automatically measure the crack length at each relevant frame. The methodology is then used to measure cyclic crack propagation rates under various load levels and fatigue lives.

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FATIGUE DESIGN 2023

FD23-59

Rolling contact fatigue design of induction hardened steels: experimental methodology

Guillaume Thoquenne[1], Luc Amar[1], Philippe Amuzuga[2], Albin Ponceau[3]

[1]CETIM, Senlis, France. [2]CETIM, Saint-Etienne, France. [3]Rollix Defontaine, La Bruffière, France

Large dimension bearings and gears are generally made of surface hardened steels after induction heating or case-hardened steels. Unlike case hardened steels, induction surface hardened steels show a drastic reduction of material properties (hardness, endurance limit…) between the treated layer and the core called "metallurgical slope of the transition zone". The combination between the use of conventional hardened depth dimensioning methods (depth greater than 2 times the maximum shear depth) and a severe metallurgical slope allows the existence of an unconventional site of fatigue cracks initiation leading to early failure.

There is no current method for sizing this phenomenon. In collaboration with users and manufacturers of slewing bearings, CETIM is thus developing a simplified sizing methodology which aims to set up easy to use design rules.

This methodology is based on the correlation between rolling contact fatigue tests performed on a twin-disc machine, which reproduced the contact between rolling elements and rings, and finite element calculations taking into account the geometry of the specimens and the gradient of mechanical characteristics.

This article presents an experimental methodology on a twin-disks test bench to reproduce this type of failure.

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FATIGUE DESIGN 2023

FD23-60

The influence of shot peening on gear teeth micropitting and contact fatigue failure

Dalia Jbily[1], Fabien Lefebvre[1], André Simonneau[2]

[1]CETIM, Senlis, France. [2]TEXELIS, Limoges, France

Case-hardened gears present a high contact fatigue load capacity in a compact and light mechanical transmission systems but sometimes, micropitting appears. This initial failure can lead to early contact fatigue failure called macropitting (NF ISO 10825-1).

A previous study has demonstrated that an appropriate shot peening treatment could reduce the micropitting phenomenon via tests on a twin disc machine.

The aim of this paper is to study the influence of shot peening on the micropitting of case-hardened gears tooth flank and its development to macropitting.

Experimental tests are carried out using a back-to-back gear test bench, an interrupted test method is defined in order to monitor the micropitting initiation and its propagation on the tooth flank. Two variations of carburized spur gear specimens are tested. The reference specimen has a case-hardened grinded tooth flanks which is a typical gear application. The other specimen has a case-hardened grinded tooth flanks with a shot peened finishing process. The fatigue tests are run until the appearance of macropitting.

The performed inspections of specimens indicate that shot peening modifies the surface roughness, the surface topography and increase the compressive residual stress.

The experimental results show that micropitting occurs on both shot-peened and non-shot-peened gears after approximately the same running time. However, a difference is observed in the propagation of micropitting on the teeth surfaces. In comparison to reference gears, shot peening has postponed the apparition of macropitting of about 50% for the tested specimens. An analytical study is also conducted to validate the prediction of micropitting using the ISO/TR 6336-22 by comparing the results with the occurrence of micropitting on the tested gears.

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FATIGUE DESIGN 2023

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Thermal and thermochemical treatments against fretting failure applied to power transmissions

Luc Amar[1], Yanming Chena[2], Michel Pasquier[3]

[1]CETIM, Senlis, France. [2]Yanming.Chen@CETIM.fr, Senlis, France. [3]CMD GEAR, Cambrai, France

Some power transmission components are subject to fretting corrosion failure mode which results in early wear of the mating surfaces or premature fatigue crack initiation. The fretting corrosion is generated by micro-movements of surfaces in contact. In mechanical transmissions, it can be found in particular at the level of shrink-fit connections (bearing rings for example) and key and spline connections when they are misaligned.

The french commission of mechanical transmissions and bearings and CETIM are studying the capacity of technical solutions to delay the fretting damage (materials, treatment, lubrication, ...). This article presents the study of the impact of thermal and thermochemical treatments of steels used in power transmissions on the appearance, morphology and intensity of corrosion fretting.

Among the usual materials and treatments in mechanical transmission (NF EN 683, ISO 6336-5), the following variants have been studied: through hardened (42CrMo4, 100Cr6), steels treated by surface quenching (42CrMo4), case hardening steels (20MnCr5) and nitrided steels (42CrMo4). These variants are compared using a standard ASTM G204 test which consists in oscillating a pin (here in 100cr6) under pressure and without lubricant on a plate (tested variant) for a period of 24 hours. The range of displacement is fixed at 50µm or 100µm depending on the variant. The tangential forces during the tests, then the mass and the topography of the impressions of the pins and plates after test are measured, analyzed and compared.

The experimental study highlights wear mechanisms and typologies that differ between the variants of thermal and thermochemical treatments and the amplitudes of microslip.

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A hybrid ann multiaxial fatigue model for the assessment of fretting fatigue under variable amplitude shear loading

Giorgio Brito Oliveira[1], Raphael Cardoso[2], Raimundo Freire Júnior[2], José Araújo[3]

[1]University of Brasilia, Brasilia, Brazil. [2]Federal University of Rio Grande do Norte, Natal, Brazil. [3]Universidade de Brasilia, Brasilia, Brazil

To foresee the life of fretting fatigue with variable amplitude loading, a hybrid model based on non-local multiaxial fatigue parameters and artificial neural networks (ANN) has been proposed. Thus, in order to compute the impact of the variable amplitude loading, the model has been developed based on equivalent stress parameters related to crack nucleation and Miner's cumulative damage rule. To validate the models, fretting fatigue tests of several different aeronautical alloys were gathered from the literature and used in the ANN training. Furthermore, the analyzed data encompass a wide range of loading conditions and different contact geometries, which contributes to the formulation of a generalized and robust approach for the assessment of fretting fatigue problems. The proposed methodology aims to effectively address the complexities inherent to fretting fatigue under variable amplitude stress. Additionally, these types of fatigue ANN models have been demonstrating a strong capacity for generalization, making them highly promising for future industrial applications.

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FD23-130

Finite elements modelling and assessment of ceramic rollers with edge cracks

Yuri Kadin, Charlotte Vieillard, Jeroen Wensing, Anand Theerthan

SKF, RTD, Houten, Netherlands

Hybrid bearings, i.e. bearings consisting of silicon nitride (Si3N4) rolling elements and steel rings, are superior over full-steel bearings in multiple aspects. This concerns lightness (essential for airspace and energy saving applications), higher stiffness, better resistance to wear and corrosion compared to the full-steel bearings. Thus hybrid bearings are becoming a common product available for multiple applications. Reliable operation of hybrid bearings is linked to the quality of ceramic rolling elements, and for this each ball or roller is optically inspected. This inspection aims to reject components, containing surface imperfections which during bearing operation can lead to the progression of Rolling Contact Fatigue (RCF) damage. In the case of ceramic roller (used in hybrid CRBs), the situation is more complex compared to balls, because in rollers the criticality is dependent on the imperfection location. Indeed, the edge imperfections are subjected to different stress state compared to the ones located at the raceway. A lot of work has been done for the imperfection criticality in rolling contact, however less attention was given to the roller chamfer and the end-face. Hence, the current work focus is the modeling of edge imperfections in order to assess the risk of RCF failure. Based on this knowledge the guidelines for the roller inspection will be developed. The imperfection considered in the proposed study is the surface crack which can be formed during sintering or machining process. Semi-analytical contact mechanics is combined here with the computational fracture mechanics, which is implemented using the Finite Elements (FE) method. The outcome of the FE model is the Stress Intensity Factors (SIF), which is used here to assess the risk of fatigue crack growth, related to the damage propagation and to spalling. Wide range of contact conditions (including the roller misalignment effect), different roller design and various imperfection dimensions are covered by the parametric analysis of the current work.

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FATIGUE DESIGN 2023

FD23-133

Characterisation of cracks growth and fatigue life distribution estimation of carburized steels

Franck Morel[1], Vincent Argoud[2,3], Etienne Pessard[1], Daniel Bellett[1]

[1]ENSAM, Angers, France. [2]ENSAM, ANGERS, France. [3]SAFRAN TECH, Magny-Les-Hameaux, France

The mechanical properties of the surface of steel gears used in turbojet and turboprop engines are generally improved via thermochemical treatments such as carburizing. These treatments induce microstructural modifications and compressive residual stresses in the sub-surface and a global increase of the hardness of the surface. Hence, the complexity of the fatigue design of a gear tooth root is due to the interaction between the mechanical loading gradient and different properties gradients. This complex situation can be studied via the analysis of notched specimens subjected to bending. This work is dedicated to the fatigue crack propagation of semi-elliptical cracks in such specimens made of carburized steel.

The crack growth of an artificial defect machined at the root of the notch is derived from optical measurements made on the surface of the specimen all along the test, and from fracture analyses performed on specimens after different number of cycles. These measurements are used to derive the evolution all along the test of the value of the stress intensity factor via weight functions proposed by Shen et al. – while taking into account residual stress field due to carburizing and crack shape change during its propagation –, and the parameters of a Paris' law.

Finally, it is proposed to predict the probability distribution of the fatigue life of the material from Monte Carlo simulations assuming this deterministic Paris' law and an initial crack size following a Fréchet distribution. The comparison between the numerical results and the experimental evidence validates this probabilistic approach.

S06

Damage Tolerance and Fatigue Life

Chairmen:

Bruno Depale & Luc Remy

Joerg Baumgartner & Franck Morel

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FD23-18

Residual life assessment of deep rolled railway axles considering the effect of process parameters

Tobias Pertoll[1], Christian Buzzi[1], Martin Leitner[1], David Simunek[2], László Boronkai[2]

[1]Graz University of Technology, Institute of Structural Durability and Railway Technology, Graz, Austria
[2]Siemens Mobility Austria GmbH, Graz, Austria

Deep rolling is a powerful tool to increase the fatigue life of railway axles. The application introduces compressive residual stresses into the area near the surface, which are the most effective positive influence on the fatigue behaviour and the remaining service life in the presence of a crack.

This paper investigates the remaining service life of deep rolled railway axles. Previous research studies are used as basis for this work whereas, firstly, an elaborated crack growth model for the application on railway axles applicable for common railway axle steels was developed. This model is based on the NASGRO equation considering crack closure as well as load sequence effects and local residual stress conditions. Secondly, a numerical deep rolling simulation model validated with experimental residual stress measurements to determine the introduced residual stress state and to investigate the influence of various process parameters such as deep rolling force, feed rate, friction coefficient and tool geometry on the introduced residual stress state.

In this study, the comprehensive outcome of both studies is connected in order to evaluate and compare the residual fatigue life with the presence of different deep rolling-induced in-depth residual stress distributions at the railway axles. The crack growth study involves combinations of different deep rolling parameters, load amplitudes as well as initial crack sizes and compares the residual life results. Finally, the study further leads to an evaluation of optimal deep rolling parameters in regard to the remaining service life which facilitates an elaborated fatigue design of railway axles.

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Analysis of dynamic features on local fatigue cracks in steel bridges

Qingyang Wei[1], Balázs Kövesdi[2], Maosen Cao[3], László Dunai[2]

[1]Hohai University, Nanjing, China. [2]Budapest University of Technology and Economics, Budapest, Hungary
[3]Hohai Univarsity, Nanjing, China

The paper presents the application of a new nonlinear damage detection method for fatigue cracks on the deck system of a steel bridge. The István Türr Danube bridge in Hungary is a truss girder-type steel mixed road/railway bridge having orthotropic deck system for highway traffic placed on the top of the main girders. Fatigue cracks have been observed on the bridge deck at the junction point of the longitudinal stiffeners and cross-girders on the stiffener welds. The fatigue cracks have been visually detected during the regular inspections. On the basis of an advanced fatigue analysis, reparation method to avoid the crack propagation and the appearance of new cracks have been designed and manufactured on the bridge. The current research has the aim to present the application possibility of an innovative measurement-based damage detection method to identify the cracks on the structure between the regular inspection periods, using the current bridge example. This method is characterized by comparing the difference in dynamic responses of two neighboring sensors. The dynamic responses are obtained by pairs of sensors at locations prone to fatigue cracks with vehicle loading. The pairs of sensors on both sides of fatigue cracks will appear to have significant differences due to the local dynamic disruption induced by the fatigue cracks. To identify the presence and severity of fatigue cracks, the correlations of the measured dynamic responses are compared in time (frequency/time-frequency) domain. The proposed method can be an efficient tool for fatigue crack detection in an early time, which can be implemented in monitoring systems operating on bridges.

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FATIGUE DESIGN 2023

FD23-66

Plasticity-induced crack closure in the presence of loading irregularities in short cracks initiated at interior defects

Kimmo Kärkkäinen[1], Joona Vaara[2], Miikka Väntänen[3], Tero Frondelius[1,2]

[1]University of Oulu, Oulu, Finland. [2]Wärtsilä, Vaasa, Finland. [3]Global Boiler Works, Oulu, Finland

Non-propagation of surface cracks in constant-amplitude loading has been widely observed empirically. The phenomenon is linked to the well-known short crack problem; short cracks have been observed to propagate at a faster rate compared to equivalent long cracks. It is also known that crack closure reduces crack driving force, but needs a certain crack propagation length to become effective. On top of this, cracks initiating at a notch are affected by the notch plasticity field, which can delay crack closure saturation. Considering these findings, it appears that the phenomena of crack closure and crack arrest are linked.

Plasticity-induced crack closure is intrinsic to Mode I crack propagation in metals. Present work attempts to determine the role of plasticity-induced crack closure in non-propagation behavior. The purpose is to gain understanding of mechanisms affecting fatigue crack propagation and non-propagation.

In present work, extensive elastic-plastic finite element analysis of near-threshold propagation of short cracks nucleating from surface defects is presented. As non-propagation behavior is typical for surface defect initiated fatigue cracks, the modeled test specimen geometry is a circular cylinder with a microscopic hemispherical pit representing a surface defect. Existing three-dimensional finite element model allows for the detailed studying of fatigue crack propagation and plasticity-induced crack closure.

It is shown that the delayed development of plasticity-induced crack closure seems to significantly promote crack non-propagation behavior in surface defect initiated cracks. Additionally, differences in plasticity-induced closure along the transition from plane stress to plane strain contribute to the shape of the growing 3D crack.

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FATIGUE DESIGN 2023

FD23-83

3D study of fatigue crack growth with overload effects in AlSi alloy through synchrotron X-ray tomography and digital volume correlation

Lucas Sanciet-Munier[1], Nathalie Limodin[1], Jean-Yves Buffière[2], Jean-François Witz[1], Michel Coret[3], Julien Réthoré[3], Ghita Bahaj Filali[3], Yves Gaillard[4], Michel Fleuriot[4], Joël Lachambre[2], Anne Bonnin[5], Goran Lovric[5], Andrew King[6], Arnaud Weck[7]

[1]LaMcube, Villeneuve-d'Ascq, France. [2]MATEIS, Villeurbanne, France. [3]GeM, Nantes, France
[4]CETIM - CTIF, Sèvres, France. [5]SLS - Paul Scherrer Institute, Villigen, Switzerland. [6]SOLEIL, Saint-Aubin, France
[7]University of Ottawa - Dpt. of Mechanical Engineering, Ottawa, Canada

Through examination of fatigue crack growth in 3D synchrotron computed tomography, and displacement fields computation with digital volume correlation, the effects of a single tensile overload on crack behaviour and growth are investigated. The experimental procedure of this study consisted in subjecting a corner-notched AlSi dog-bone type samples to cyclic tensile loading in-situ at a synchrotron X-ray tomography beamline. During the loading sequence, 3D reconstructed scans of the samples were regularly acquired. When nominal crack growth is achieved, single overloads in the loading sequence were applied. Characteristic periods of crack retardation after overloads have been observed, with crack growth recovery occurring preferentially in the bulk of the sample, rather than close to the free surfaces.

Extracting crack opening displacement maps from displacement fields allows the crack closure phenomenon to be studied qualitatively and quantitatively by trying to link areas affected by crack closure to the plastic zones created by the overload.

In order to quantify crack growth behaviour, crack growth rates and stress intensity factor ranges are computed. The systematic study of these parameters is expected to yield quantitative insight into the retardation phenomenon.

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FD23-88

Digital twin for predicting progressive damage in operating pressure vessels

Izat Khaled[1], Mohamed Bennebach[1], Salim Chaki[2], Modesar Shakoor[2], Dmytro Vasiukov[2], Jean-Louis Iwaniack[1], Philippe Rohart[1], Samir Assaf[1]

[1]CETIM, Senlis, France. [2]IMT Nord Europe, Douai, France

Pressure vessels (PV) are intended for the production, storage, or transportation of products under high pressure. The energy contained in these equipment's is often very important and can, in case of failure of the enclosure, cause human, material and environmental damages in the vicinity of the accident. Thus, optimal design, maintenance and structural health monitoring of pressure vessels are major concern for the industrial actors of this field.

The first objective of this study is therefore to contribute to the development of a methodology for real-time assessment of the integrity of PV, by implementing a novel predictive maintenance strategy based on the Internet of Things (IoT) and digital twin technologies. The second technological goal is to develop methods to optimize the design of the next generation pressure vessels and increase their operational reliability.

According to the definition of the Alliance Industry of Future: "A digital twin is an organized set of digital models representing a physical entity of the real world to respond to specific problems and uses". The digital twin is a virtual clone of a physical system or process. It systematically implies the existence of a «digital model» coupled with the object it copies. Depending on the system concerned and the desired use, it can be a geometric, multi-physical, functional, behavioral, and decision-making model. It must evolve over time like its real twin. It makes it possible to understand, analyze, predict, or optimize the operation and management of the real entity.

In this paper, first is presented a state of the art on the pressure vessels design according to codified rules (CODAP…), and on various existing maintenance strategies. Then the developed physical model is presented and discussed. This, considering specificities like welds, complex stress states and local defects. Welds are modeled and analyzed according to IIW recommendations based on a stress life approach, non-welded regions with complex stress states are analyzed with multiaxial fatigue criteria and damage tolerance is applied for zones with local defects.

The developed model, once calibrated with experimental results, allows also generating data (stress, strain, damage…) to feed the data science model and reconstruct the stress field in the complete equipment from a reduced number of sensors. The latter is done thanks to development and improvement of an intelligent sensor placement code, with the aim of minimizing the number of sensors needed to monitor the health of the equipment.

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FATIGUE DESIGN 2023

FD23-114

Local relaxation of residual stress in HFMI-treated high-strength steel welded joints subjected to high-peak loads

Yuki Ono[1], Heikki Remes[1], Koji Kinoshita[2], Halid Can Yıldırım[3], Alain Nussbaumer[4]

[1]Aalto University, Espoo, Finland. [2]Gifu University, Gifu, Japan. [3]Aarhus University, Aahus, Denmark. [4]Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland

Lightweight welded steel structures with high fatigue strength are demanded in various industrial applications such as wind farms, offshore structures, ships, and bridges. High-frequency mechanical impact (HFMI) treatment is an effective tool for this demand. Applying the HFMI treatment introduces compressive residual stress in the weld toe and material hardening in the surface layer, improving the local weld geometry and removing typical weld defects. A matter of concern in real situations is the alteration in compressive residual stress layer by high-peak loads, which may suppress the benefit of HFMI treatment. Since the crack initiation and propagation periods within short crack lengths significantly contribute to the total fatigue life for the HFMI-treated welds, a deep understanding of local evolution and relaxation of residual stress at a potential crack initiation site is needed. Thus, this study aims to clarify the local relaxation of residual stress in HFMI-treated high-strength steel welded joints subjected to high-peak loads. First, experimental measurements characterize residual stress, local notch geometry, and material properties for the HFMI-treated welds. Then, the weld joint behaviour is simulated with FE analyses incorporating those experimental measurements and load cycles, including high tensile and compressive peak loads. This simulation considers two types of HFMI geometry models: with or without roughness effect on the HFMI groove surface. Finally, the changes in residual stress due to the applied loads at different crack initiation potential sites and the influence of the model definition of HFMI geometry on residual stress relaxation are discussed.

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FD23-123

Active thermography techniques for the analysis of residual stresses in materials and components

Francesca Curà, Raffaella Sesana, Luca Corsaro, Luca Santoro

Politecnico Di Torino, Torino, Italy

Active Thermography (AT), also called stimulated thermography, is a Non Destructive Technique (NDT) widely used to detect defects, concentrated and distributed, and to generally characterize damaging conditions in materials and components.

Unlike Passive Thermography, Active Thermography requires an external excitation source that may be optical (flash lamps, halogen lamps, laser) or inductive (electro-magnetic coils), as well as an infrared thermocamera as response sensor.

Object of this work is the definition of a method based on Active Thermography for detection and measurement of residual stresses on materials and components.

The problem to determine local residual stresses values is well known in industrial environment, where only destructive techniques are available to characterize residual stresses in components. The necessity to establish a nondestructive procedure is a primary issue.

The proposed method aims to relate thermal parameters (as, for example, the thermal diffusivity) of the system to surface residual stresses in the material and to provide a corresponding quantitative local characterisation.

To set up the method and to define the best procedure for measurements, an experimental activity was organized with a particular attention devoted to both specimens and excitation source choice.

Specimens were chosen without and with residual stresses, due to thermal and mechanical surface treatments. In particular, steels gears with and without thermal and mechanical treatment were analysed and stress entity characterised.

Different excitation sources were chosen, as laser source and lamps, and corresponding power and time period for excitation were tested.

The final aim of this activity was to make a cross check between experimental set up parameters and obtained results in terms of residual stresses distribution and entity for each case of study.

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FD23-124

Measuring mechanical properties and residual lifetime by micro-sampling & fractography

Laurent Ponson

Tortoise, Paris, France. CNRS-Sorbonne Université, Paris, France

Predicting the residual lifetime of structures require the prior knowledge of the material failure properties and the applied loading conditions, two crucial information that are generally missing for in-service structures.

Here, we propose a new methodology of predictive maintenance that provides such information without requiring to destructive testing. Instead, our approach measures both the residual mechanical properties and the applied load amplitude from the sampling and then the test of a (non-destructive) millimetric sample. This innovative approach relies on the determination of the fracture properties of materials through the scan and analysis of their fracture surface by statistical fractography, an engineering technique that can be applied robustly and safely to submilimetric specimens.

In this presentation, I will show how this innovative approach paves the way for the reliable predictions of the residual lifetime of structures for various ranges of applications, including cracked structures under fatigue conditions. I will also finally the applications of this methodology and its implications in maintenance of old structures through industrial use cases.

S07

Experimental and Numerical Design and Validation Methods

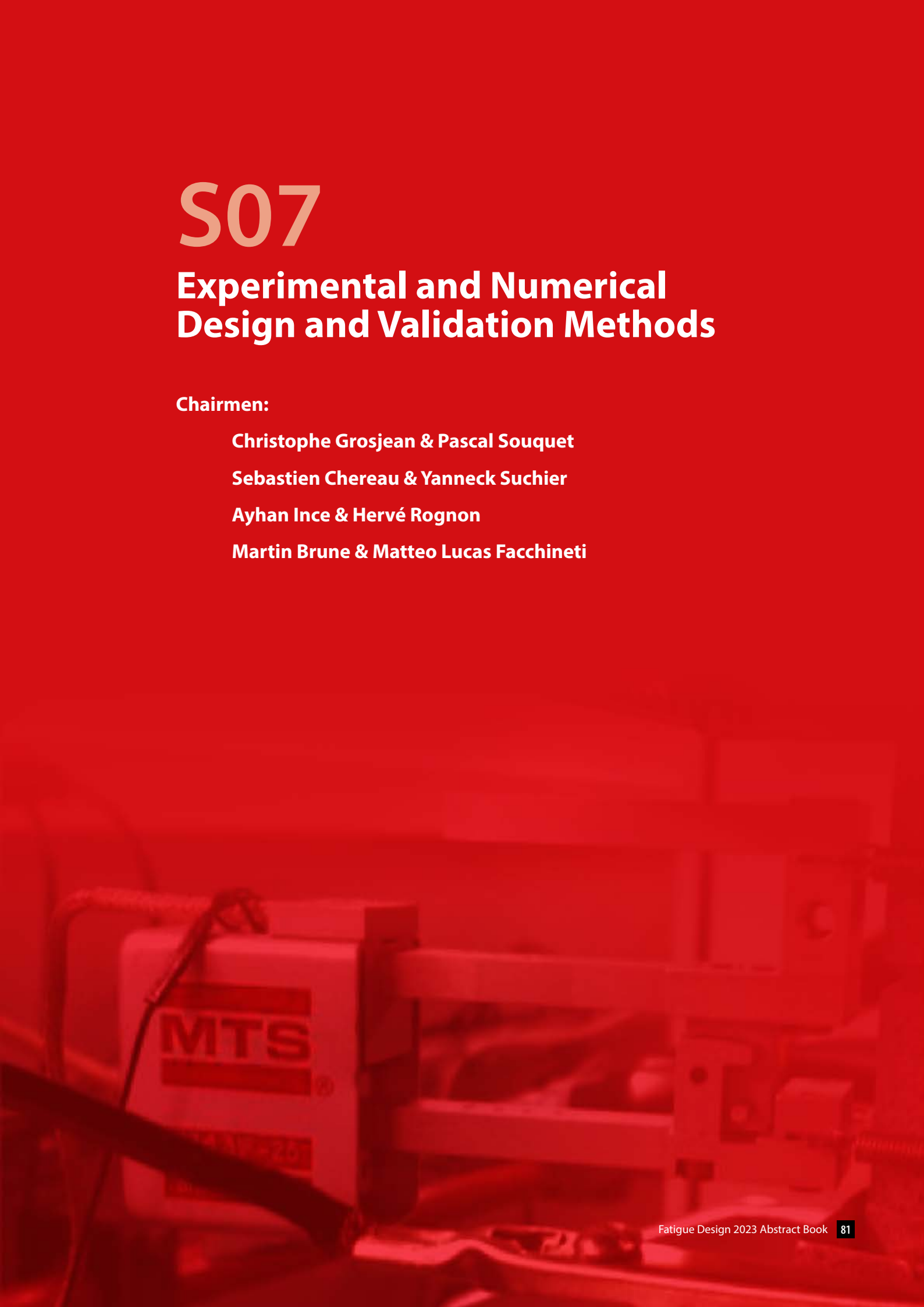
Chairmen:

Christophe Grosjean & Pascal Souquet

Sebastien Chereau & Yanneck Suchier

Ayhan Ince & Hervé Rognon

Martin Brune & Matteo Lucas Facchineti



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FATIGUE DESIGN 2023

FD23-12

New test-based detail categories for fatigue design of crane runway beams

Mathias Euler

Brandenburg Technical University, Cottbus, Germany

Top-running overhead bridge cranes are frequently supported by welded crane runway beams whose wheel loaded constructional details, such as the welded flange-to-web connections and the continuous double fillet welds to fasten the crane rail, are subject to multiaxial fatigue. The fatigue stressing is composed by normal and shear stresses due to the local wheel load introduction and global bending. As the fatigue stressing exhibits a phase shift between the stress components, it is referred to as nonproportional.

The currently applicable detail category of welded flange-to-web connections according to Part 1-9 of Eurocode 3 is derived theoretically and does not appropriately address the specifics of these connections. A classification of rail welds including a detail-related nominal stress formula is missing.

A design proposal for both constructional details is presented that is based on fatigue tests on girders under traveling and stationarily pulsating wheel loads to simulate the nonproportional fatigue stressing. To derive new detail categories from the test results, a fatigue failure hypothesis is formulated modifying Findley's critical plane approach for the evaluation of welded constructional details with partial penetration and weld root failure on the basis of notch stresses and accounting for the residual stress state.

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FD23-39

A simplified fracture mechanics method for fatigue life analysis of weld roots

Magnus Andersson, Per-Olof Danielsson

Volvo CE, Braås, Sweden

Volvo CE currently uses the effective notch stress method for assessing fatigue life in welded structures. For large structures such as frames, a sub modelling technique with a very fine mesh is necessary using millions of DOF. Stress tensors from unit load cases, estimated with FEA, are combined with time history loading from Multi Body Simulations of the complete machine operating on digitized test tracks. A critical plane approach (the Modified Wöhler Curve Method) is used to estimate the fatigue life. The usage of the effective notch method implies a very time-consuming design process.

An LEFM approach for weld roots would be even more time-consuming but would be a more natural approach since the weld root consists of crack like defects. To overcome the drawbacks with the current design process that involves usage of the effective notch method, a hybrid method is defined using pre-calculated geometry factors for different crack sizes and weld geometries. The geometry factors as a function of crack size, and the weld geometry, are stored in a database. From the unit load cases the structural stress using a coarse mesh in the weld is extracted. Together with the geometry factors, the stress intensity factors may be estimated and used with Paris law to calculate the fatigue life of welds.

A comparison between the effective notch method, LEFM and the new hybrid method is carried for typical fillet welds are presented in this paper.

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FD23-42

Nominal stresses in continuous and intermittent rail welds of crane runway beams

Elena Sidorov, Mathias Euler

Brandenburg University of Technology, Cottbus, Germany

Crane runway beams of hot-rolled I sections are frequently the supporting structures of top-running overhead bridge cranes. In case of light crane service, the crane rails are usually fastened to top flange of the crane runway beams by fillet welding. A survey among steel construction companies is presented showing that continuous rail welds as well as intermittent rail welds are commonly used.

The rail welds are subject to multiaxial fatigue since they are exposed to normal and shear stresses due to the local wheel load introduction and global bending. Currently, Part 1-9 of Eurocode 3 neither provides an appropriate detail category nor a nominal stress formula for rail welds.

The paper describes the differences in the stress analysis between intermittent and continuous rail welds because of the contact between rail and top flange that has to be assumed for intermittent rail welds. Based on work samples, the contact conditions of intermittent rail welds are characterized as ‚technical contact' (in contrast to ‚ideal contact') due to imperfections within the contact surfaces that are described in detail.

A Finite Element model is presented that accounts for the ‚technical contact' between rail and flange. This model is analysed in a parametric study to identify the decisive contact parameters on the nominal stresses in intermittent rail welds. A nominal stress formula is proposed.

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FATIGUE DESIGN 2023

FD23-50

The effect of heat treatment on fatigue strength of additively manufactured AlSi10Mg

Martin Matušů[1], Jan Papuga[1], Jakub Rosenthal[2], Jan Šimota[1], Libor Beránek[1], Ludmila Růžičková[1]

[1]CTU in Prague, Prague, Czech Republic. [2]OTH Amberg-Weiden, Amberg, Germany

This presented study focuses on examining four different heat treatment conditions and their impact on fatigue life performance of additively manufactured AlSi10Mg specimens. The main focus is on the High Cycle Fatigue (HCF) domain and its transition to the Fatigue Limit (FL) domain. Four different heat treatments are applied to obtain four series of specimens with an identical hourglass geometry. Fatigue experiments have been carried out in the uniaxial tension with the stress ratio of 0.1 on a resonant machine. All specimens are additively manufactured using Selective Laser Melting (SLM) technology in a single print batch to eliminate any inconsistence caused due to their printing in several platforms. The surface of specimens in the active area is kept as printed, without any additional machining operation. The temperature was measured with a thermal camera during cyclic dynamic loading as an additional parameter for the characterization of different heat treatments of all tested specimen. The surface temperature is thanks to the Self-Heating effect (S-H) directly linked with a heat dissipation during dynamic loading. A specific self-heating test with subsequently increased load amplitude in individual load steps is presented to determine a stabilized temperature in each step for a further analysis. The paper thus presents the standard HCF response of AM specimens and the thermal response to the applied heat treatment and discusses the observed output.

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Study and modeling of fatigue properties at very large cycles from self-heating tests under cyclic loads

Théo Sévédé[1], Shabnam Arbab Chirani[1], Younes Demmouche[2], Sylvain Calloch[1]

[1]IRDL, Brest, France. [2]IRDL, BREST, France

For several years, research teams have been interested in characterizing HCF properties from self-heating tests. This method reduces the time and cost of characterizing the fatigue properties of materials. It is based on temperature monitoring of the specimen during cyclic loading.

This method has been widely studied and validated at room temperature and at low frequency on many materials. However, the application of this method to high frequency tests requires the development of a new approach. Indeed, the particular conditions of the high frequency test at the geometrical, thermal and mechanical level makes the classical 0D approach impossible and forces to use a 1D approach.

An experimental protocol was therefore set up to perform self-heating tests on a high frequency VHCF machine as well as a numerical model of the test in order to test different virtual test configurations. The objective of the study is to adapt the self-heating method for high frequency solicitations in order to determine the VHCF properties of different metals, to be able to relate these measurements to failure mechanisms and to know how the high frequency thermal signature can help us to better understand and model the VHCF properties of metals.

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Fatigue strength of synthetic rope

Francis Blanc[1], Antoine Nicolle[2], Yan-Ming Chen[1], Sophie Toillon-Rey Flandrin[1], Fabien Lefebvre[1], Jérémy Blasiak[3], Olivier Gay[3], Frédéric Fayolle[4], Vincent Leray[5], Arnaud Miton[4]

[1]CETIM, SENLIS, France. [2]SENLIS, SENLIS, France. [3]MANITOWOC Cranes, Dardilly, France. [4]REEL, Saint-Cyr-au-Mont-d'or, France. [5]NOV BLM, Carquefou, France

Crane industries and industrial lifting companies aims to reduce the overall weight of the winch and limit the systematic use of steel wire rope in order to increase their competitiveness. This overall weight reduction can result from the lightering of the rope using synthetic material. Metallic rope fatigue behaviours are well documented and criteria for maintenance are established in the ISO 4309 standard unlike non-metallic ropes fatigue behaviours. Many unknowns remain as failure modes, fatigue strength, ratting criteria, tribological behaviour and friction, etc...

In this context, CETIM and its industrial partners within a working group have launched research program to evaluate the fatigue performance of synthetic ropes subjected to periodic bending stress. A specific scale 1:1 test bench which simulates the winding of the rope around the pulleys and drums was developed and Fatigue tests was performed on synthetic ropes. This test bench can be used on several rope geometries and dimensions, material (aramid, HMPE…), and loadings.

This paper presents the test bench and discusses the experimental methodology developed to test synthetic ropes in fatigue bending mode.

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Fatigue crack growth and closure: effect of load ratio and specimen geometry

Théotime Asselin[1,2], Gilbert Hénaff[2], Olivier Ancelet[1], Guillaume Benoit[2]

[1]*Framatome, Courbevoie, France.* [2]*Institut P', Chasseneuil du Poitou, France*

The design of a nuclear power plant component requires a sound assessment of the risks of crack initiation and propagation. The field experience of French Pressurized Water Reactors (PWR) indicates that fatigue and stress corrosion cracking are the two main damage mechanisms observed. Therefore, it is necessary for the manufacturer and the operator to have a better understanding of those mechanisms to improve the associated design rules. In this context, a part of the research conducted at Framatome focuses on the understanding of fatigue crack propagation for specific loadings in relation with crack closure effects to accurately determine the crack propagation life.

During their life, components must endure primary (stress-controlled) and secondary (strain-controlled) loadings. As regards crack propagation, the commonly used CT-specimen geometry is however limited to primary loadings at positive load ratios, which are not representative of the actual loading conditions. To overcome this limitation, a cylindrical specimen containing an initial defect as starter is here introduced, allowing to conduct tests under primary or secondary loading, as well as negative load or strain ratios. Yet, as this geometry is not standardized, it is necessary to compare the results obtained with it to a standard CT specimen. Standard tests conducted using CT specimens at different load ratios on two different steel grades (304L Stainless Steel and French Reactor Pressure Vessel steel 18MnD5) including crack closure measurements are replicated on these cylindrical specimens where the crack propagation is monitored by the Potential Drop Method. The present paper compares and analyses the results in terms of fatigue crack growth rates and crack closure effects.

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FATIGUE DESIGN 2023

FD23-79

Fatigue design of chains in mooring lines

Per Haagensen[1], Mads Aursand[1], Gunnstein Frøseth[1], Jorge Mendoza[2], Jochen Köhler[1], Bjørn Skallerud[3]

[1]Norwegian Univ Science and Technology, Trondheim, Norway. [2]Equinor, Trondheim, Norway. [3]Norwegian Univ Science and technology, Trondheim, Norway

Fatigue is a critical failure mechanisms of catenary type mooring lines since failure in one or more lines causes drift of the vessel and thereby jeopardizes the safe flow of oil and gas through subsea installations and riser pipes. The fatigue strength of chains is influenced by several factors, the main ones being the number of stress cycles, mean stress, corrosion state and length of the mooring lines. In order to predict the reliability in the residual service live of the mooring line the effect of these factors must be understood and integrated in a corresponding probabilistic model representation of the fatigue phenomenon. Since the validity of Miner's rule is also important for the prediction of life under variable amplitude loading a wave spectrum was developed and tests were carried out under service loading.

This paper presents results from tests on R4 high strength steel chains that had been in service from 9 to 20 years in the North Sea. The main objectives of the tests were to determine remaining life and the correlation between the state of corrosion damage and life. A considerable effort was made to determine surface damage criteria in terms of damage categories from 3D scans that were tied to fatigue life.

The results are expected to provide input to future revisions of fatigue design guidance for mooring chains, in particular changes to the design S-N curves in DNV GL-OS-E301 Position Mooring.

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FD23-84

Integration of fatigue analysis in FEM solver for faster more reliable process

Michael Klein[1], Jacques Marchesini[2], Laurent Dastugue[2]

[1]INTES GmbH, Stuttgart, Germany. [2]INTES France, Rambouillet, France

Fatigue analysis is established in industrial applications. The findings are used for the design of components in lightweight construction.

The classic fatigue analysis leads to additional requirements for the simulation process. The exchange of large amounts of data between software/compute servers with different interface formats is necessary. The implementation and error-free use of this process is the responsibility of the user. In addition to data handling, the different release periods of the software involved must also be considered.

The full integration of the fatigue analysis into a general FEM solver solves the process issue. Both parts of the analysis, the classic stress analysis, and the fatigue analysis, are based on a common data model and use the same resources. This ensures data efficiency (large data stays internal, double data handling is avoided) and the import/export of intermediate results is no longer necessary.

Stress gradients, previously additionally calculated by the fatigue software based on its own model data, are now available in better quality directly within the FEM software based on the original FEM model. This can be used to increase the quality of results. Due to the elimination of data exchange and the HPC orientation of the FEM software, the integrated fatigue analysis benefits significantly in terms of performance.

New analysis classes are made possible by reduced amounts of data. Thanks to the integration, the complete stress results for all calculation steps no longer must to be saved, but are used directly («on-the-fly») by the fatigue analysis in each calculation step and then immediately deleted again. This significant process improvement means that new classes of model variables and significantly more result steps can be considered. The results are then much more accurate.

The new integrated fatigue life analysis improves the process by orders of magnitude. A robust process means process reliability. Stress calculation and fatigue life analysis are integrated in one software and do not require any interfaces. Therefore, there are no complications with data management. Accuracy is increased through improved accuracy for the stress gradients and run time has been drastically reduced.

Basic technology and infrastructure for fatigue analysis in the FEM solver is developed, a perfect starting point for functional expansion, like extension by further fatigue approaches, optimization with damage as objective functions and design constraints. Integration, process reliability and short run times allow the industrial usage of fatigue optimization and sampling.

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FD23-107

Evaluation of the severity of the frequency effect in UFT of structural steels

Lewis Milne, Yevgen Gorash, Tugrul Comlekci, Donald MacKenzie

University of Strathclyde, Glasgow, United Kingdom

In recent years, Ultrasonic Fatigue Testing (UFT) has become a common method of carrying out rapid fatigue tests at a frequency of 20kHz, thereby enabling the cost-effective production of fatigue data into the Very High Cycle Regime (>107 cycles). It has been observed, however, that the increased test frequency can have significant influence on the fatigue results, depending on the material being tested. In particular, structural steels exhibit a phenomenon known as the "frequency effect", in which the increased test frequency leads to an increase in the apparent strength of the material, and a corresponding improved fatigue performance. Until this effect can be quantified, the use of UFT to produce practical design data for structural steels remains limited.

Therefore, this investigation aims to quantify the severity of the frequency effect in UFT of structural steels. The fatigue performance of several structural steel grades will be evaluated at 20Hz and 20kHz and correction factors will be applied to results in order to relate the SN curves at the two frequencies. A cyclic correction factor will be applied by evaluating the cyclic yield behaviour of the materials and a strain rate correction factor will be applied following a range of high strain rate tensile tests.

Finally, a frequency sensitivity parameter will be defined by evaluating the discrepancy between the SN curves at the two frequencies. This parameter will be compared against several key material properties for the tested steels in order to evaluate their influence on the frequency sensitivity.

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FD23-127

Non-contact extensometer for dynamic testing Toward a new standard for characterization of materials in fatigue ?

Pascal Daguier

ZwickRoell France, METZ, France

Intensive characterization of fatigue properties of materials is a key feature for industries with high-end safety rules and regulation, like for aerospace or nuclear industries.

Moreover, relevant information and prediction which could be extracted from data analysis of huge database needs numerous characterization, reliable and reproducible testing conditions, and detailed description of specimen and/or component tested (mechanical properties, manufacturing route, residual stresses, microstructure and treatment ,…).

If manual testing is today the most common way of mechanical testing of materials, massive characterization linked to quality control or new material development required the use of automatic system, which give access to high specimen throughput, high repeatability and reproducibility of testing conditions, which is a key for relevant and valuable data.

If most of high cycle fatigue test are performed today without any extensometers, some important material properties require the use of local displacement and/or strain measurement like the low cycle fatigue test, the fatigue crack propagation rate, the fracture toughness.

For such characterization, the use of contacting extensometer, sometime imposed by existing standard (because the only reliable technology existing at that time), prevent/complexify the use of automatic characterization, may induce damage when attached to specimen, or may prevent / generate complex solution to characterize thin specimen.

Non-contact extensometer is use for mechanical characterization of material since years. If most of the technology need markings of specimen with stickers or sprayed pattern, some solutions use physical interaction of monochromatic light with the surface of material to generate natural pattern without any marking. However, the use of extensometer dedicated to static test could not be used for fatigue testing, because of sampling frequency and/or data transfer and treatment.

After a brief description of the real time technology mandatory for dynamic non-contact extensometers, this paper gives numerous example of the comparison between contacting/non-contacting extensometers in fatigue of materials, opening new doors for material characterization.

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FD23-129

Exploration of the orientational dependent fatigue response of triply periodic minimal surface cellular structures: A numerical study

Sudeep Kumar Sahoo, Nicolas Saintier, Yves Chemisky

Université de Bordeaux, Laboratoire I2M, UMR CNRS 5295, Arts et Métiers Institute of Technology, F-33400 Talence, France

Recently, Triply Periodic Minimal Surfaces (TPMS)-based lattices have received significant attraction in structural applications across a variety of engineering sectors, including automobile, aerospace, and biomedical, owing to their improved mechanical properties and lightweight potential. The mechanical characteristics of these lattices are intrinsically linked to the design-related topological descriptors that include the spatial arrangement of their topological cell wall, geometrical sizes, and relative density. In practical applications, however, these structures are often exposed to fluctuating loads that can induce depreciation of their mechanical properties and eventually fatigue failure. Therefore, it is crucial to conduct a comprehensive analysis of their orientational-dependent fatigue response and explore the structure-property relation under fatigue subjected to various loading conditions. To address this challenge, a novel numerical framework based on the Finite Element Method has been proposed and employed to investigate the fatigue strength of TPMS lattices under diverse loading conditions, including uniaxial tension, equi-biaxial and simple shear. The stress-based Crossland criterion has been adopted as the fatigue criterion, and the fatigue strength of the considered volume is computed using a fatigue indicator parameter (FIP).

The developed framework is undertaken to examine the performance of three sheet-based TPMS lattices, namely Schoen Gyroid, Schwarz Primitive, and Schoen IWP. Besides, the approach permitted to demonstrate the influence of localized material distribution and loading direction towards the evaluation of fatigue strength and structural efficiency. It is observed that among all the proposed lattices, Schoen Gyroid is shown to exhibit better fatigue properties in accordance with the existing literature studies. Our observations are consistent with these findings and through our proposed methodology, we demonstrate that its enhanced performance can be attributed to the helical configuration of its cell walls which facilitates load distribution evenly throughout the entire cell volume, regardless of the loading orientation. On the contrary, Schwarz Primitive and Schoen IWP lattices exhibited more localized stress fields in the loading direction relative to other directions, indicating their sensitivity to loading direction and thus their fatigue response. A comparative analysis is also conducted to determine whether a correlation exists between the fatigue response and the effective mechanical properties obtained through the homogenization approach. In conclusion, the proposed numerical framework serves as a promising means of solving topology optimization problems involving lattices, wherein not only the selection of the lattice but also their preferred orientation can be taken into account as design variables.

S08

Fatigue and Manufacturing Process (Effect of Microstructure, Welding, Residual Stresses,…)

Chairmen:

Romain Chantalat & Jean-François Flavenot

Benaouda Abdelaoui & Marion Risbet

Etienne Pessard & Catherine Peyrac

Mansour Afzali & driss El Koukhi

Jean-François Flavenot & Ahmad Hayder

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FD23-14

Modelling of size effect in fatigue strength for welded joints using effective notch stress and probabilistic methods

Mehdi Ghanadi[1], Gustav Hultgren[1], Mattias Clarin[2], Zuheir Barsoum[1]

[1]KTH Royal Institute of Technology, Department of Engineering Mechanics, Stockholm, Sweden
[2]SSAB Special Steels AB, Borlänge, Sweden

The decreased fatigue capacity of welded components with increasing plate thickness, known as the size effect, is a well-known phenomenon in most fatigue design standards. The size effect links directly to the probabilistic nature of fatigue failure, where the extent of stress concentrations and stress gradients through the thickness govern the fatigue capacity of the joint. Fatigue design standards and recommendations address the thickness effect by reducing the S-N curve for joints thicker than the reference thickness value, where the increase in fatigue strength is often not considered due to the thinness effect.

The probabilistic nature of fatigue failure for welded joints is studied here using the weakest link modelling approach based on the stress distribution within the body of the joint. The modelling approach is evaluated and compared with the effective notch stress method for literature fatigue data on non-load carrying welded joints. The differences and similarities between the probabilistic and effective notch stress methods give a good insight into how the fatigue strength of welded joints is affected by the size effect.

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FD23-17

High cycle fatigue performance of bare 300M steel by self-heating tests under cyclic loadings

Pierrick Lepitre[1,2], Cédric Doudard[1], Matthieu Dhondt[1], Martin Surand[2], Sylvain Calloch[1]

[1]ENSTA Bretagne, IRDL UMR CNRS 6027, Brest, France. [2]Safran Landing Systems, Vélizy-Villacoublay, France

300M, an ultra-high strength steel used in aeronautics for landing gears, is generally shot-peened and coated with High Velocity Oxygen Fuel sprayed WC-10Co-4Cr to improve corrosion resistance and tribological behavior. In the literature, few process parameters have been tested to characterize the effect of surface integrity on fatigue properties. The self-heating method under cyclic loading is used to quickly determine fatigue properties by coupling the fatigue mechanisms with dissipation mechanisms. This paper focusses on the results obtained on the bare and shot peened materials.

For bare 300M steel, analyses show a good correlation between the steel self-heating model and the conventional fatigue data, as well for mean properties as for its scattering. Several parameters have been tested, such as load ratio, coupon volume, loading history and material orientation.

For shot peened 300M steel, correlation is not direct, as tests only determine the average dissipation whereas the configuration is highly heterogeneous. A comprehension and predictive model has been built by splitting the global dissipation into several dissipation areas. To investigate the dissipation of those areas, the fatigue mechanisms and the influence of shot peening, the bare steel is tested under different mean stresses, load ratios and plastic pre-deformations. Those results help to parametrize the model and so to interpret the temperature signal as a characterization of fatigue properties. This is the first step to build a lifespan forecast model based on temperature measurements to study shot-peening and coating influence on fatigue properties.

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FD23-31

Analysis of the uniaxial fatigue behaviour of 42CrMo4 Q&T specimens extracted from the big end of a marine engine connecting rod using the heat energy-based approach

Sofia Pelizzoni, Mauro Ricotta, Alberto Campagnolo, Giovanni Meneghetti

University of Padova, Padua, Italy

Among the energy-based approaches for fatigue life estimation of steel specimens, the experimental method based on the specific heat loss per cycle Q proved effective. The parameter Q is readily evaluable using temperature measurements and was validated through a considerable number of experimental results. It constitutes an effective fatigue damage index able to synthesize in a single scatter band results generated from fatigue tests in different conditions for a given material. More in detail, testing conditions differed for (i) specimens' geometries, i.e. plain and notched, (ii) loading conditions, consisting of pure axial or torsion, and multiaxial loadings and (iii) mean stress, the latter requiring the use of a properly defined temperature-corrected parameter Q^- . Therefore, the Q-based approach has been employed in the present investigation for fatigue strength assessment of plain and bluntly notched specimens, extracted from a 42CrMo4 Q&T connecting rod big end of a marine engine. Stress- and strain-controlled constant amplitude fatigue tests were carried out on an axial servo-hydraulic MTS machine, adopting R=-1 and R=0.5. For each specimen, the Q parameter evolution was monitored by suddenly stop the fatigue test several times during the same test and measuring the cooling gradient of material temperature. As result, two types of fatigue curves were obtained: 1) the traditional stress-life (S-N) curves, each of them fitted on results derived from the same geometry and R-ratio, 2) the single Q^--N curve, fitted on all results independently of the geometry and R-ratio, assuming the Q^- representative value at 50% of total life.

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FD23-34

Improved lifetime estimation of shot-peened shaft bores using a numerical approach

Felix-Christian Reissner[1], Lars Uhlmann[2], Jörg Baumgartner[1], Tim Herrig[2], Thomas Bergs[2,3]

[1]*Fraunhofer Institute for Structural Durability and System Reliability (LBF), Darmstadt, Germany*
[2]*Laboratory for Machine Tools and Production Engineering (WZL), Aachen, Germany*
[3]*Fraunhofer Institute for Production Technology (IPT), Aachen, Germany*

Shot peening is commonly used to improve the fatigue strength of mechanical components. The peening process involves the use of high-energy mechanical impacts to create compressive residual stresses and a material hardening on the surface of the component, which can significantly increase its resistance to fatigue. Accurate lifetime prediction is important for optimizing the design of shot-peened components and ensuring their reliability and safety. Due to nonlinear material behavior and the simulation of contact, estimating the lifetime of shot-peened shaft bores under cyclic loading conditions remains a challenge.

In this study, the lifetime estimation of shot-peened shaft bores using a combination of experimental testing and finite element analysis is investigated. A series of experiments was conducted on shot-peened shaft bores made of EN-GJS-700 and 34CrNiMo6, using different peening parameters such as intensity and coverage. The specimens with shot-peened shaft bores were subjected to cyclic loading in a fatigue testing machine and the lifetime was experimentally identified.

The results were used to develop a methodology based on finite element analysis, which considers the effect of the shot peening parameters on the residual stress distribution, hardening and the resulting fatigue life. The results of the proposed methodology were validated against the experimental data and showed good agreement with the experimental results.

The derived methodology can be used to estimate the lifetime of shot-peened shaft bores under different loading and peening conditions and provides a useful tool for optimizing the design of shot-peened components in fatigue engineering applications.

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FD23-35

Hole-making and cutting effects on fatigue performance of ultra high strength steels

Okan Yilmaz, Dennis Van Hoecke

ArcelorMittal Global R&D Gent - OCAS NV, Zelzate, Belgium

Ultra high strength steels provide opportunities for reduced-weight designs since they have higher tensile and fatigue strengths than the conventional mild steel grades. For typical applications such as telescopic cranes, tippers, chassis, and agricultural machinery, lower weight leads to lower fuel consumption and better road homologation. Before the start of their service life, steel components must be machined to their final shape as they are supplied in standardized shapes and sizes. Mechanical and thermal cutting strategies invoke various physical phenomena within the cut material affecting the in-use properties. The objective of this study is to quantify the effect of hole-making processes and edge-preparation on fatigue performance of ultra high strength steels. A series of fatigue experiments were conducted on steel grades with yield strengths from 700 to 960 MPa using axially loaded coupon samples with a hole manufactured by punching and laser cutting. Fatigue performance is compared to the detail categories provided by design standards. Additional tests under four-point bending loading were conducted to focus on flat edges machined by laser cutting and milling. Especially at high-cycle and infinite-fatigue lives, tested grades were superior to the typical design curves when the holes were punched with low clearance or laser cut.

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FD23-46

Effect of local weld geometry and its variability on the local weld stress

Gustav Hultgren, Zuheir Barsoum

KTH Royal Institute of Technology Department of Engineering Mechanics, Stockholm, Sweden

The local weld geometry and its variability can significantly affect the fatigue strength of structures, especially for non-load-carrying welds. The local stress-raising effects at the weld toe are for these joint configurations governed by standardised definitions such as sharp transition radii or adverse undercuts. Nowadays, digitalised tools for weld quality assurance accurately determine these standardised geometrical definitions with a high resolution, making it possible to study how the variability in geometry affects the fatigue strength further.

Perfect weld transitions with constant radii and smooth surfaces, which make the standardised geometrical definitions easily definable are, however, seldom seen in real welds. Actual weld sections can instead have multiple transition radii, undercuts, and ripple lines which introduce some uncertainty in the geometry estimations. Numerical simulations of the actual weld geometry, with all its variations, in combination with probabilistic evaluations, have shown great potential for studying the influence of competing notches in the weld. In this study, the probabilistic evaluation of simulated welds is used to analyse the relationship between the local weld stress, derived from the weakest link theory, and the standardised geometrical definitions determined by a commercial digital quality assurance system. The results show that the interactions of geometrical definitions greatly impact the local fatigue strength properties, with some features, such as the weld toe radius, which has a stronger influence.

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FD23-47

Stress ratio effect on the fatigue of welded joints assessed via thermoelastic stress analysis

Bruno Levieil[1], Corentin Guellec[1], Lorenzo Bercelli[1], Cédric Doudard[1], Sylvain Calloch[1], Florent Bridier[2]

[1]ENSTA Bretagne, Brest, France. [2]Naval Group Research, Bouguenais, France

The fatigue performance of welded joint is strongly dependent on welding residual stresses as well as the local geometry of the weld toes. To ensure the structural integrity over time of such components, fine predictive models must be proposed together with efficient experimental methods for their assessment.

This study proposes a model based on linear elastic fracture mechanics to forecast fatigue life in service of high strength steel welded joints. This model considers the effect of the local stress ratio (dependent on stabilized residual stresses) on the crack growth rate through the definition of an effective stress range.

The use of Thermoelastic Stress Analysis (TSA) is used to perform in-situ monitoring of fatigue cracks on welded joints to experimentally determine crack growth rates at different load ratios Indeed, under adiabatic conditions, the temperature's first harmonic at the surface of a structure submitted to cyclic loading is proportional to the stress tensor's first invariant's amplitude. As a result, the presence of a surface crack can be witnessed based on the post-processing of infrared films. Moreover, it is shown that new infrared data post-processing methods allow for a fine detection of crack propagation phenomena (such as crack closure) and their assessment.

Firstly, the experimental technique and infrared post-processing is detailed and demonstrated in the case of a controlled specimen. Secondly, the identification of the model parameters is presented. Finally, the model is applied and validated on a real application case.

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FD23-56

Numerical and experimental fatigue strength evaluation of thin-walled aluminum components for aerospace application manufactured by roll forming

Boris Spak, Markus Kästner

Technische Universitaet Dresden, Dresden, Germany

The use of structural components in the aviation space places high demands on the safety under static and cyclic loading conditions during the total operating time. With immerging innovative developments in the production of thin-walled sheet metal components, savings in energy consumption and material are achievable by switching from metal-cutting production to forming operations. As the forming process has an impact the local material properties due to cold working, resulting residual stress state and surface finish, the fatigue life estimation requires the consideration of the forming history.

The structural component under consideration from aluminum alloy 7475 T761 is manufactured by automated, robot-assisted roll forming. Local changes in mechanical material properties are assessed trough hardness measurements and microscopic surface examination. Potentially existing residual stresses are determined via process simulation of the angled profile utilizing commercial finite element solver LS-Dyna. The process simulation is validated by comparison to the physical component. Local strains in the vicinity of the assumed failure location in cyclic loading regime are determined using full-field displacement measurements. A comparison to the results of a loading simulation with appropriate boundary conditions is carried out. The fatigue life assessment is performed using the Local Strain Approach.

The process-structure-property relationships are evaluated with respect to crack initiation for different tooling paths. The knowledge gained will be used to specifically control the roll forming process in the future in order to maximize the component performance of the lightweight structure.

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FATIGUE DESIGN 2023

FD23-58

Various influences on the fatigue resistance of important steel details

Gloria Hofmann[1], Helen Bartsch[2], Ulrike Kuhlmann[1], Markus Feldmann[2]

[1]University Stuttgart, Insitut of structural design, Stuttgart, Germany
[2]RWTH Aachen, Institute for Steel and Lightweight metal construction, Aachen, Germany

Due to the revision of the Eurocode, two research projects funded by AiF-DASt-FOSTA reinvestigate the detail categories of EN 1993-1-9.

Among others, investigations on the influence of weld imperfections on the fatigue strength of typical steel construction details are presented. For this purpose, own fatigue tests were carried out on cruciform joints and transverse stiffeners with internal and external imperfections. Numerical simulations based on these tests show that dependencies of the fatigue strength on sizes of different weld imperfections can be derived quantitatively.

Furthermore, the influence of geometry is investigated for 2 specific details: the plate thickness on butt welds and the length and end geometry of longitudinal attachments. The results of a meta-study based on tests of various research projects and own tests on butt welds up to 80 mm will be presented. In contrast, previous meta-studies could not provide a clear result on the influence of the attachment length and whether the transition radius of the ends larger than 150 mm or only the ground flush of the reinforcement improves the fatigue resistance. Additional tests and evaluation will try to give an answer.

A database established in the projects allows to integrate and assess the specified details in the context of the overall approach in EN 1993-1-9 to enable an efficient design, in which the fatigue strength is estimated as accurately as possible.

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FD23-68

Effect of the grain boundary on the fatigue crack growth for aluminum bi-crystals

Wilmer Velilla-Díaz[1], Habib Zambrano[2]

[1]Universidad Austral de Chile, Valdivia, Chile. [2]Universidad del Norte, Barranquilla, Colombia

Grain boundaries (GBs) are relevant as structural barriers for deformations in nano-crystalline materials and their resistance against fatigue crack propagation. The overall behavior of the material's microstructure is the result of a complex interaction of multiple grains with a variety of relative orientations and their mechanical response in the presence of small defects. The effect of the grain boundaries on the crack propagation constitutes an important factor to determine the mechanical behavior of nano-materials under static and dynamic loads. The purpose of this study is to analyze the effect of relative tilt and twist angles on the crack propagation of single edge cracked bi-crystlas of a FCC microstructure. In this research, molecular dynamics simulations at room temperature under increasing cyclic loads are performed to characterize the effect of different grain miss-orientations on the crack propagation. The results show that high twist angles have a greater effect on the resistance to crack propagation.

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FATIGUE DESIGN 2023

FD23-77

Life-cycle cost assessment of post weld treatments: effect of local weld geometries

Kaushik Iyer, Zuheir Barsoum, Malin Åkermo

KTH Royal Institute of Technology, Stockholm, Sweden

The local weld geometry and its quality can significantly impact the fatigue life of non-load-carrying welds in structures Therefore, optimizing the manufacturing processes to improve the local weld geometry can considerably affect the fatigue life of the structure.. Post-weld treatments such as burr grinding and High Frequency Mechanical Impact (HFMI) treatment are commonly used techniques to extend the fatigue life of a weld by modifying the local weld toe geometry. However, employing additional manufacturing processes can have an adverse effect on the Life-cycle cost of a welded structure by increasing production costs. On the other hand, extending the fatigue life of a structure can result in lower maintenance and replacement costs. Therefore, a thorough yet predictive life-cycle cost assessment is required to assess the viability of such treatments and design economically efficient weld structures.

This study assesses the life-cycle cost of welded joints. The fatigue life of the weld in this study is analyzed using the effective Notch Stress method (NSM). Furthermore, the weld is post-treated with an automated HFMI treatment to prolong its fatigue life. Moreover, the effect of weld quality on the production cost is analyzed. The results show that every phase of the weld's life-cycle has a significant contribution to the life-cycle cost with the use-phase being the more dominant. The results also depict the impact of the changes in weld quality in the overall life-cycle cost.

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FATIGUE DESIGN 2023

FD23-82

Study of crack growth behaviour in a cast magnesium alloy

Hayder Ahmad, Mark Craig, Barry Luckett

Safran Electrical & Power, Pitstone, Buckinghamshire, United Kingdom

Magnesium alloys are widely used in aerospace and automotive industries due to their superior density to strength ratio (high specific strength) compared with other structural materials. They also provide a number of attractive properties such as dimensional stability, good heat dissipation and good damping effects. Furthermore, magnesium alloys provide a more cost-effective solution compared to other high strength metals.

Therefore, many researchers carried out the study of the microstructure, physical and mechanical specification and manufacturability (casting, forging, machining, weldability –etc) of the Magnesium and its alloys.

Casting is one of the common techniques used to manufacture parts out of the Magnesium alloys. Despite the fact that casting is a good manufacturing process for mass production and cost effective process, it has problems. For example, the microstructures of these castings tend to be coarse with large grain size that will influence the mechanical properties. Furthermore, the crystal structure of the magnesium alloys are hexagonal close packed (HCP) structure which make the materials more brittle, which provides fewer independent slip systems.

The second and most common problem with the sand casting of the magnesium alloys is the potential reaction with the commonly used silica containing as constituents of plaster or shell mould materials. Therefore, the reaction of the Silica with Magnesium produces Magnesium Oxide and Magnesium Silicates.

In this paper, the effects of the Magnesium Silicates on the crack initiation will be studied. The most fascinating part of this study is the propagation of the crack in the magnesium alloys under a static load by what may be the cause of the magnesium hydrogen embrittlement. Detail fractography of the fracture surfaces will be presented in this paper.

Finally, a recommendation to reduce the risk of the Magnesium Silicates will be listed in this study.

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FD23-86

The effect of the microstructure on torsional fatigue crack initiation and propagation mechanisms in the cast AlSi7Mg0.3 aluminium alloy using in-situ 3D X-ray CT and diffraction contrast tomography in a synchrotron beamline

Viet-Duc Le[1], Franck Morel[1], Jean-Yves Buffière[2], Nicolas Saintier[3], Pierre Osmond[4], Daniel Bellett[1]

[1]Arts et Métiers Institute of Technology, Angers, France. [2]INSA de Lyon, Lyon, France.
[3]Arts et Métiers Institute of Technology, Bordeaux, France. [4]CETIM, Nantes, France

The objective of this work is to understand the effect of grain crystallographic orientation, the grain size and the porosity on the crack initiation mechanisms in torsion, not only on the surface but also in the volume. In order to achieve this objective, in-situ fatigue tests have been conducted in a synchrotron beamline at the ESRF in Grenoble, France. These experiments made it possible, on one hand, to obtain high resolution 3D tomography images of the microstructure in which we can observe the eutectic Si particles or micro-cracks. On the other hand, thanks to the Diffraction Contrast Tomography technique, the 3D images have been rendered which include information about the grains size, the grain morphology and orientation.

Two crack initiation mechanisms were observed. The first one concerns crack initiation inside grains from the PSBs. The second mechanism concerns crack initiation from pores. For the first mechanisms, crack initiation occurs in a shear mode and is greatly influenced by the grain orientation. A slight effect of the grain size is observed. The presence of a pore diminishes this effect and reduces the resolved stress threshold activating this mechanism. The crack initiation mechanism due to pores occurs in the opening mode. No link to grain orientation was found while the pore size is the key factor. In spite of the presence of a large number of pores, the number of cracks initiated in this mode is smaller than the ones initiated from PSBs and the crack growth rate is also lower.

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FD23-93

Numerical study on effects of microstructure randomness on fatigue fracture of non-oriented electrical steels

Sanjay Gothivarekar, Grzegorz Glodek, Reza Talemi

KU Leuven, Gent, Belgium

Fatigue characterisation of thin steel sheets is often prone to a large amount of scatter in the observed lifetime. It has been found that microstructure-induced lifetime variance can be caused by the local elastic and plastic inhomogeneity of neighbouring grains. in other words, the material properties can vary between adjacent grains near the material surface, thereby influencing the fatigue crack initiation and propagation mechanism. The main objective is understanding the effects of microstructure randomness on the fatigue fracture of electrical steel. A finite element modelling approach is proposed that includes randomly generated shapes and sizes of grains with different elasto-plastic material behaviour. Multiple simulations are used to explore the influence of randomness in the material properties considering the distributed elastic modulus and local strain hardening at a microstructural level. Complementary, the impact on variance in fatigue life prediction is investigated by using a critical plane approach.

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FD23-97

Specimen design for gigacycle fatigue testing of structural steel welded joints

Andrew England, Athanasios Toumpis, Yevgen Gorash

Department of Mechanical and Aerospace Engineering, University of Strathclyde, Glasgow, United Kingdom

It has been demonstrated in industrial case studies and the technical literature that the assumption of a fatigue limit is not valid for steel welds, with fatigue failures occurring in the gigacycle (1 billion stress cycle) regime. Structures and components across a range of industries have service lives above 107 cycles, but there is limited fatigue data in this domain. Conducting fatigue tests in the gigacycle regime is only feasible by using ultrasonic fatigue testing machines in which specimens are excited at 20 kHz.

This research focuses on butt joints of S275 structural steel, fabricated using gas-shielded flux-core arc welding. A novel specimen was produced which captures the geometric stress concentration at the weld toe, as an alternative to typically used cylindrical hourglass shaped specimens. Specimens were tested in fully reversed axial loading at room temperature using a Shimadzu USF-2000A commercial ultrasonic fatigue testing machine, up to the gigacycle regime. An elevated fatigue strength is often observed with ultrasonic fatigue testing for materials with a ferritic microstructure, a phenomenon known as the frequency effect. Therefore, specimens with the same gauge geometry were tested at 20 Hz using a conventional servo-hydraulic machine. This study presents the fatigue data obtained at both ultrasonic and conventional loading frequencies alongside complementary metallography, microhardness and fractography results.

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Analysis of the effect of "large" internal defects on the fatigue strength of the G20Mn5-QT cast steel alloy

Driss El Khoukhi[1], Bholah Bhimal[1], Osmond Pierre[1], Abdellaoui Benaouda[2], Le Breton Guillaume[3], Gilles Regheere[3]

[1]CETIM, Senlis, France. [2]CETIM, Saint Etienne, France. [3]CTIF, Sèvres, France

Gas and shrinkage pores in cast alloys are known to have a strong detrimental effect on the high cycle fatigue strength of materials, as stress-raisers that lead to fatigue crack initiation. Size and location of defect have been identified as parameters of tremendous importance to investigate defect severity. The effect of defect on fatigue strength have been largely documented for cast alloys, especially for surface defects with size less than 1mm. Few studies are available for defects larger than 1mm and the literature related to "large" internal defect is even more limited. However, many of the issues met in casting production are related to this last category of defect, justifying further investigations. This is one of the objectives of the DEFOND project launched by CETIM where samples having internal controlled defects, with dimensions appropriate for studying "large" defects under small scale yielding conditions, are used to promote initiation and propagation from internal defects. The present contribution aims to present the first results of this project, focusing on the link between features of internal defects responsible for crack initiation and fatigue strength of G20Mn5 QT cast steel alloy. After analysis of damage mechanisms, the relationship between internal defects features, with particular attention on defect size and morphology, will be assessed through classical Kitagawa-Takahashi approach. As a first phase for further applications to fatigue design, the performance of the main models available in the literature to account for "large" internal defects on fatigue strength is evaluated.

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FATIGUE DESIGN 2023

FD23-135

Fatigue assessment of defective A 357-T6 cast aluminum based on affected depth

Nesrine Majed, Marwa Youssef, Anouar Nasr

National engineering school of Monastir, Monastir, Tunisia

In the presence of casting defects, aluminum components are subjected to multiaxial loadings. The objective of this study is the estimation of the fatigue limit for defective cast aluminum alloy A357 with T6 post heat -treatment. This investigation is based on the analysis of the Crossland equivalent stress in the vicinity of the casting defect using the finite element (FE) method. The defect shape is a semi-spherical void at the surface of a sample submitted to tension fatigue loading. The affected depth of this material is calculated and defined as the depth from the tip of the defect to the interior of the specimen. The Kitagawa-Takahachi diagrams corresponding to different microstructures and two loading ratio R=- 1 and R=0 are simulated based on the affected depth approach. Simulations were compared to the experimental results carried out on the same alloy. The calculations agree well with results inferred from experimental results. Finally, a comparative analysis is carried out between A356 and A357 built on the affected depth approach.

Key word- cast A357 /high cycle fatigue/defect/ affected depth

S09

Fatigue of Assemblies (Mechanical, Welded, Adhesive-bonding, Multimaterials,…)

Chairmen:

Lauriane Guilmois & Henri-Paul Lieurade

Pingsha Dong & Isabel Huther

Laurent Jubin & Mladen Lukic

Guy Fournel & Jan Schubnell

Maximilien Chollet & Eric Feulvarch

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FATIGUE DESIGN 2023

FD23-4

Life extension of pre-damaged existing crane runway girders

Matthias Winkler, André Dürr

University Of Apllied Sciences - Munich, Munich, Germany

Crane runway girders are subjected to cyclic loading and must therefore be designed against fatigue failure. For existing structures, however, there are no standards for handling pre-damaged components at the end of their calculated lifetime. The university of applied sciences in Munich examines different approaches on how to deal with existing welded steel structures. The research project addresses the following questions:

How can pre-damaged components without visible cracks be strengthened?

How can components with visible cracks be repaired in a fatigue-proof manner?

How can pre-damaged components be reinforced through a low-notch application of steel lamellas?

In order to answer these questions several numerical and experimental investigations are carried out. Different innovative fastening techniques like lockbolts, adhesives and self-tapping screws for attaching reinforcement lamellas are tested on small and large specimens. Within this paper the research project will be presented and results will be summarized.

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FATIGUE DESIGN 2023

FD23-10

Fatigue strength assessment of aluminium welded joints under variable amplitude loading using the Peak Stress Method

Luca Vecchiato, Alberto Campagnolo, Giovanni Meneghetti

Department of Industrial Engineering, University of Padova, via Venezia, 1 – 35131, Padova, Italy

One of the simplest and most efficient ways to design lightweight structural components is the combination of welding and aluminum alloys. However, aluminum welded joints are extremely sensitive to fatigue failure and making accurate lifetime predictions is still challenging when Variable Amplitude (VA) loading conditions are involved. Among all design criteria available in the literature for the fatigue strength assessment of welded structures, the present work focuses on the Peak Stress Method (PSM), which is an engineering finite element (FE)-oriented technique to rapidly estimate the notch stress intensity factors (NSIFs) at the weld toe or weld root, both modeled as sharp V-notches having null tip radius. The fatigue strength of welded components under Constant Amplitude (CA) loading is then evaluated by combining the simplicity and rapidity of the PSM in evaluating the NSIFs with a robust fatigue strength criterion such as the one based on the averaged Strain Energy Density (SED), which can be written as a function of the relevant NSIFs. The theoretical formulation of the PSM for the fatigue strength assessment of welded joints made of steel and subjected to VA loadings has been recently proposed by combining its CA formulation with the Palmgren-Miner's cumulative linear damage rule. In the present contribution, the VA formulation of the PSM has been further extended and validated against experimental data taken from the literature and generated by testing welded joints made of aluminum alloys.

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FD23-11

Implementation of the Peak Stress Method for the automated FEA-assisted design of welded joints subjected to variable amplitude multiaxial fatigue loads

Luca Vecchiato[1], Alberto Visentin[1], Daniele Rigon[1], Alberto Campagnolo[1], Vittorio Babini[2], Giovanni Meneghetti[1]

[1]Department of Industrial Engineering - University of Padova, Padova, Italy
[2]Antonio Zamperla S.p.a, Vicenza, Italy

The Peak Stress Method (PSM) is a FE-oriented local approach to evaluate the notch stress intensity factors. In fatigue design welded structures, the PSM allows to estimate the fatigue lifetime of steel welded joints under constant amplitude (CA) loads and has been previously validated against more than 1300 experimental data. However, real engineering welded structures are generally subjected to complex variable amplitude (VA) multiaxial loads in service. Accordingly, the PSM has been recently re-formulated to account for VA uniaxial as well as multiaxial loadings. To this purpose, the PSM has been combined with Palmgren-Miner's Linear Damage Rule and the extended formulation has been successfully validated against a large bulk of VA fatigue data available in literature. Moreover, an automated analysis tool has been recently developed in Ansys® Mechanical, taking advantage of Ansys® Customization Toolkit, in order to support the FE analyst in the fatigue design of welded structures according to the PSM. The automated algorithm, which was initially developed to analyze structures subjected to CA loadings, has been extended in the present investigation to implement the newly developed multiaxial VA formulation of the PSM. As an output, the automated tool generates fatigue life edge-contour plots and graphs in Ansys® Mechanical, allowing the analyst to rapidly single out the most critical point in the structure among all competing crack initiation sites. The present investigation offers a deeper insight on the automated fatigue strength assessment of steel welded details subjected to VA loadings, according to the PSM.

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FD23-13

Experience with high-frequency mechanical impact method for weldments of sheets of different thicknesses

Miloslav Kepka jr., Jan Tittel, Miloslav Kepka

University of West Bohemia in Pilsen, Pilsen, Czech Republic

The Regional Technological Institute, a research center of the University of West Bohemia, is currently working on two larger projects, the subject of which is the investigation of the potential of the high-frequency mechanical impact method (HFMI) for welds from steel sheets of various thicknesses and in a wide range of strength of welded steels.

The potential of the application of this method in designing the structures of rolling stock and steel bridges is investigated.

Partial results have already been presented at the 23rd European Conference on Fracture - ECF23, Procedia Structural Integrity 42 (2022) 762–768. The new results are based on a larger number of test samples and include results using the HFMI method for thin (4 mm) and very thick (90 mm) sheet welds. For these extreme values, results are not available in open sources. The results are compared with the recommendations of the International Institute of Welding.

The fatigue tests are complemented by measuring residual stresses by X-ray diffraction in several test specimens with the application of the HFMI before and after completing 10 million cycles at load values around the so-called fatigue limit.

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FATIGUE DESIGN 2023

FD23-16

Thick-walled welded joints in the range of high load cycles Design of monopiles for offshore wind turbines in the limit range

Mareike Collmann[1], Stefanie Steppeler[2]

[1]Leibniz Universitaet Hannover, Hannover, Germany.
[2]University of Applied Sciences and Arts Hildesheim/ Holzminden/ Göttingen, Hildesheim, Germany

Monopiles are still the predominant support structure for offshore wind farms in Europe with a market share of around 80 % in 2020. Due to greater water depths and increasing turbine dimensions, current monopiles have a diameter up to 10 m and maximum plate thicknesses up to 150 mm. Due to wind, wave and turbine operation, the monopile experiences up to 109 load cycles during its design service life of 20 years. The fatigue resistance is often decisive for the design. Circular and longitudinal welds are designed using the nominal stress approach based on experimentally determined SN curves. With increasing plate thickness, a thickness-dependent reduction of the fatigue strength becomes necessary. Due to the high test loads required, this reduction has hardly been experimentally proven so far. The influence of the sheet thickness and the medium stress sensitivity are difficult to differentiate in test series with small specimens. In this paper, existing test series from older and more recent literature as well as own test series are therefore statistically evaluated and assessed again. Even in the region of high cycles with N > 107, an experimental validation of the generally assumed fatigue limit is still insufficient due to the long duration of tests. Alternative high-frequency testing techniques are required to test specimens up into high cycle fatigue region. In this paper test results are shown and the sensitivity to medium stress and the dependency on frequency are evaluated. Finally, these results are placed in the context of data already evaluated.

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FD23-27

Multiaxial fatigue on cableway installations components: use of the Dang Van criterion based on detail categories of EN_1993-1-9 standard

Benjamin Causse[1], Rémy Bernot[1], Noé Poyet[2,1], Françoise Fauvin[2], Pierre-Henri Manioulloux[3], Nicolas Fleurisson[4], Jean-Christophe Roux[2], Eric Feulvarch[2]

[1]STRMTG, Domaine Universitaire de Grenoble - 1461 rue de la Piscine 38400 Saint-Martin d'Hères, France.
[2]Univ. Lyon, Ecole Centrale de Lyon, LTDS UMR 5513 CNRS, ENISE, 42023 Saint-Etienne cedex 02, France.
[3]CETIM, Saint-Etienne, France. 4GMM, Saint-Martin le Vinoux, Grenoble area, France

In order to predict fatigue lifetime of cableways installations components, EN 1993-1-9 standard (Eurocode 3) is commonly used. However, EN 1993-1-9 is based on a major hypothesis : stress state has to be uniaxial. But for some components, this uniaxial hypothesis is not verified (for example : fixed grip of chairlift submitted to horizontal tightening stress and vertical load stress, or chairlift structure stressed by gravity and lateral shake when passing a pylon). It then appears important to use a fatigue criterion taking into account multiaxial stress state. Our research work proposes to apply for fatigue study the Dang Van criterion, which takes into account multiaxial stress state. Results are then compared to Eurocode SN curves, representing a huge experimental database on unixaxial fatigue, that we propose to use in multiaxial fatigue thanks to an appropriate recalibration. The scientific originality of this work lies in the justification of that Dang Van criterion's recalibration. Therefore, a theorical study ensures that our use of Dang Van's multiaxial criterion is still consistant with the Eurocode SN curve even if these SN curves are experimentally performed under uniaxial stress state. Finally, that hitherto unpublished use of the Dang Van criterion makes it possible to consider the entire database of detail categories defined in EN 1993-1-9, by generalising their use for components under multiaxial fatigue.

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FD23-37

Damage modelling of structural adhesive under cyclic sollicitations: Automotive application

Sidonie Pinaroli[1], Véronique Favier[1], Katell Derrien[1], Léo Morin[2], Anthony Reullier[3]

[1]ENSAM, Paris, France. [2]Université de Bordeaux, I2M, Bordeaux, France. [3]Renault SA, Guyancourt, France

Structural adhesives are commonly used in the automotive field. They have undeniable qualities, but their introduction in the phases of numerical simulations requires a good knowledge of their behavior. For now, the endurance characterization of bonded assemblies is carried out by a succession of costly and time-consuming tests that are incompatible with a project schedule. The presented work is setting up a methodology in order to numerically determine the endurance life of a bonded assembly from experimental tests on the adhesive only. These experimental tests determine the simulation parameters needed to apply the Crossland fatigue criterion on a simulated bonded joint using cohesive element. The results of this methodology allow the construction of a reference curve which is the link between the induced displacements in the cohesive elements and an associated life time of the assembly.

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FATIGUE DESIGN 2023

FD23-45

Influence of preload on fatigue behaviour of welded joints

Isabel Huther[1], Laurent Jubin[1], Lauriane Guilmois[1], Théo Leblanc[1], Fabien Lefebvre[1], Vincent Leray[2]

[1]CETIM, Nantes, France. [2]NOV-BLM, Carquefou, France

Preload application techniques are often used to assess the structural integrity of mechanical systems. Generally, these procedures are performed after the fabrication but before the commissioning of such equipment, without any verification of the preload impact on fatigue behaviour.

These approaches are often imposed by standards such as ASTM or DNV that define applicable preload conditions but neither technical justification nor quantification of the positive or negative impacts are usually given.

Following initial researches on a preloading influence on welded S355 longitudinal stiffeners where a benefit effect was highlighted (Huther, Lefebvre, Abdellaoui, & Leray, 2022), the present work described in this paper focuses on two aspects in order to extend the initial conclusions in:

- Completing the previous work for loaded welds of structural steel S355 on transverse stiffeners where the crack can initiate:
    1. at the weld toe in a case of angle butt weld,
    2. and at the root in the case of fillet weld without complete penetration.
- Verifying if the benefit is greater on a high-strength steel (S690): meaning that the use of a steel with better tensile properties leads to delay the crack initiation phase.

As described in the former study, a pre-loading in the range 1.56 times the YS (local) can increase the fatigue life if the level of pre-loading is sufficient enough to imply a decrease of the residual stresses due to the welding operation thanks to plastic deformation.

Isabel Huther, Fabien Lefebvre, Benaouda Abdellaoui, Vincent Leray, Influence of overload on fatigue behaviour of longitudinal non-load-carrying welded joints, Procedia Structural Integrity, Volume 38,2022, Pages 466-476, ISSN 2452-3216, https://doi.org/10.1016/j.prostr.2022.03.047.

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FATIGUE DESIGN 2023

FD23-48

New developments on fatigue verification in Eurocode on steel structures

Mladen Lukić[1], Mathias Euler[2], Alain Nussbaumer[3], Marion Rauch[4], David Pope[5]

[1]Centre Technique Industriel de la Construction Métallique, Saint-Aubin, France. [2]Brandenburgische Technische Universität, Cottbus, Germany. [3]Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland. [4]Hochschule Kaiserslautern, Kaiserslautern, Germany. [5]Carba Consulting Ltd., London, United Kingdom

The design rules for the verification of civil engineering steel structures against fatigue are compiled in the European harmonized design standard Eurocode EN 1993-1-9 released in 2005. Currently, this design standard is under revision. Besides the inclusion of new developments and clarification, this revision aims for an improvement of the user-friendliness and an extended degree of harmonization by reducing the number of the so-called nationally determined parameters. The structure of the revised standard has been modified in comparison to the current one in order to facilitate the application of the standard. In addition, the following major changes have been implemented:

- Improvement of S-N curves in terms of the nominal stress method: clarification of stress computation, re-organization of detail category tables.
- New design rules for the hot-spot-stress and the effective notch stress methods, in separate annexes.
- New annexes to determine the most common magnification and stress concentration factors for the modified nominal stress method and the stress ranges in preloaded bolts.

Meanwhile, the final document of the project of the European design standard Eurocode prEN 1993-1-9 has been submitted to the "CEN Enquiry". Thereafter it will go through the Formal Vote, planned for October 2024, before replacing the 2005 version throughout Europe.

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FATIGUE DESIGN 2023

FD23-49

Detection and monitoring of the fatigue crack growth on welds Application-oriented use of NDT methods

Mirjana Ratkovac, Paul Gerards-Wünsche, Marc Thiele, Daniel Brackrock, Michael Stamm

Bundesanstalt für Materialforschung und -prüfung, Berlin, Germany

Early detection of fatigue cracks and accurate measurements of the crack growth play an important role in the maintenance and repair strategies of steel structures exposed to cyclic loads during their service life. Observation of welded connections is especially of high relevance due to their higher susceptibility to fatigue damage. The aim of this contribution was to detect and monitor fatigue crack growth in thick welded specimens during fatigue tests as holistically as possible, by implementing multiple NDT methods simultaneously in order to record the crack initiation and propagation until the final fracture. In addition to well-known methods such as strain gauges, thermography, and ultrasound, the crack luminescence method developed at the Bundesanstalt für Materialforschung und -prüfung (BAM), which makes cracks on the surface particularly visible, was also used. For data acquisition, a first data fusion concept was developed and applied in order to synchronize the data of the different methods and to evaluate them to a large extent automatically. The resulting database can ultimately also be used to access, view, and analyze the experimental data for various NDT methods. During the conducted fatigue tests, the simultaneous measurements of the same cracking process enabled a comprehensive comparison of the methods, highlighting their individual strengths and limitations. More importantly, they showed how a synergetic combination of different NDT methods can be beneficial for implementation in large-scale fatigue testing but also in monitoring and inspection programs of in-service structures - such as the support structures of offshore wind turbines.

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FATIGUE DESIGN 2023

FD23-67

Fatigue assessment of fillet welded doubling plates using different methods

Inge Lotsberg, Wenbin Dong

DNV, Oslo, Norway

In this paper analysis results using finite elements are compared with strain measurements and laboratory fatigue testing of doubling plates used in floating production platforms. Circular and quadratic doubling plates of thickness 10 mm with diameter and length equal to 150 mm fillet welded to a main plate of thickness 20 mm were tested. The doubling plates were fatigue tested to failure and the number of test cycles was compared with design standards. This assessment was also performed by using finite element analyses of the doubling plates using different methods for hot spot stress derivation in combination with relevant S-N curves. The analyses included:

- The nominal stress method
- Different hot spot stress methods
- The notch stress method
- Crack growth analysis using fracture mechanics.

Analyses were performed using 8-node shell elements and 20-node solid elements. Different methods were used for assessment of hot spot stresses based on calculated surfaces stresses at the weld toe. Also stresses through the thickness of the main plate were used for assessment of the hot spot stress. The main attention was made to the weld toe. However, the main reason for performing the fatigue testing was related to concern for crack growth from the weld root. This failure mode was found to be less critical than fatigue crack growth at the weld toe. The results from this work are being used for developing more reliable analysis methods to be included in design standards.

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FATIGUE DESIGN 2023

FD23-70

Fatigue strength of adhesively bonded deep drawn sheet specimens under multiaxial loading with variable amplitudes

Matthias Hecht[1], Jörg Baumgartner[2]

[1]Technical University of Darmstadt, Darmstadt, Germany. [2]Fraunhofer LBF, Darmstadt, Germany

Adhesive bonding is a frequently used joining technology in the manufacturing of vehicle bodies. In comparison to conventional spot-welded designs, adhesive bonding provides a higher stiffness due to a planar load transfer. Furthermore, there are advantages in damping behavior and chemical separation in multi-material designs.

Up to now, there exists still quite some uncertainty in the fatigue assessment of adhesively bonded joints due to a lack of reliable assessment approaches. This is especially true for the case of more complex in-service loading conditions as variable amplitude and multiaxial loading. For example, the experimentally determined actual damage sum in the literature shows a high scatter and is well below the theoretical value of Dth = 1 proposed by Palmgren-Miner. This uncertainty is typically countered by an over-dimensioning of the bond.

In order to increase the accuracy of fatigue methods for vehicle bodies, tests were carried out on component-like specimens, so called "bowl specimens". These specimens consist of a deep drawn sheet that is bonded with a thermosetting structural adhesive to a planar sheet and are subjected under cyclic loading. They were loaded uniaxially and multiaxially, with ($\varphi = 90°$) and without phase shift ($\varphi = 0°$). Even uniaxial loading results in multiaxial stress due to the complexity of the geometry.

A comparison is made between the actual damage sums according to Palmgren-Miner of homogeneously butt-bonded hollow cylinders (presented at the Fatigue Design 2021) and these complex bowl specimens. Additionally, a difference in the influence of the phase shift on the fatigue behavior of these two specimen types is shown.

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FATIGUE DESIGN 2023

FD23-104

Investigation of the fatigue strength of shape optimized gusset plates in rectangular and circular hollow section k-joints

Philipp Ladendorf[1], Stefan Herion[1], Matthias Winkler[2], André Dürr[2]

[1]Centre of Competence for Tubes and Hollow Sections CCTH, Karlsruhe, Germany
[2]Institute for Material and Building Research, University of Applied Sciences Munich, München, Germany

The fatigue strength of structures made of rectangular (RHS) and circular hollow sections (CHS) is characterized by inhomogeneous stiffness distributions in the connection areas of braces and chord, which lead to high stress concentration factors (SCF). Using these SCFs in conjunction with structural SN-curves, the fatigue life can be estimated.

In the preceding research project FOSTA P1132, K-joints made of CHS used a special weld design resulting in a local reinforcement of the gap area. The fatigue tests showed an increase in fatigue strength compared to conventional CHS K-joints.

Based on this, in the research project FOSTA P1442, numerical and experimental fatigue investigations were carried out on K-joints with shape-optimized gusset plates.

The use of gusset plates was intended to increase the fatigue strength of K-joints by relocating the position of the hot spot to areas with lower stresses or by reducing the stresses at the hot spot.

For this purpose, three different gusset geometries were investigated for five RHS- respectively three CHS-geometries. Variant 1 (shortened, slotted braces and gusset plate attached to the chord), variant 2 (slotted braces also attached to the chord) and variant 3 (like V2, gusset plate additionnally passed through the underside of the chord). All components are circumferentially welded.

The SCF of the three gusset plate geometries are compared with the SCF of conventional K-joints. In addition, the SCF are compared with the required fabrication effort for the geometries under investigation. Finally, on this basis, a manufacturing recommendation for practical use is presented.

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FATIGUE DESIGN 2023

FD23-105

A practical methodology for the fatigue life estimation of adhesive joints

Cristian Bagni, Andrew Halfpenny, Michelle Hill

Hottinger Bruel & Kjaer UK Ltd, Rotherham, United Kingdom

The use of adhesives in structural joints as an alternative to traditional joining techniques, such as welding and rivets, is becoming increasingly popular in the transportation industry, including (but not limited to) automotive and aerospace. This trend is driven especially by the increasing need and focus on greener ways of transportation and the consequent light weighting requirements. Furthermore, adhesives have the significant advantage, over traditional joining techniques, of allowing joining of dissimilar materials, including composites. Therefore, to optimise the design of adhesively bonded structures and reduce the risk of in-service fatigue failures, the transportation industry needs efficient, robust, and easy-to-use approaches for the modelling and fatigue life estimation of adhesively bonded joints.

This work presents a practical methodology for estimating the fatigue life of adhesively bonded joints that can be easily adopted by companies in the transportation industry. The proposed methodology includes Finite Element (FE) modelling guidelines to recover the required stresses along the bond lines, with limited changes to the typical FE modelling strategies currently used, especially in the automotive industry. It is proposed to model the adherends using shell elements and the adhesive layer with solid elements. The exposed edges of the adhesive are then wrapped with membrane shell elements used to extract the peel stresses. The solid elements and the shell elements are connected using 'bonded contacts' (or similar tools, depending on the Finite Element software used). The proposed modelling guidelines provide FE models that are not computationally too onerous, with a good level of mesh insensitivity and that do not require congruent meshes. The peel stresses recovered from the FE model along the bond lines are then used as an input into nCode DesignLife to estimate the fatigue life of the bonded joints in the analysed structure. The fatigue life estimation is carried out using the standard nCode DesignLife SN analysis engine and bespoke SN curves obtained through testing of adhesively bonded specimens, representative of the joints in the production parts.

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FATIGUE DESIGN 2023

FD23-116

Ultrasonic fatigue testing of welds made of structural steels S355JR and S275JR

Yevgen Gorash[1], Tugrul Comlekci[1], Gary Styger[2]

[1]University of Strathclyde, Glasgow, United Kingdom. [2]Weir Minerals, Johannesburg, South Africa

There is very limited fatigue data over 10 million cycles for structural steel welds. Unalloyed low-carbon steels according to EN 10025 are dominant structural materials of the heavy machinery for minerals and mining applications. The main purpose of this research is a fatigue performance comparison of the welds made of currently preferred steel S355JR and the candidate steel S275JR. Welded machinery assemblies are designed to work for several years at typically 16-20 Hz frequencies of loading under low stress amplitudes. In order to reach a few billion cycles within a practically sustainable testing time, an accelerated fatigue testing is required. The goal of reaching gigacycle fatigue domain is achieved using the ultrasonic fatigue testing approach with Shimadzu USF-2000A system. The fatigue samples for S275JR and S355JR steels have a standard tapered shape are cut out of the welded plates to have a HAZ in the middle. The fatigue samples are prepared to investigate the influence of two surface conditions – polished and pre-corroded. In the polished samples, fatigue failures are driven primarily by the welding porosity with the fatigue life duration dependent on the size and location of pores. In the pre-corroded samples, fatigue failures are driven primarily by the corrosion pitting with the fatigue life duration dependent on the amount of corrosion damage to the surface. Visual comparison of fatigue data for S275JR and S355JR steels poses a challenge, because of the massive scatter of experimental data points making the determination of SN curves impossible. Therefore, statistical approach is used.

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FATIGUE DESIGN 2023

FD23-122

3D numerical simulation of fatigue crack growth in welded connections of gantry cranes for residual life assessment

Dhahri Marwa[1], Stephane Kemgang[2], Bhimal Bholah[2], Isabel Huther[2], Bruno Depale[2], Julien Malrieu[2], Delphine Brancherie[1], Piotr Brietkopf[1]

[1]UTC, Compiègne, France. [2]CETIM, Senlis, France

This paper proposes a numerical tool for residual life assessment of metal active gas (MAG) welded structures such as gantry crane forestay and boom connections. These structures are submitted to cyclic loadings, which can cause fatigue damage around microcracks in the heat-affected zones (HAZ) of the welded joints, leading to safety and reliability issues. The numerical implementation of a crack propagation methodology in welded structures is complex due to the need for experimental validation tools, determination of the microstructural and physical properties in the HAZ, and efficient fracture mechanics simulation tools. In that context, a 3D tool – Z cracks – has been used to simulate the rate and direction of crack growth of a predefined flaw along the HAZ, the latter also acting as a stress raiser. Z-cracks is a finite element crack analysis toolbox for Stress Intensity Factors (SIF) computation.

It uses the G-θ method in the Linear Elastic Fracture Mechanics (LEFM) regime and a three-dimensional automatic adaptive mesh refinement algorithm for crack advancement. The numerical results are compared with fracture analysis obtained from experimental test bench results on a reduced-sized replica of the forestay and boom substructure. The numerical tool implementation procedure has allowed to identify the prospects and limitations of the use of LEFM-based crack growth simulation tools and perspectives to further tailor the experimental procedures of such welded structures. Based in a better understanding of the crack propagation, the results obtained should contribute to the improvement of engineering practices for the prediction of the residual service life of welded structures and to the definition of improved procedures maintenance procedures.

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FATIGUE DESIGN 2023

FD23-150

Recent update of the IIW-recommendations for fatigue assessment of welded joints and components

Jörg Baumgartner[1], A. Hobbacher[2], Fabien Lefebvre[3]

[1]LBF, [2]Jade Hochschule, Wilhelmshaven, Germany , [3]CETIM

The IIW-Recommendations for Fatigue Design of Welded Components and Structures are an international guideline that contains all relevant information to design welded structures under cyclic loading. Within the recommendations, all relevant assessment approaches, i.e., nominal, structural and notch stresses as well as fracture mechanics, are included. In addition, the relevant influences are covered, such as the effect of post-weld treatment, mean resp. residual stresses and wall thickness. In the current update, the structure is enhanced and straightened and with it the applicability is improved. As completely new content, the assessment of welded thin joints with the notch stress approach and the impact of post-weld treatment procedures on the endurable stresses and the slope of the S-N curve is added. It is expected that the new update will have the same impact on design and other codes as the old one.

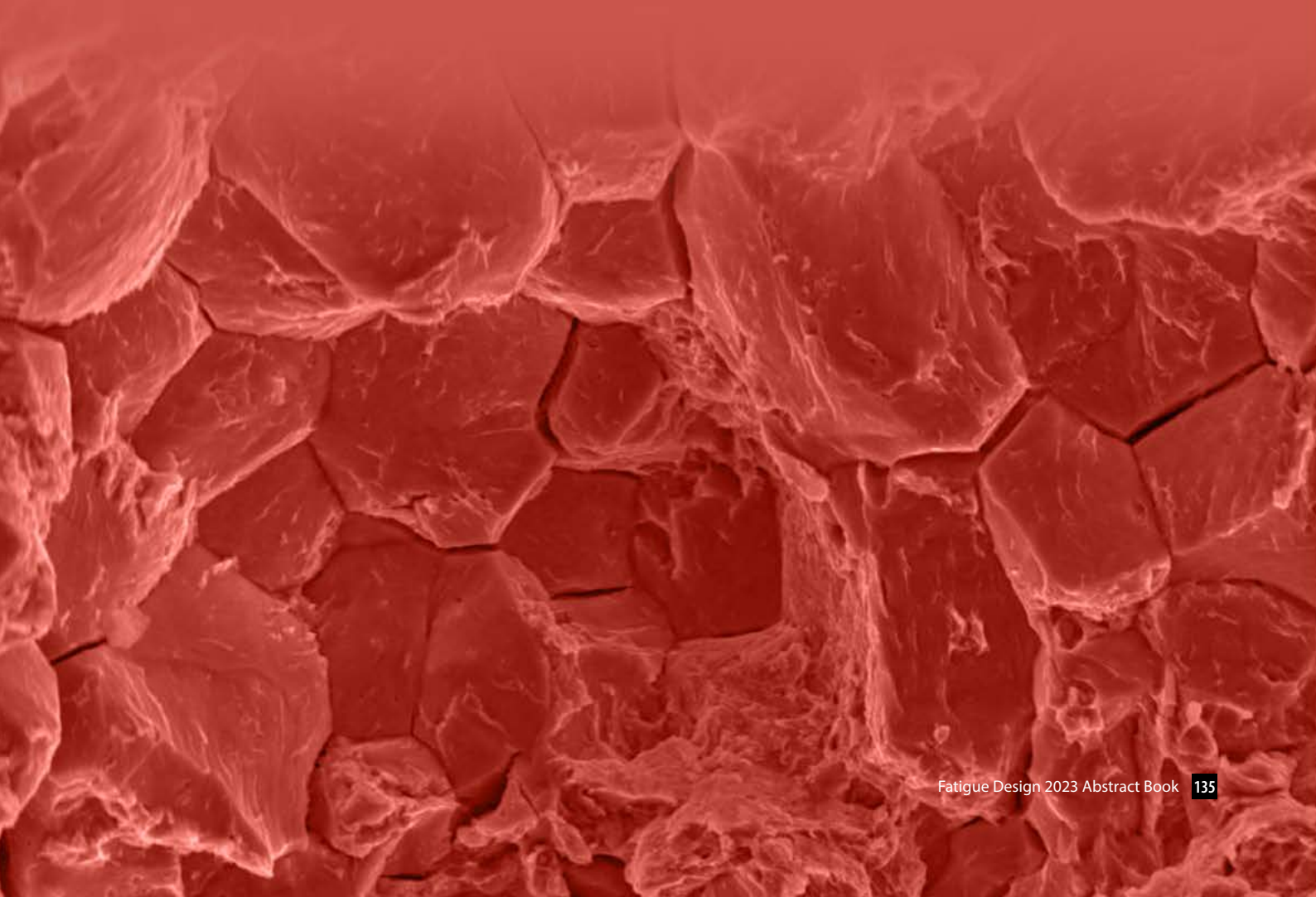
S10

Fatigue Under Severe Environmental Conditions

Chairmen:

Pierre Osmond & Nicolas Saintier

Romain Chantalat & Gouenou Girardin



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FATIGUE DESIGN 2023

FD23-20

Rapid estimation of fatigue properties of high temperature materials using self-heating tests

Alexis Mion[1,2], Cédric Doudard[1], Jonathan Cormier[3], Vincent Roué[2], Dimitri Marquié[2], Sylvain Calloch[1]

[1]IRDL, Brest, France. [2]Safran Aircraft Engines, Villaroche, France
[3]Institute Pprime, Chasseneuil-du-Poitou, France

The hottest parts of turbojet engines are exposed to high thermomechanical stresses, particularly of the vibratory type. The improvement of the efficiency of aeronautical engines (obtained with an increase in operating temperatures), as well as the need to reduce mass, mean that the parts have to withstand ever more severe mechanical and thermal loadings. It therefore seems particularly important to improve the fatigue design methods of these parts, especially in the High Cycle Fatigue (HCF) and Very High Cycle Fatigue (VHCF) domains. However, fatigue property determination is time-consuming as the fatigue behavior depends on many parameters (nature of loading, microstructure, manufacturing process, temperature, etc.).

The self-heating method, which is based on the measurement of the temperature evolution of a specimen during cyclic loadings, makes it possible to considerably reduce characterization times. The effectiveness of this method has been demonstrated over a wide range of metallic materials at various temperatures.

High temperature self-heating tests at different load ratios are conducted on two nickel-based superalloys: INCONEL 718, a polycrystalline alloy, and AM1, a single crystal alloy. The first focus is on self-heating tests in the HCF range, performed at a frequency of 20 Hz. Then, in a second step, a protocol of self-heating tests on AM1 specimens in the VHCF domain at 20 kHz and at 1000°C on a gigacyclic machine is set up. Different models are then proposed to describe each experimental result. The link between the self-heating measurements and the fatigue properties for each configuration is also discussed.

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FATIGUE DESIGN 2023

FD23-26

Phase field modelling of fatigue in hydrogen environments

Alireza Golahmar[1,2,3], Christian F. Niordson[1], Emilio Martínez-Pañeda[2]

[1]Department of Civil and Mechanical Engineering, Technical University of Denmark, Kgs. Lyngby, Denmark
[2]Department of Civil and Environmental Engineering, Imperial College London, London SW7 2AZ, United Kingdom. [3]Vattenfall Offshore Wind, Copenhagen, Denmark

Phase field fracture modelling has emerged as a promising variational approach to capture complex cracking conditions, such as nucleation from multiple sites or the coalescence of numerous defects, in arbitrary geometries and dimensions [1]. The method builds upon Griffith's thermodynamics framework and has recently been extended to fatigue damage [2], showing that features such as stress-fatigue life (S-N) curves or fatigue crack growth rate curves can be predicted without any prior assumptions. However, most structural failures often occur due to the synergistic effects of fatigue damage and environment. One of the most important environmental effects is what is generally referred to as hydrogen embrittlement [3]. Hydrogen is ubiquitous and it significantly reduces the ductility, strength, toughness, and fatigue crack growth resistance of metallic materials.

In this work, we present the first multi-physics phase field-based model for hydrogen-assisted fatigue. The modelling framework builds upon the success of a recent phase field fracture formulation for hydrogen assisted cracking under static loads [4]. The model is first used to gain fundamental insight and provide a mechanistic rationale for the trends observed in the fatigue experiments. The comparison with experiments reveals that the model can accurately predict fatigue lives and endurance limits, as well as naturally capture the influence of the stress concentration factor and the load ratio. In addition, the model is employed to capture hydrogenassisted fatigue damage in case studies of particular technological interest. We show that the modelling framework presented can be used to predict the impact of the environment on fatigue crack growth rate curves and S-N curves, enabling optimising design and maintenance through Virtual Testing, as well as planning efficient and targeted experimental campaigns.

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FATIGUE DESIGN 2023

FD23-38

Effects of high energy laser peening followed by pre-hot corrosion on stress relaxation, microhardness and fatigue life and strength of single crystal nickel CMSX-4® superalloy

Lloyd Hackel

Curtiss Wright Surface Technologies - Metal Improvement Company, Livermore, USA

This study investigated thermal and mechanical relaxation of residual stresses and fatigue strength following hot-corrosion of single-crystal CMSX-4 laser peened (LP) and a cyclic LP plus annealing (LP+TME) processes. Stress measurements showed LP plastic penetration exceeded shot peening depth by a factor of 25. Specimens were exposed to sulphate corrosives at 700°C for 300 hours and then fatigue tested. Five non-LP specimens failed in low cycle whereas three LP samples achieved multi-million-cycle runout, indicating consistent large benefit by laser peening. Fatigue strength tests achieved improvement of 2:1. Post-fatigue RS measurement showed 5 mm depth eigenstress remaining in an LP specimen.

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FATIGUE DESIGN 2023

FD23-53

Fatigue methodology for the qualification of polymer grades used as pressure sheaths and sealed outer sheaths in unbonded flexible pipes for the offshore Oil & Gas industry

Laetitia Fraisse, Yann Chevalon, Thomas Iversen Solfeldt, Christian Wang

NOV Flexibles, Brøndby, Denmark

Polymer layers have been used in the offshore Oil & Gas industry for many years in unbonded flexible pipes for static and dynamic applications. The evaluation of fatigue performance for polymer grades in such applications is complex and no qualification method is well defined nor standardized.

Though historically no reported polymer fatigue field failures, the complexity of unbonded flexible pipes and the conservatism of this industry make the introduction of new polymer grades in risers for dynamic applications challenging. The development of a polymer fatigue methodology will allow the industry to quantitatively evaluate risks of fatigue failure of polymer sheaths and thereby be important in introducing new material grades.

In this study, a design fatigue methodology is built based on inputs from a specific project and results from small- and full-scale tests. The pipe curvature ranges from the project are used to obtain the accumulated tensile strain that is then converted into an accumulated tensile stress. The fatigue damage can then be determined using a design curve established from bending or tension-tension fatigue testing performed on dumbbells and pipe samples. Parameters are included to reflect geometrical effects from manufacturing process but also service life conditions with several temperature profiles.

This method can be applied for pressure sheaths as well as sealed outer sheaths with relevant inputs related to their operating conditions. The obtained fatigue damage can then be used to validate the use of polymer grades for specific unbonded pipe designs under their service conditions.

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FATIGUE DESIGN 2023

FD23-101

Influence of the interaction hydrogen/microstructure on low-cycle fatigue behavior and crack initiation in a nickel base superalloy

Achraf Radi[1,2], Marion Risbet[3], Gilbert Henaff[2], Abdelali Oudriss[4], Romain Chantalat[5], Xavier Feaugas[6]

[1]UTC, Compiègne, France. [2]ENSMA, Poitiers, France. [3]UTC, compiègne, France
[4]LaSIE, la rochelle, France. [5]CETIM, Senlis, France. [6]LaSie, La rochelle, France

Nickel-based superalloys are known for their excellent mechanical strength, especially in fatigue, as well as for their good resistance to corrosion and oxidation. However, when these materials are exposed to hydrogen, their cyclic response may be altered, which can lead to premature damage under hydrogen's effect (HE: hydrogen embrittlement). Many mechanisms have been proposed to describe hydrogen embrittlement, with the most commonly cited being hydrogen enhanced localized plasticity (HELP), hydrogen-enhanced decohesion (HEDE), and adsorption-induced dislocation emission (AIDE) [1]. Additionally, a wide variety of previous research has identified that hydrogen modifies the elementary processes associated with plasticity. However, some questions remain about the antagonist effects of hardening and softening induced by hydrogen on cyclic stress-strain behavior in the case of nickel-based alloys with a given precipitation state. In the present work, the impact of hydrogen on the fatigue behavior of a nickel-based superalloy (Waspaloy) was studied at room temperature in relation to the precipitation state in the underaged domain, where plasticity is localized and precipitates are shearable. For this, two precipitation states (HT0 and HT4) were considered for a constant grain size of 100 µm and varying precipitate sizes, d= 10nm and d= 30nm respectively. The two states were cathodically precharged with hydrogen, and then their cyclic behavior was compared to that of uncharged states. Internal stresses were evaluated using Cottrell-Dickson partitioning of hysteresis loops [2-3]. For these two microstructural configurations, it was found that hydrogen induced a mechanical softening in relation to the specific evolution of back stress and the effective stress. The relation between internal stresses, the dislocation structures and the extrusion heights of slip bands characterized respectively using TEM and AFM, is analyzed in order to account for the observed softening.

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FATIGUE DESIGN 2023

FD23-115

Carbon steel wires fatigue assessments for flexible pipe used for gaseous hydrogen transportation

Fagner Fraga[1], Sabesan Thavagunaseelan[1], Florian Bienvenut[1], Romain Chantalat[2]

[1]TechnipFMC, Le Trait, France. [2]CETIM, Senlis, France

In the current offshore perspectives, the energy transition initiative is involved in the expansion of knowledge and the development of new systems, thus appealing expanded use of Flexible Pipes to integrate renewable energy with hydrogen applications. Within this context, subsea pipelines are needed to transport gaseous hydrogen, a non-usual gas within standard offshore Oil & Gas sector and well known for its ability to cause steel embrittlement. For these reasons, caution must be taken, and suited qualification testing needs to be conducted to propose a reliable transportation solution. Therefore, to better understand the influence of H2 on carbon steel armour wires used in unbounded flexible pipes, mechanical tests, such as fatigue, toughness and crack propagation tests have to be performed. This study seeks to correlate the bending behaviour in air and in H2 environment in order to identify possible mechanical property changes due to the hydrogen environment.

The work presented here focuses on the characterisation of two carbon steel grades tested in air and H2. The impact of H2 on the toughness, the crack growth and performance in fatigue will be addressed. The data allows to select materials compliant with the hydrogen transport application and to acquire the data needed to perform the detailed engineering of the flexible pipe.

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FATIGUE DESIGN 2023

FD23-149

Fatigue crack acceleration in martensitic steels under high-pressure hydrogen

Hisao Matsunaga[1, 2]

[1]Kyushu University, Fukuoka, Japan. [2]

Quenched and tempered low-alloy steels with a martensitic microstructure show promise as materials, particularly in the realm of pressure vessels intended for storing hydrogen gas at hydrogen refueling stations. According to NASA's database, low-alloy steels fall into either the "severely embrittled" or "extremely embrittled" categories when exposed to hydrogen. Therefore, when these steels are intended for use in a hydrogen gas environment, it is essential to thoroughly consider the hydrogen-induced degradation of their mechanical performance in the strength design.

The hydrogen sensitivity of low-alloy steels varies based on their strength levels and microstructural morphologies. This susceptibility is especially noticeable in the fatigue crack growth (FCG) properties. The presenter's research group conducted FCG tests on low-alloy steels JIS-SCM435 and JIS-SNCM439, with tensile strengths (TSs) ranging from 820 to 1130 MPa and test frequencies from 0.001 to 1 Hz. The key findings are summarized as follows:

(1) When TS is below 900 MPa, FCG is accelerated by a factor of 20 to 30 in a hydrogen gas environment compared to an in-air condition. However, the acceleration rate is unaffected by the test frequency. Specifically, the acceleration is "cycle-dependent", and the fatigue life (i.e., the number of cycles to failure) can be determined through crack-growth analysis, assuming the presence of pre-cracks.

(2) For TS greater than 900 MPa, the rate of hydrogen-induced crack acceleration progressively intensifies with a decrease in test frequency. This acceleration is "time-dependent", making the fatigue life unpredictable in terms of the number of pressurization cycles to failure. Consequently, fatigue life design is not applicable. Despite significant progress in phenomenological understanding, the rationale behind the strength- dependence of hydrogen sensitivity remains poorly established. This knowledge gap is crucial not only for ensuring the reliable use of components but also for developing novel materials with both superior strength and adequate hydrogen compatibility.

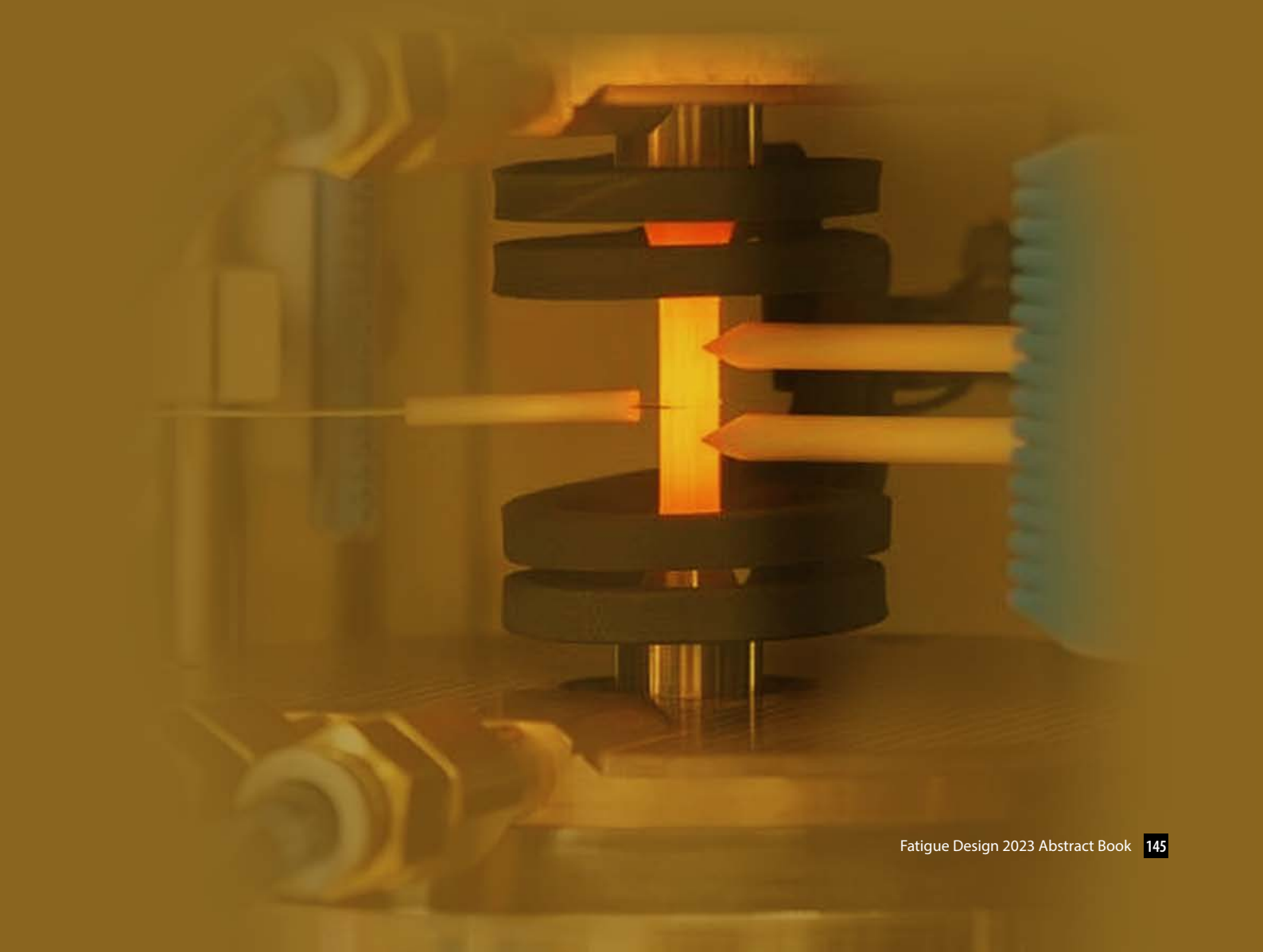
The presentation will showcase a series of experimental results on the fatigue crack-growth properties of various steels in high-pressure hydrogen gas, along with microscopic processes of hydrogen-induced degradation. Based on these findings, the hydrogen compatibility of steels will be discussed, and future research challenges in the field of hydrogen gas embrittlement will be proposed.

S11

Non-linear Behavior and Cumulative Damage

Chairmen:

Stephan Courtin & Driss El Khoukhi



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FATIGUE DESIGN 2023

FD23-29

Fatigue analysis of steering knuckles using the local strain approach

Ahmad Qaralleh[1], Andreas Maciolek[1], Benjamin Möller[1], Jan Weichert[2], Tobias Melz[1]

[1]*Fraunhofer Institute for Structural Durability and System Reliability LBF, Darmstadt, Germany*
[2]*Research group System Reliability, Adaptive Structures, and Machine Acoustics, Darmstadt, Germany*

The study investigates the mechanical properties and fatigue behavior of steering knuckles used on commercial vehicles. The steering knuckle is made of hot forged bainitic steel, which is known to show high levels of strength, toughness, and hardness. The local strain concept was adopted to assess the cyclic behavior of the axle stub based on the stabilized cyclic material parameters using the Ramberg-Osgood equation. For this purpose, experimental investigations have been conducted on both the steering knuckle as well as fatigue specimens under constant and variable amplitude loadings. The fatigue specimens were removed from the area next to the crack initiation location, to represent the microstructure in the critical area of the component. Finite element models of the steering knuckle and the specimens were examined in more detail using ABAQUS software to determine the local equivalent stress/strain (Von Mises) values in the critical areas. For this purpose, a mesh convergence study was performed on the FE models to ensure the accuracy of the solution. Furthermore, the influence of the size effect (notch factor, stress gradient, highly stressed volume HBV90, surface roughness) on the fatigue strength of the component was also taken into consideration for the assessment.

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FD23-81

Cyclic mechanical behavior of electro-welded meshes used as structural reinforcement

Camilo Gonzalez Olier[1,2], Carlos Arteta Torrents[2], Michael Miranda Giraldo[2], Habib Zambrano Rodriguez[2]

[1]Universidad Simon Bolivar, Barranquilla, Colombia. [2]Universidad del Norte, Barranquilla, Colombia

Electro-welded wire mesh is a grid formed by longitudinal and transverse wires welded by means of electrical resistance at the intersection points. This mesh is widely used in civil constructions in different applications that include as reinforcements in structural elements. Due to its reduced cost and installation time, is frequently utilized in Latin American countries. However, the use of this mesh in structural elements is at least controversial due to its limited ductility in combination with the welding process used to join the wires during the manufacturing process of the mesh. In this work, the monotonic and cyclical behavior of electro-welded meshes manufactured in Colombia is studied experimentally. The meshes in this study fulfil the requirements for the standard ASTM 1064. The cyclic mechanical behavior of the material is modeled using Ramberg-Osgood model, and the model parameters are adjusted based on experimental data and using Least squares. The results show that Ramberg-Osgood model predicts accurately the cyclic mechanical behavior.

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An overview of the mechanism-based thermo-mechanical fatigue method (DTMF) and its application in the design of automotive components

Giovanni Teixeira

Dassault Systemes UK, Sheffield, United Kingdom

The DTMF damage Parameter described in the paper is the generalization of the creep fatigue parameter (DCF) proposed by Riedel, which quantifies the amount of damage produced by a non-isothermal loading cycle. The entire design methodology is outlined in the text, starting with the calibration of Chaboche's viscoplastic model and then the determination of the thermomechanical fatigue (TMF) parameters. Chaboche is generally a good choice for its ability to describe well both kinematic and isotropic hardening behaviors, also enabling stress relaxation and strain rate dependency to be considered. The DTMF method is based on the fracture mechanics concept of cyclic crack tip opening displacement (CTOD) where the effective stress range takes the crack closure effect into account. This method is typically used to describe the thermomechanical low cycle fatigue behavior of cast irons, cast steels, stainless steels, Inconel, HiSiMo and nickel-based alloys. These materials are used in components that need to withstand high temperatures (higher than half of the melting point) in service as exhaust manifolds, cylinder heads, valves, turbochargers and disk brakes. Three failure mechanisms are detailed here: oxidation, creep and fatigue. Oxidation is a complex phenomenon that may occur when the material is hot under tensile in-phase loading or hot under compressive out-of-phase loading. Creep is a time and temperature dependent diffusion process which is incorporated into the DTMF parameter as a multiplicative factor. In this context fatigue life is defined as the number of cycles to propagate an existent microcrack up to an arbitrary size that is defined on a case-by-case basis.

S12

Reliability–based Approaches and Probabilistic Methods

Chairmen:

Denis Chojnacki & André Bignonnet

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Probabilistic inspection planning for fatigue cracks in floating production, storage, and offloading units

Arne Fjeldstad, Frode Bratbak

DNV, Oslo, Norway

Due to the nature of the fatigue phenomena it is well known that small changes in basic assumptions for fatigue analysis can have significant influence on the predicted fatigue lives. Calculated fatigue lives based on the S-N approach are sensitive to input parameters. Fracture mechanics analysis is required for prediction of crack sizes during service life in order to account for probability of detection after an inspection event. Analysis based on fracture mechanics needs to be calibrated to that of fatigue test data or S-N data. Calculated probabilities of fatigue failure using probabilistic methods are even more sensitive to the analysis methodology and to input parameters used in the analyses. Thus, use of these methods for planning inspection requires considerable knowledge and engineering skill. Therefore, the industry requested guidelines that could be used to establish reliable inspection results using these methods. Consequently, DNV performed a joint industry project on establishing probabilistic methods for planning in-service inspection for fatigue cracks in offshore structures. The recommendations from this project were later included in a Recommended Practice (DNV-RP-C210). The essential features of the probabilistic methods developed for this kind of inspection planning and experiences with the use towards floating production, storage and offloading units (FPSO's) are described in this paper.

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FATIGUE DESIGN 2023

FD23-85

Pratical use of data lake for better fatigue life estimation

Amaury Chabod

Hottinger Bruel & Kjaer France SAS, Sucy-en-Brie, France

The qualification of components in terms of Durability and Reliability is based on the analysis on a lot of sensors, CAN, IIOT data, which needs a data management infrastructure, to understand the customer usage and variability. Such big data infrastructure are often called « data lake », and may lead to store huge amount of data. This infrastructure must be generic and test data-oriented, to understand the data structure and its analysis required, and to be optimized for such application. All those data may come from connected equipments, instrumented fleets, test bench or proving ground measurements, digital twins and multi-body dynamics simulations, and must be managed in terms of quality and traceability, indexed to be able to be retrieved through request tags (customer, vehicle, measurement site, engine specification, road condition, usage conditions).

Once this step is achieved, the research and development department is able to have a better understanding of customer usage, inputs variabilities, in different environments and conditions, which have to be taken into account in the mission profile. This ad-hoc mission profile derives realistic and iso-damage usage scenarios on proving ground, test flights, or test bench specifications.

Understanding the customer usage and input variabilities enables to achieve a probabilistic fatigue analysis. The uncertainties on inputs (geometry, material and loading) may be propagated on life results, knowing the probability distribution function, using a Monte Carlo analysis. The infrastructure proposes to launch multiple runs on cloud-oriented server, which enables to automatize and streamline the whole process. A use case will be presented, which will illustrate the approach and its benefits.

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Enhancement of fatigue life modeling using a metamodel-based global sensitivity analysis framework

Khashayar Shahrezaei[1,2], Sara Eliasson[1,2,3], Per Wennhage[1,2], Zuheir Barsoum[1]

[1]KTH Royal Institute of Technology, Department of Engineering Mechanics, Stockholm, Sweden.
[2]The Centre for ECO2 Vehicle Design, Stockholm, Sweden. [3]Scania CV AB, Södertälje, Sweden

Global sensitivity analysis (GSA) is a well-established approach to support simulation-driven design decisions, where the dependency between the simulation's output and the model's input is quantified. However, classical GSA approach, such as Sobol' indices based on Monte Carlo Simulations (MCS), is not convenient when computationally expensive simulation models such as Representative Volume Elements (RVE) are used. The study develops a simulation framework with a metamodeling-based GSA to overcome the aforementioned cost of the MCS approach. The developed framework has been applied in a multi-scale modelling framework replacing the RVE simulations, for CFRP material with three different metamodels for performing GSA. The objective is to predict how the manufacturing process and introduction of defects may influence the fatigue behavior of the material. A robust model to predict the fatigue life of these materials is in need and therefore it is important to determine how to consider defects in these simulation frameworks, and how defects may affect the fatigue life.

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FD23-103

Achieving high confidence in fatigue reliability by quantifying the effects of uncertainty

Andrew Halfpenny[1], Tudor Miu[1], Balaje Thumati[1], Amaury Chabod[2]

[1]Hottinger Bruel & Kjaer UK Ltd., Rotherham, United Kingdom.
[2]Hottinger Bruel & Kjaer France SAS, Sucy-en-Brie, France

All new electric vehicles sold in the US require an 8-year/100,000 mile (160,000 km) battery warranty. Electric vehicle batteries are complex mechanical structures that support dynamic masses, and transmit loads and vibration through many thousands of joints and components. Fatigue failure therefore presents a significant risk to the overall reliability of the battery system.

The design requirement over a population of electric vehicles is frequently expressed in terms of a statistical reliability target; for example:

"Over a warranty period of 8 years/100,000 miles, I require greater than 95% reliability (i.e. fewer than 5% failures), with no less than 90% confidence in my estimation."

This paper considers how digital simulation along with physical component testing and statistical reliability analysis, are used to support the fatigue design requirement and thereby reduce a company's exposure to unacceptable warranty risk.

The paper addresses the following challenges:

- The advantages of 'Stochastic Design' concepts over more traditional 'Deterministic Design'.
- Statistical methods for characterising the variability in customer usage severity.
- Statistical methods for quantifying the effect of uncertainty in fatigue life simulation.
- The roles of simulation alongside physical testing in providing both simulation parameters, and verification of the simulation model.
- The statistical comparison of fatigue simulation with physical tests – especially in considering the limited number of physical tests usually performed, and the wide variability associated with fatigue failure.
- The scaling of many in/dependent failure modes when representing the overall reliability of a complex battery system using 'System-of-Systems' reliability simulation methods.

The paper demonstrates how simulation, properly verified using suitably improved physical testing, (consisting of additional measurements and run to failure in an efficient manner), may be used to validate the reliability design requirements for complex structural systems – "SV&V – Simulation, Verification & Validation".

The significance of this approach extends beyond electric vehicle battery systems to any complex system where a high confidence in fatigue reliability is required.

S13
Vibration Fatigue

Chairmen:

Maurin Berger & Marco Bonato

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FD23-7

Investigation of an automotive subsystem submitted to vibration loads considering scatter of influence parameters

Sven Maier[1,2], Florian Bachmann[2]

[1]TU Darmstadt, Darmstadt, Germany. [2]BMW Group, Munich, Germany

Modern vehicles contain numerous subsystems for comfort, safety, electrification and autonomous driving functions that are mounted to the body-in-white structure. These subsystems are submitted to stochastic vibrational loads induced by the road unevenness. The vibration fatigue behaviour of the subsystems and their connection to the body-in-white structure depend on a great number of influence parameters and associated uncertain scatter bands that are usually unknown and difficult to consider in the design process.

This study investigates the oscillation behaviour and fatigue life of a current car component excited by vibrational loads focusing on scatter of relevant influence parameters (mass, stiffness) on a pronounced statistical sample basis. An experimental modal analysis is used to determine eigenmodes and damping characteristics for the 3 variants: nominal value, increased mass and reduced stiffness. As a further experimental investigation vibration fatigue tests are performed.

A simulation tool chain using commercial CAE programs is applied to consider scatter effects on the fatigue life of the component under vibrational loads and its connection to the body-in-white structure. The simulation quality when using uncertain broader scatter bounds is compared to simulation quality using measured data and modal analysis output. Furthermore, correlations between the vibration behavior and the fatigue of the component are derived. Finally, the hardware fatigue testing results are compared to the simulation results and conclusions are drawn.

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FATIGUE DESIGN 2023

FD23-21

Fatigue simulations for automotive components undergoing vibration loadings: effect of non-linear behavior

Maciej Majerczak[1], Ewelina Czerlunczakiewicz[1], Marco Bonato[2]

[1]Valeo Thermal Systems Poland, Skawina, Poland. [2]Valeo Thermal Systems France, La Verrière, France

Modern automotive customers are demanding for faster and faster product development, from initial response for quotation (RFQ) to serial production. Finite Element Analysis (FEA) is a powerful tool applied to design validation (DV). In Valeo, FEA and Reliability teams have been working together to establish a robust methodology based modern simulation tools to validate the desing of the components undergoing vibration fatigue validation tests.

Previous investigations had shown that "simple" DV simulations based on the material's ultimate tensile strength (UTS) rely on conservative criteria and basically target an infinite fatigue life endurance.

The present study aims at predicting the cumulative vibration damage of relatively complex systems (multi-materials components, prototype parts and representative system integration) in the high cyclic fatigue domain: the goal is to run representative FEA simulations as early as possible even before official nomination (RFQ phase).

In a numerical example, the fatigue damage simulations are calculated on a car Engine Cooling Module (ECM) undergoing vibration fatigue loadings. Various types of calculation methods are considered, which include modal linear and non-linear approaches and time domain methods.

We will illustrate the results as a comparative analysis between the presented methods. The objective of the study is to compare the vibration fatigue damage estimations obtained from the different approaches when applied to durability design validation of an automotive cooling system undergoing vibration fatigue loadings.

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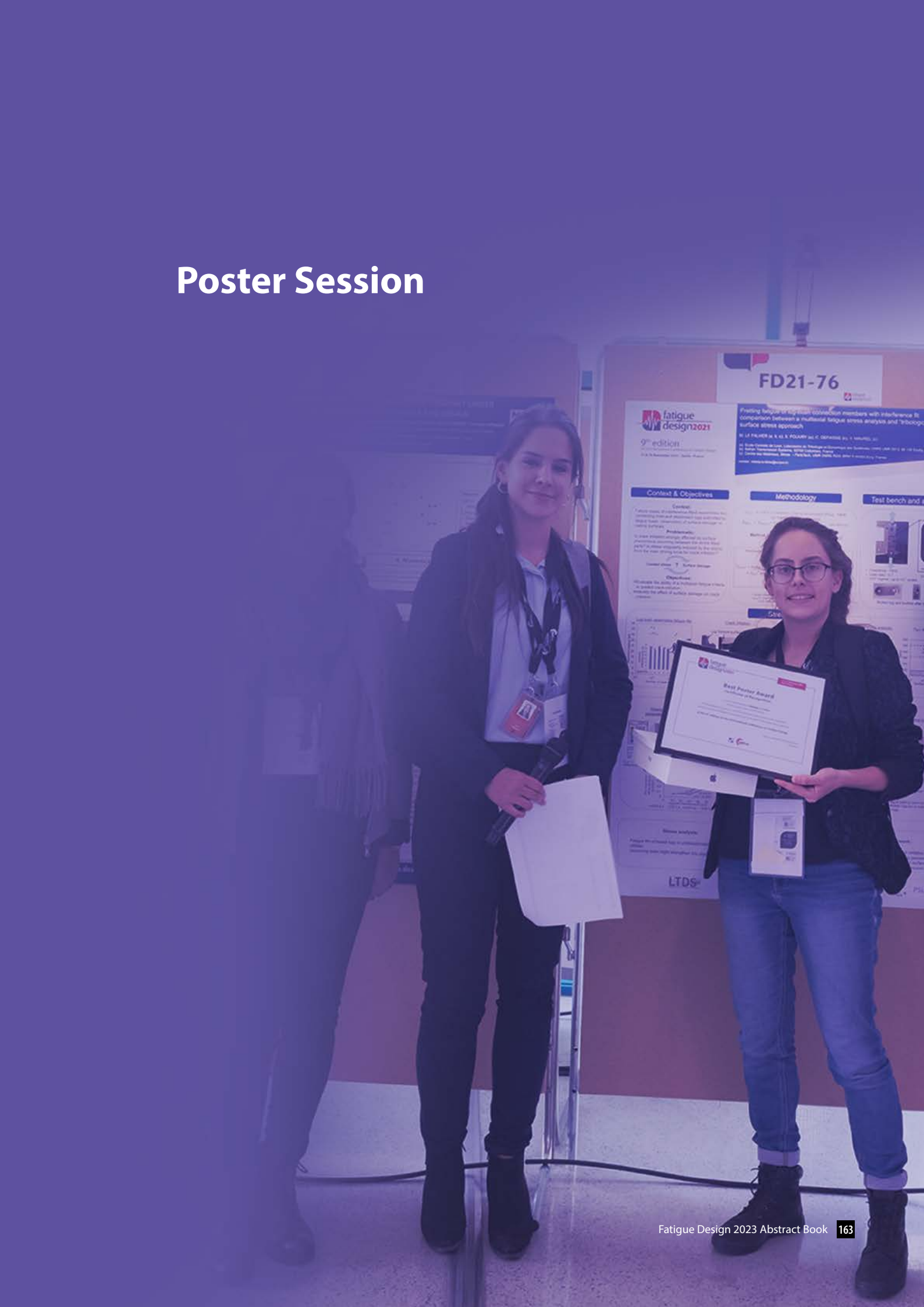
Fatigue life assessment of a slender lightning rod due to wind excited vibrations

Andi Xhelaj, Andrea Orlando, Luisa Pagnini, Federica Tubino, Maria Pia Repetto

Department of Civil, Chemical and Environmental Engineering, University of Genoa, Genoa, Italy

The wind-excited vibrations of structures induce fluctuating stresses that lead to fatigue damage accumulation and can determine structural failure. This paper presents the findings of a research program assessing the fatigue life due to wind induced vibrations of a 30 m high slender and tapered lightning pole. The structure analyzed in this work is part of a group of lightning rods located in an electric power plant. Over the course of 10 years after installation, some of the lightning rods presented fatigue problems due to wind actions. One of these poles collapsed, while some others suffered from crack damage at the pole-to-base plate connection detail. A four-stage study has been conducted to understand the causes of fatigue damages. In the first step, a climatological analysis has been carried out, obtaining the probability density function of wind velocity in the area, starting from 49 years of anemometric records measured at the site. In the second step, a full-scale experimental investigation based on pull and release tests was conducted to identify the natural frequencies and modal damping ratio of one of the uncracked lightning rods under investigation. The results of the test show very low modal damping ratios, especially concerning the second mode of vibration. In the third step, results from the dynamic identification test were used to estimate the response of the structure induced by turbulence and vortex shedding induced vibrations (VIV). Critical resonant conditions on the first and second modes of vibration have been considered, adopting standard (Italian CNR-DT 207 R1/2018, Eurocode 1 and 3) and advanced calculation techniques from the literature. Severe VIV response in the second mode produced very high stress conditions at the base, however not exceeding the ultimate limit state of the structure. Finally, in the fourth step, the fatigue damage induced by each excitation mechanism was estimated. Calculation reveals that the degradation of the lightning rod is predominantly related to the VIV in the second mode, even if also the effects of turbulence and VIV in the first mode give non negligible contributions. The findings demonstrated that the limited fatigue life of the lightning rod depends primarily on the stress range at the base of the pole attributable to wind-loading effects. The paper also discusses the large uncertainties affecting the analysis, stressing out the limitations of current standard methods in VIV response and fatigue assessment, even in the case of a very simple structure.

Poster Session



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FD23-15

Fatigue calculation at hot spots in cope hole welded details using finite element analysis

Kashif Toor[1], Inge Lotsberg[2]

[1]Vattenfall, Kolding, Denmark. [2]DNV, Oslo, Norway

Finite Element Analysis (FE) is widely used to perform fatigue calculations for geometric singularities at welded components. The analysis methodologies are described in design codes and recommended practices such as DNV, IIW, and Eurocodes. The focus of the present study is the application of hot spot stress methodology to a weld detail located at the cope hole in a pile sleeve connection of a jacket substructure. FE analysis is used to calculate the geometric stress where the influence factor (INF) technique has been implemented to calculate the hot spot stress at the weld location. Generally, a mid-surface shell model excluding the weld is used to model the welded components in FE analysis and a stress extrapolation method is applied to calculate the hot spot stress. The extrapolation method recommended for the plate edge has been found too conservative to be applied to the cope hole type welded details. A full solid model of the cope hole detail has been used for fatigue calculation and is used as benchmark to calibrate the weld modeling techniques using shell elements for the analysis. The results confirmed the weld stiffness has a significant influence on the hot spot stress calculation at the considered cope hole. Thus the weld geometry and stiffness shall be included into the finite element model for an accurate fatigue damage calculation of such details. The calibrated results showed that the mid surface shell model can still be used if the appropriate weld stiffness is included in the finite element model.

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Influence of shear cut holes on the fatigue performance of hot-rolled 800 MPa automotive steel grades

Kalle Lipiäinen[1], Pekka Plosila[2], Antti Kaijalainen[2], Antti Ahola[1], Timo Björk[1]

[1]LUT University, Lappeenranta, Finland. [2]University of Oulu, Oulu, Finland

Experimental fatigue tests were carried out for two t = 3 mm 800 MPa hot-rolled (HR) steel grades. These steels have good formability, and it is possible to use shear cutting to enable high productivity. The test campaign included unnotched base metal specimens to evaluate the fatigue performance of HR surface, and for shear-punched and electrical discharge-machined circular holes to evaluate the effect of cutting process and geometrical shape on the fatigue strength capacity. In this context, the properties shear-cut affected zone (SAZ) and resulting high tensile residual stresses, and their effects on the fatigue performance, were evaluated. The fatigue test results were first evaluated based on the nominal stress approach, followed by the applications of local approaches. The mean fatigue strength of the perforated specimens in the nominal stress system was 125 MPa (with a slope parameter of m = 3) which is at the comparable level to laser cut holes. Fractography analysis, conducted with scanning electron microscopy (SEM), showed local crack-like defects at the SAZ, and the characterization of local defect feature was utilized in the fatigue strength assessment using a multiparametric theory of critical distances-based method.

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FD23-23

A pragmatic method to account for seismic stress cycles contribution in fatigue assessment compliant with RCCM French design code

Sandy LIMOUZI

Technicatome, Aix en Provence, France

Seismic Fatigue risk assessment of mechanical components is required by the RCCM design code. This risk is evaluated by calculating a codified criterion named "Usage Factor" which represents the cumulated damage on a mechanical component submitted to stress/strain variation cycles during its entire life. When dealing with change of plant operating conditions, the stress variation magnitudes and associated number of cycles are easy to define. Therefore, the calculation of cumulated fatigue damage is straightforward. However, the contribution of the seismic stress cycles in the Usage Factor calculation is less obvious to handle. First, this paper proposes accessible guidelines aiming at defining the seismic solicitation with regard to fatigue risk assessment. Then, a codified approach for the calculation of the Usage Factor accounting for specific RCCM design rules is proposed. Finally, the margins resulting from this codified approach are compared with margins resulting from a rainflow counting method.

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FATIGUE DESIGN 2023

FD23-25

System reliability - eDrive

Karthik Krishnasamy

Valeo, Amiens, France

Since a few years, the electrification of the automotive powertrain has led to major technical challenges. Among them the proof of reliability for an eDrive system is a key requirement addressed by Valeo through a dedicated methodology. The most important criteria for the design of a complete eDrive system is a sufficient strength of all components. The permissible stress is determined based on a failure probability of the material strength value determined during the measurement of the S-N curve. In drivetrain, example gear strength is expressed in safety factors for bending, contact etc, and bearing strength are expressed in life time. In such situations, how to identify the eDrive system is safe, also the inherent failure of probability of the methods for different components varies. This paper presents a method to transfer the safety factor of each component into a failure probability based on a Weibull distribution, taking material properties into account. After this step it is easy to obtain a probability function for the failure of the full system over lifetime.

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FD23-28

Equivalence of vibration signals for fatigue simulation effect of parameters on durability predictions

Marco Bonato[1], Renan Leon[1], Karthikeyan Sridhar[2], Arumugapandian Duraipandi[2]

[1]Valeo Thermal System, La Verrière, France. [2]Valeo, Chennai, India

The reliability design process of automotive components requires the products to be validated according to sign-off vibration tests that are given by each car manufacturer.

From a supplier perspective, the Finite Element Analysis (FEA) is a power tool applied to rapidly detect structural weaknesses that would compromise the reliability of the products.

One of the main challenges is the complexity of vibration signals that are provided by each carmaker (validation specifications). For FEA simulations, vibration analysis is performed in the frequency domain, therefore only "pure" random PSD (power spectrum density) or harmonic (sine sweep) signals can be used. In case of complex vibration signals (sine-on-random, shocks-and-random, multiple-PSDs) an approach to tranform them to a fatigue damage equivalent random PSD or Sine Sweep has been developed by Valeo.

The choice of two main parameters plays an important role in the definition of the final equivalent signal: the fatigue life exponent (Basquin's factor) and the damping ratio (Q factor). Also the nature of the output signal (purely random or harmonic) highly affects the predicted fatigue damage.

In this study we analyze the influence of the variables on the generated equivalent-damage signal (PSD and sine sweep) and the consequence on the fatigue simulation life predictions.

Numerical examples of vibration fatigue simulation will illustrate the effect of the mentioned parameters applied to sine-on-random and shock-and-random signals (used to validate the design of an alternator bracket and a high voltage heater inverter, respectively) when transformed into an equivalent random PSD or sine sweep.

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FD23-30

Fatigue assessment of steel tube-to-flange welded joints with reinforcement ribs subjected to multiaxial loads according to the Peak Stress Method

Alberto Visentin[1], Alberto Campagnolo[1], Vittorio Babini[2], Giovanni Meneghetti[1]

[1]*Department of Industrial Engineering, University of Padova, Padova, Italy*
[2]*Antonio Zamperla S.p.A., Altavilla Vicentina, Italy*

In fatigue design of welded structures, the Peak Stress Method (PSM) is a FE-oriented tool to estimate the Notch Stress Intensity Factors (NSIFs). In compliance with proper design curves validated against more than 1300 experimental data, the PSM allows to estimate the fatigue lifetime of welded structures made of aluminium alloys or structural steels and subjected to uniaxial and multiaxial constant amplitude (CA) as well as variable amplitude (VA) loads. Moreover, an interactive analysis tool has also been developed in Ansys® Mechanical in order to automate PSM application on welded structures and support the FE analyst. In this work, the fatigue strength of complex steel tube-plate welded joints with reinforcement ribs has been experimentally investigated under bending, torsion and in-phase as well as out-of-phase combined bending and torsion CA as well as VA loads. The specimen consists of a steel SHS tube having 6.3 mm thickness, which is joined at both ends to a 15-mm-thick plate. In addition, tube and plates are joined by fillet welding to 6-mm-thick steel reinforcement ribs. A test rig has been designed in order to perform the experimental fatigue tests, taking advantage of two 15 kN MTS hydraulic actuators. The test program involves six series of CA tests in the fatigue life range 5·104 ÷ 2·106 cycles, each series consisting of six specimens. Additional specimens are being tested under uniaxial as well as multiaxial VA loads. The experimental fatigue results have been compared with fatigue lifetime estimations performed using the automated PSM tool.

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FD23-33

Fatigue behavior of a nodular cast iron subjected to a variable amplitude strain-based load spectrum applied in bench tests of an Off-highway axle

Alberto Campagnolo[1], Carlo Dengo[2], Jacopo Pelizzari[1,2], Giovanni Meneghetti[1]

[1]University of Padua, Padua, Italy. [2]Carraro S.p.a., Campodarsego, Italy

Nodular cast irons are commonly adopted in Off-highway applications, owing to the possibility to shape complex components and to guarantee good mechanical properties. In the fatigue strength assessment of axles made of nodular cast irons, engineers have to deal with external loads that turn into local strain spectra at the fatigue crack initiation zones, which are usually located in areas weakened by notch-like geometrical details. Moreover, Off-highway axles are subjected to variable amplitude load histories during their service life; during the design phase, the field load histories are usually applied to the axles in the form of simplified bench load spectra. In this paper, the mechanical properties of EN GJS 500-7 have been investigated through static tensile tests and strain-controlled fatigue tests performed on specimens with machined surface extracted from a real axle. Furthermore, a local strain-based load spectrum has been derived by means of strain gauges which have been applied at the failure location of the axle during the bench tests. The bench load spectrum has been replicated on the specimens to define the damage index based on the linear damage rule proposed by Palmgren and Miner. Finally, by using the Miner's damage index at failure returned from the specimens' testing and the mean stress corrected life equation according to Smith, Watson and Topper, the theoretical fatigue life of the axle has been compared with the experimental fatigue life obtained from bench load spectra.

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FD23-55

Influence of temperature on tensile and fatigue behavior of premium quality Inconel 718

Lyne Meouchy[1,2], Manuel Paredes[1], Alain Daidie[1], Christian Paleczny[2], Pauline Girot--Person[3]

[1]Institut Clément Ader (ICA), Université de Toulouse, INSA, IMT MINES ALBI, ISAE-SUPAERO, UT III, CNRS, Toulouse, France. [2]Safran Aircraft Engines, Villaroche, France. [3]Safran Helicopter Engines, Bordes, France

The advancements in the aeronautical field are often accompanied by new advancements in the materials used in the field. The most used metal alloys nowadays are the nickel based superalloys for their excellent mechanical properties even at high temperatures.

In this paper, the aim is to study the static and fatigue behavior of a premium quality Inconel 718 at different temperatures. An experimental campaign on round test specimens was carried out and compared to existing data. Tensile tests at room temperature, 250°C and 450°C helped to identify the evolution of the Young's modulus with the increase of temperature.

Fatigue testing at the same temperatures, and at two load ratios: 0.5 and -1, aimed to determine the endurance limit of the material at 10^5 cycles. The fatigue tests showed material softening during cycling and a decrease of the endurance limit with the increase of the temperature.

A microstructural analysis is done on the specimens and compared to the existing data in aim to understand the correlation between grain size and mechanical behavior for the Inconel 718.

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FD23-69

FEA Design optimization for Mining Excavators based on field measurements

Farid Ahdad, Theo Citerne

Liebherr Mining, Colmar, France

Hydraulic excavators for mining applications are commonly used to load and unload significant volumes of gravel and all types of ore. The structural dimensioning of an excavator and its components as well as the risk assessment of the weld joints strongly depend on the frequency of the loads, the type of loads and the amount of moved matter.

The instrumentation of an excavator turned out to be necessary to determine the real loads on the field. For this purpose, strain gauges were installed on the boom of the excavator. A calibration process is performed to determine the transfer matrix linking the electric signals from the strain gauges to the efforts seen by the structure. In this way, we determine the out-of-plane loads which turn out to be the most difficult to evaluate without measurements. The state of art is presented in this work.

The data processing has been performed on a range of 1000 hours on a 600-tons excavator in an Iron ore mine in Australia. The newly determined loads provide additional information on stressed areas compared to the current validation process. That allows a better structural dimensioning. Consequently, the inputs from the field measurements will be used in our standard validation process with static calculations.

A new fatigue approach has been developed considering the field measurements. It consists in determining an equivalent damage for a specific event. It helps optimize the weld joint assessment by using FEMFAT.

The "Field Measurements" approach turns out to be necessary and brings lots of useful information for the design of Mining application structures and avoid over designing.

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FATIGUE DESIGN 2023

FD23-78

Numerical investigation of the influence of defects on the multiaxial fatigue behaviour of additively manufactured alloys

Sai Sreenivas Penkulinti[1], Matthieu Bonneric[1], Nicolas Saintier[1], Benoit Verquin[2], Fabien Lefebvre[3], Pascal Ghys[4], Thierry Palin-Luc[1]

[1]I2M Bordeaux, ENSAM, Bordeaux, France. [2]CETIM, Saint-Étienne, France. 3CETIM, Senlis, France. [4]ALSTOM, Saint-Ouen, France

Whether it's automotive, bio-mechanics or aeronautical industry, additive manufacturing (AM) is already in reality due to its wide range of advantages. But limitations, like the presence of defects induced by the fabrication process that depends on the input process parameters, continue to be a crucial issue for the design of industrial components regarding fatigue damage. The present work aims to use numerical simulation to study and understand the impact of typical AM defects, and especially the lack-of-fusion (LoF) defects, on the multiaxial fatigue behaviour of high-strength materials. Studies have shown that the local approaches lead to conservative fatigue behaviour predictions [F. Morel et al., International Journal of Fatigue, 2009, A. Karolczuk et al., Computational Materials Science, 2008, Y. Nadot & T. Billaudeau, Engineering Fracture Mechanics, 2006], and the stress and strain distributions around the defects depend on the size, position and morphology. For that, a numerical methodology has been formulated to carry out simulations on 10 LoFs (real defect geometries observed from CT scans) that were induced during the fabrication of TA64 using an SLM process. Simulations were performed on ideal spherical defects at different loading modes (tension, torsion, and tension-torsion) to determine the stress distribution around the defect. Repeating the same on 10 critical LoFs and able to compare the results with some experimental data. The analysis helps to quantify the impact of stress gradient (resulting from the different defect morphology) on fatigue behaviour under multi-axial loading conditions.

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FATIGUE DESIGN 2023

FD23-80

Numerical modeling of high-frequency fatigue testing for short crack propagation from tailored defect

Marie Bouyx[1,2], Chiaruttini Vincent[1], Vattré Aurélien[1], Vincent Bonnand[1], Antoine Blanche[3]

[1]ONERA, Châtillon, France. [2]Ecole Centrale Nantes, Nantes, France. [3]SAFRAN, Villaroche, France

This work focuses on damage tolerance study and fatigue life prediction of aeronautical parts. The goals are to understand fatigue short crack growth initiated from surface defect and to analyze the microstructure effects on propagation path and velocity in INCO718DA specimens.

The defect size chosen is the smallest experimentally feasible while still bigger than natural microstructural ones (50µm). Three grain sizes – ranging from conventional material size (8µm) to millimetric size – are set up in order to better understand grain boundary impact on crack propagation and on dislocation mechanics.

Modelling of the fatigue crack growth mechanism is investigated within a representative polycrystalline aggregate as simulations of the entire specimen microstructure cannot be computationally realistic (we use a generic multi-model approach recently developed at Onera). Implementation of the digital chain has already been completed for oblate spherical defect.

We will present its application to digital reproductions of experimental tests with crack propagation, still restricted today to simplified materials (heterogeneous elastic behavior).

In parallel, a theoretical work is carried out to understand interactions between crack and grain boundary with an ad-hoc representation of discrete dislocation at the cracktip. Based on the linear elasticity theory of dislocations in bi-materials coupled with the linear elastic fracture mechanics, this approach makes it possible to understand complex interactions, in a heterogeneous anisotropic microstructure, in the vicinity of the cracktip, such as the possible blocking of dislocation stacks by a grain boundary. It's employed to characterize microstructural barriers role to the plastic flow and crack propagation.

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FATIGUE DESIGN 2023

FD23-87

Mitigating the risk for creep-fatigue cracking in steam turbine rotors: an end user's perspective

Malik Spahic, Dario Guarino, Clément Brichart, Dieter Billet, Frits Petit

Engie Laborelec, Linkebeek, Belgium

Over the last few years, cracks appeared at an early stage of operation on several steam turbine rotors due to low cycle fatigue induced by thermal transient events. These cracks led to expensive maintenance and unavailability. An extensive fatigue lifetime assessment program was set up to avoid similar issues in other units. Although numerical and finite element (FE) models can offer accurate results in this matter, regular 3D and 2D FE models are too time-consuming when simulating the rotor's entire operational history. Instead, a more time-efficient numerical method, using the rotor's measured physical data as input, was developed.

This method follows two steps.

In a first step, a 2D axisymetric thermomechanical finite element model is used to define accurate stress levels on a reference period of a few days.

In a second step, the simulation parameters of a simplified time-efficient thermomechanical finite differences model of the rotor are calibrated to give the same results as the 2D model for the reference period. It is then processed over the rotor's entire operational history to determine the stress history at the most critical location of the rotor.

In combination with theoretical fatigue models, this method was able to reliably reproduce the crack initiation in several cracked rotor cases. The results were then used to extend the operational period of different steam turbine units by modifying their operational parameters or by doing skim cuts to remove damaged metal surfaces.

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FATIGUE DESIGN 2023

FD23-88

Digital twin for predicting progressive damage in operating pressure vessels

Izat Khaled[1], Mohamed Bennebach[1], Salim Chaki[2], Modesar Shakoor[2], Dmytro Vasiukov[2], Jean-Louis Iwaniack[1], Philippe Rohart[1], Samir Assaf[1]

[1]CETIM, Senlis, France. [2]IMT Nord Europe, Douai, France

Pressure vessels (PV) are intended for the production, storage, or transportation of products under high pressure. The energy contained in these equipment's is often very important and can, in case of failure of the enclosure, cause human, material and environmental damages in the vicinity of the accident. Thus, optimal design, maintenance and structural health monitoring of pressure vessels are major concern for the industrial actors of this field.

The first objective of this study is therefore to contribute to the development of a methodology for real-time assessment of the integrity of PV, by implementing a novel predictive maintenance strategy based on the Internet of Things (IoT) and digital twin technologies. The second technological goal is to develop methods to optimize the design of the next generation pressure vessels and increase their operational reliability.

According to the definition of the Alliance Industry of Future: "A digital twin is an organized set of digital models representing a physical entity of the real world to respond to specific problems and uses". The digital twin is a virtual clone of a physical system or process. It systematically implies the existence of a «digital model» coupled with the object it copies. Depending on the system concerned and the desired use, it can be a geometric, multi-physical, functional, behavioral, and decision-making model. It must evolve over time like its real twin. It makes it possible to understand, analyze, predict, or optimize the operation and management of the real entity.

In this paper, first is presented a state of the art on the pressure vessels design according to codified rules (CODAP…), and on various existing maintenance strategies. Then the developed physical model is presented and discussed. This, considering specificities like welds, complex stress states and local defects. Welds are modeled and analyzed according to IIW recommendations based on a stress life approach, non-welded regions with complex stress states are analyzed with multiaxial fatigue criteria and damage tolerance is applied for zones with local defects.

The developed model, once calibrated with experimental results, allows also generating data (stress, strain, damage…) to feed the data science model and reconstruct the stress field in the complete equipment from a reduced number of sensors. The latter is done thanks to development and improvement of an intelligent sensor placement code, with the aim of minimizing the number of sensors needed to monitor the health of the equipment.

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FD23-94

An additive manufacturing database to support the development of metal AM applications

Benaouda Abdellaoui, Pierre Auguste, Nicolas Bachelard, Adrien Barroux, Bhimal Bholah, Mohammed Amine Cheikh, Karim Cheikh, Lucie Demaret, Caroline Depredurand, Julius Domfang Ngnekou, Florence Dore, Nadège Ducommun, Driss El Khoukhi, Robin Hauteville, Yassine Hfidh, Alexian Juin, Mathilde Labonne, Clément Laleve, Pauline Leborgne, Pierre Osmond, Maxime Robert, Hervé Rognon, Quentin Saby, Socona Traore, Benoit Verquin

CETIM, Senlis, France

Metal Additive Manufacturing (MAM) technologies are recent compared to traditional manufacturing processes like casting and forging, and are scarce in material databases used to design mechanical components. This is especially true for fatigue data, making the design of parts more challenging and hindering the growth of additive manufacturing technologies in the industry.

This work aims to present the database set up by CETIM, as well as main trends observed in different material/process couples studied. This work undertaken within the BDD-FA (Additive Manufacturing Materials Database) project at CETIM will be put into perspective for an industrial exploitation of the data.

Firstly, the experimental campaign was launched on more than 5400 specimens divided into nine material/process couples (Powder Bed Fusion - Laser Beam (PBF-LB) with AISI420, 316L, Copper, Inco625 and Inco718 ; Metal Binder Jetting (MBJ) with 17-4PH ; Direct Energy Deposition –Wire Arc (DED-WA) also known as Arc Additive Manufacturing (WAAM) with 17-4PH and Duplex 2209. Then, mechanical and microstructural properties of these materials have been characterized both in the as-printed state and after heat treatment. Particular attention was given to the influence of manufacturing defects on fatigue strength. Kitagawa diagrams have been established and the Paris law has been defined [1]–[7].

This database contributes to an easy reading of material data and fatigue strength analysis of additive manufacturing parts for industrial purposes. Finally, this tool helps sizing AM parts for fatigue applications and contributes to the implementation of these technologies in industry.

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FD23-99

Elastoplastic behavior of 316L stainless steel (SS) and the analysis of the Ratcheting phenomenon under cyclic loading

Aboussalih Amira[1], Zarza Tahar[2], Fedaoui Kamel[1]

[1]*L'institut des Sciences Techniques Appliquées (ISTA) l'université Constantine 1., Constantine, Algeria.*
[2]*Civil engineering Constantine 1 University, Constantine, Algeria*

The present work, is concerned with the evaluation of the nonlinear behavior of 316L steel used in several fields, industry, automotive, aeronautics, medicine .... subjected to sinusoidal movements. This investigation allowed us to analyze the different responses of steel in low cycle fatigue, and to perceive the phenomenon of ratcheting leading, to the damage of the structure by an excess of plastic deformation, under loading cycles. The prediction of the behavior of the steel studied, reveals that the ratcheting increases according to the average stress when the stress amplitude is constant, and decreases according to the attenuation of the stress amplitude when the average stress is constant.

The simulation campaign allowed us to present an assessment, of the conditions favoring the acceleration of the ratcheting, includes several scenarios of periodic loadings, with strain and stress imposed under uniaxial tension/compression and biaxial tension/torsion loading.

The quality of the model to predict, the macroscopic elastoplastic behavior of 316 L is considered as a basic step for the description, of the hardening produced during cyclic loading. In the present work we have chosen the Chaboche model, this model is capable of translating the real behavior of materials; it is based on the use of a law combining an isotropic hardening and a nonlinear kinematic hardening.The predictions of this model are evaluated by subjected to cyclic loading within the software ZébuLon.

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FATIGUE DESIGN 2023

FD23-102

Effects of pre-strain, surface condition and residual stresses on the structural fatigue damage of wheel bearings: implementation of a numerical workflow from the manufacturing processes to the fatigue resistance

Vo-Huu-Thuc Nguyen[1,2], Etienne Pessard[2], Franck Morel[2], Daniel Bellett[2], Viet-Duc Le[2], Sébastien Guillaume[1]

[1]NTN-SNR, Annecy, France. [2]Arts et Metiers Institute of Technology, LAMPA, Angers, France

The aim of this study is to propose a reliable and generalizable flexible numerical approach for the fatigue life calculation of fatigue life of automotive wheel bearings manufactured by NTN-SNR Europe. The proposed methodology will take into consideration the impact of the manufacturing processes, including forging, shot blasting and orbital forming on the structural high cycle fatigue resistance of the component. Note that Rolling Contact Fatigue of the component is not considered in this work. The influences of pre-strain, surface condition and residual stresses will be characterized by fatigue tests at different levels: normalized specimens, elementary structures and the component itself. The results of the fatigue tests on normalized specimens with different surface conditions and under different load ratios will be compared with the results obtained by validation tests on the wheel bearings to determine the security zone in which there is no risk of cracking the component. using the Dang Van criterion. Fatigue tests on elementary structures will make it possible to further understand the cracking mechanisms by decoupling different effects of fabrication processes. Based on these experimental data and the analysis of the tested samples, fatigue criteria adapted to each critical zone of the bearing will be developed. These will be implemented into a numerical simulation workflow, including the manufacturing process and the use of the final component, with the commercial finite element software, Forge and Abaqus. The final objective is to improve the precision and reliability of the structural fatigue life predictions.

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FATIGUE DESIGN 2023

FD23-106

A pragmatic approach for the fatigue life estimation of hybrid joints

Cristian Bagni, Andrew Halfpenny, Michelle Hill

Hottinger Bruel & Kjaer UK Ltd, Rotherham, United Kingdom

The need for more environmentally sustainable ways of transportation and for a reduction in emissions and fuel consumption make lightweight structures essential. Together with the use of lightweight materials and design optimisation, the use of hybrid joints represents one way to reduce the weight of components and it is becoming increasingly popular in the transportation industry. The name 'hybrid joint' refers to a connection where adhesive bonding is used in conjunction with traditional joining techniques, such as spot welds and rivets with the aim of combining and exploiting the advantages of the individual joining techniques. To optimise the design of hybrid joints and minimise the risk of in-service fatigue failures, the transportation industry needs efficient, robust, and easy-to-use approaches for the modelling and fatigue life estimation of hybrid joints.

This work presents two practical methodologies for estimating the fatigue life of hybrid joints that can be easily adopted by companies in the transportation industry. The first methodology neglects the life given by the mechanical joints after failure of the adhesive (the joint is considered failed when the adhesive fails), while the second methodology considers the life of both the adhesive and the mechanical joints. In the first methodology, just one configuration would need to be analysed ('hybrid' joint or 'purely bonded' joint, if this simplification is considered reasonable). In the second methodology, instead, the analysis of two configurations would be required (the previous configuration followed by a configuration where only the mechanical fasteners are considered). The second methodology would produce more realistic fatigue life estimations compared to the first methodology, but it would be more onerous both in terms of modelling and computationally. For both methodologies, FE modelling guidelines to recover the required stresses are suggested. These guidelines require limited changes to the typical FE modelling strategies currently used, especially in the automotive industry. Furthermore, the proposed modelling guidelines provide FE models that are not computationally too onerous, with a good level of mesh insensitivity and that do not require congruent meshes. The relevant stresses recovered from the FE model are then used as an input into nCode DesignLife to estimate the fatigue life of the hybrid joints in the analysed structure. The fatigue life estimation is carried out using the standard Stress-Life (SN) based nCode DesignLife analysis engines and bespoke SN curves obtained through testing of hybrid joint specimens, representative of the joints in the production parts.

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FATIGUE DESIGN 2023

FD23-118

Effects of hydrogen on fatigue properties of austenitic stainless steels at low temperature

Romain Chochoy[1], Gilbert Hénaff[1], Pierre Osmond[2], Denis Bertheau[1], Guillaume Benoit[1]

[1]Institut Pprime, Poitiers, France. [2]CETIM, Nantes, France

The design of a liquid hydrogen tank requires a good comprehension of the influence's factors of crack initiation and propagation under hydrogen at cryogenic temperatures. Indeed, the hydrogen embrittlement (HE) is the main damage mechanism observed. Therefore, it is necessary to improve the understanding of the main parameters governing the HE in fatigue at cryogenic temperatures. In this context, the work conducted in this study focuses on the interaction between hydrogen and crack initiation at different loads and the determination of the fatigue life associated.

During their life, the components endure a high temperature range (between -253°C and 25°C) which induce properties variations. Indeed, one of the parameters contributing to these phenomena is the martensite transformation (MT), when the temperature is decreasing, the transformation is facilitated. At -120°C, for two different steel grades (304L and 316L Stainless steel), the MT become spontaneous, it means that only de temperature is governing the phase transformation between austenite and martensite, this temperature is called Ms. In hydrogen environment, the maximum hydrogen embrittlement is observed at -120°C. It seems that below this temperature, HE is controlled by the MT and above HE is controlled by the hydrogen diffusivity. It is necessary to conduct test at Ms temperature and above in different environments (air, hydrogen, nitrogen) to evaluate the embrittlement only induced by MT and not by the environment. The first stage of this work focused on the fatigue behaviour at room temperature in air, self-heating and ratcheting were studied.

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FATIGUE DESIGN 2023

FD23-131

Assessment method for fatigue regarding existing motorway bridges made of weathering steel

Jacques Berthellemy

Cerema, Champs sur Marne, France

This communication will discuss the importance of the correct evaluation of the fatigue category of resistance for bridges made of weathering steel.

Clause 7.1(5) of the French National Annex to EC3 1-9 has put bridges designers under the obligation to take into account stress concentration factors since 2011.

However, the temporary version of a french guidance document published in 2015 about weathering steel considered that there was no specificity of these steels regarding fatigue.

This document was rewritten in 2023 to take into account all the clauses provided for in Eurocode 3 part 1-9 concerning weathering steels. In addition, the monitoring and maintenance actions needed by these bridges have been specified because they are actually much more demanding than for painted steels. As an example, various deposits, in particular bird droppings, must be removed as quickly as possible when they occur on horizontal surfaces. This applies to I-beam bridges, whereas box girder bridges do not have horizontal surfaces wide enough to allow deposits to form or birds to land.

Bird droppings adhere to weathering steel, whereas paints are designed to be water-repellent. This case is worse than the effect of sea water: the likely occurrence is the formation of corrosion pits. The effects of corrosion pits on the category of detail is studied with a finite element model.

Even in the absence of bird droppings, studies by Ludwig Kunz have shown that craters form on the surface of weathering steel. The effects of these corrosion craters on the category of detail is again studied with the effective notch stress method. The thickness transition zone of the I-beam bridge is particularly sensitive to the presence of corrosion craters. Model shows that the presence of other craters in the vicinity of the crater placed at the hot spot does not improve the category of detail by a smoothing effect.

A confocal microscope can be used to analyse in detail the corrosion effects on the surface over an affected area in order to asses an existing bridges. A chart is provided to deduce the category of detail based on the depth of the observed craters. Prudent road owners can also use this data in France to design new structures using both the Clause 7.1(5) of the French National Annex to EC3 1-9 and the work of L. Kunz which is referenced in the Cerema-UGE 2023 guidance document about weathering steel.

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FATIGUE DESIGN 2023

FD23-132

Considerations regarding the fatigue design of the steel bridges

Jacques Berthellemy[1], Franziska Schmidt[2], Guillaume Bianne[2], Grégoire Leclerc[3]

[1]Cerema, Champs-sur-Marne, France. [2]Uni. Gustave Eiffel, Champs-sur-Marne, France.
[3]Cerema, Champ-sur-Marne, France

The fatigue damage of steel bridges is prone to occur under a large amount of heavy traffic and be a worldwide problem leading to serious disasters. This communication will discuss the importance of the correct evaluation of the fatigue category of resistance for the safety and durability of bridges. Although much attention is usually rightly paid by engineers to the effects of traffic, on the other hand the effect of stress concentrations which modify the category of detail of the tables of the Eurocode is still very poorly known.

We will deal with multiple examples to illustrate the question: the replacement of the cylinder head of the François I bridge in Le Havre at the very beginning of the 80s is an excellent example of an approach to the calculation of stress concentration factors by finite elements, which made it possible to solve the fatigue problems of this movable bridge.

On the other hand, the cracking of the bridges of Chamousset where a then forbidden constructive arrangement was nevertheless built shows that the question is not a view of the mind: If the problem had not been identified and the bridge put under annual surveillance for the hot spots concerned, the two bridges could have collapsed. The case of this real french bridge carrying an heavy international motorway traffic is used to test the coefficients applied to the FLM3 model of eurocode. The bridge presented simultaneously many cracks at a wrong detail after 25 years of service. The detail category of the features is recalculated using FEM and the real fatigue truck is successfully applied on a bridge model to demonstrate its accuracy.

Today, Clause 7.1(5) of the French National Annex to EC3 1-9 has put manufacturers under the obligation to take into account stress concentration factors since 2011.

And finally, many features will be reviewed, such as for example the thickness transition zones with and without cope hole, the anchorages of hangers, the studs under tension and bending, the bottom cuts of the vertical stiffeners that actually do not help regarding fatigue, the effects of corrosion, and the interruptions of guide rails.

Notes

References

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Notes

X-Raybot mini

IN DEVELOPMENT
2023

Compact diffractometer

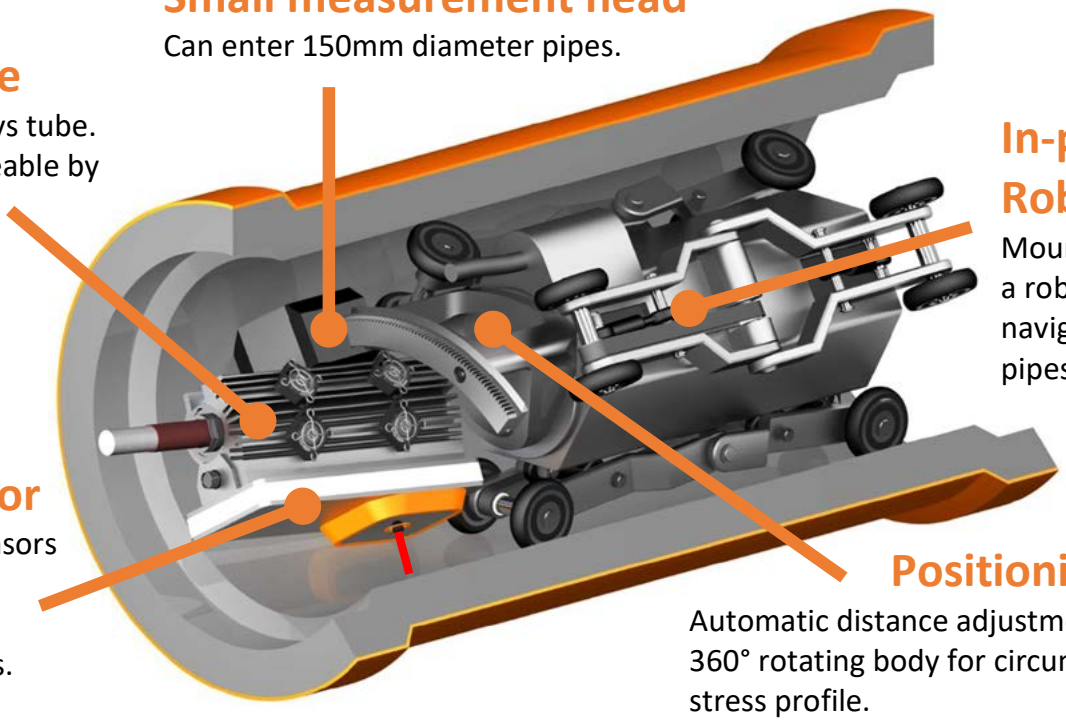
Complete stress tensor components evaluation.

Small measurement head

Can enter 150mm diameter pipes.

X Ray Tube

Air cooled X-rays tube. Easily exchangeable by the user.



In-pipe Robot

Mountable on a robot to navigate in pipes.

2D Detector

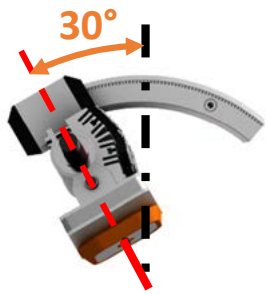
4 Silicon 2D sensors permitting to acquire the diffraction rings.

Positioning

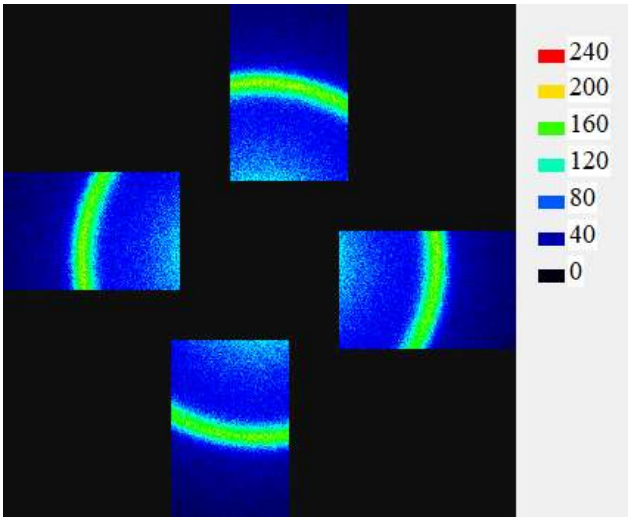
Automatic distance adjustment. 360° rotating body for circumferential stress profile.

SOFTWARE

- ✓ Multiple exposures with the tilting of the measurement head from -30° to 30°, to evaluate the complete stress tensor components.



- ✓ Robust error bars evaluation according to the Guide of Uncertainties in Measurements (GUM).
- ✓ Each diffraction pattern is fully fitted through a non-linear best fit method that permits to account for overlapped peaks.



Example of raw counts on a single exposure

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