fatigue design 2019

8th edition

of the International conference on fatigue design

PARTNER COUNTRY: JAPAN

20 & 21 November 2019
Senlis
France

fatiguedesign.org

ABSTRACTS BOOK

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20 & 21 November 2019
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Fabien Lefebvre

Pascal Souquet

Introduction Message

On behalf of the Fatigue Design 2019 International Scientific Committee and Organizing Committee, we would like to welcome you all to the 8th edition of Fatigue Design 2019 taking place at Cetim, Senlis, France on November 20 & 21 2019.

Since 2005, and every two years, the conference takes place at Senlis, the City of culture and history, located at 45km from Paris with more than 2000 years of history. The Notre-Dame Cathedral of 12th century, Saint-Pierre church, Medieval ramparts of 13th - 16th century, the château royal and 4 museums are among the most attractive places to be visited.

Organized by Cetim and his partners, the 8th Fatigue Design 2019 International Conference aims to present the most innovative approaches, scientific and technological progress in design methodologies, testing methods and tools to evaluate and extend the fatigue life time of the industrial equipment. The papers are mostly focusing on the industrial applications.

Japan has been proposed as the “partner country” for Fatigue design 2019 in respect to the japan advance research works in the area of fatigue and fracture mechanics in the last decade. More than 20% of conference speakers are coming from Japan including 2 plenary key speakers.

This edition of the conference will cover the following scientific and technical topics:

- additive manufacturing
- experimental and numerical design and validation methods,
- damage tolerance and fatigue life,
- reliability-based approaches and probabilistic methods,
- fatigue under severe conditions environment (corrosion, low temperature...),
- nonlinear behavior and cumulative damage,
- fatigue of assemblies (mechanical, welded, adhesive-bonding, multimaterial...),
- composite and elastomers,
- contact fatigue,
- vibration fatigue behavior,
- complex loadings,
- thermal and thermo-mechanical fatigue,
- taking into account manufacturing process in fatigue analysis (effect of microstructure, welding, stress relief techniques...).

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 8th edition of the Fatigue Design International conference is organized in close collaboration with Elsevier editor for the proceedings' publication through Structural Integrity Procedia. The papers are published online on ScienceDirect, which makes available worldwide for a better dissemination and maximum exposure. In this respect the selection and peer review of the papers have been done in collaboration with the International Scientific and Organizing Committees.

"Fatigue Design" became the reference conference to address the concerns of industrials on fatigue design of structures and components. It is also considered as the trade crossroads between industry and academia: 84 oral presentations are performed with 50% by industry.

We hope that the speakers and the delegates would have a fruitful exchange and discussions on technical and scientific developments and issues during the conferences. The poster sessions and exhibition stands are the complementary opportunities to facilitate the exchanges between the Scientists, industry participants, PhD students and the solution providers.

We would like to thank members of the International Scientific and Organizing Committees for their valuable scientific support for the selection and paper reviews, the authors, delegates for their contributions, exhibitors and sponsors, and SF2M and the colleagues of Cetim for the organization and to make this conference successful one.

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

Fabien Lefebvre
Chairman
Organizing Committee
Fatigue Design 2019

Pascal Souquet
Co-Chairman
Organizing Committee
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Organizing committee

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STEP LAB
STRESSMAP
UTC-LAB. ROBERVAL

Poster Award 2019

The poster session of the 8th edition of the Fatigue Design conference includes more than 25 posters. This session will offer the opportunities for the technical exchanges between the scientists, industry participants, PhD students.

In order 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 bestposter 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 7th Fatigue Design 2017 conference, the Poster Award has been dedicated to Richard Coquet for his thesis work and poster on " Damaging of PA6.6 GF30 products under combined stresses: random vibrations and temperature".

Plan

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4	UTC-LAB. ROBERVAL
5	CURTISS-WRIGHT
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Poster session

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Chairmen:

F. Lefebvre & F. Morel

F. Lefebvre & P. Souquet

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Fatigue Design 2019

FD19-122

Defect analysis for additively manufactured materials in fatigue from the viewpoint of quality control and statistics of extremes

Yukitaka Murakami

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Additive manufacturing (AM) is expected to be a promising new manufacturing process for components having complex geometry. High strength or hard steels and also light metals such as Ti and Al alloys are expected to be used for the aerospace, biomedical and automotive industry components having complex shapes. The advantages of additive manufacturing (AM) have been emphasized, especially for high strength or hard steels, which are difficult and costly to manufacture by traditional machining to complex shapes. However, a disadvantage or challenge of AM is the presence of defects and surface roughness which are inevitably produced by the manufacturing process. Until now the papers which focused on the quantitative evaluation of defects and surface roughness are relatively sparse among the flood of publications. Without strict and reliable quality control of components regarding defects and surface roughness, we cannot positively admire the advantages of AM as the new technology.

In this presentation, the method of quantitative evaluation of defects with complicated shapes and configurations, will be explained from the viewpoint of small 3D cracks. Practical guides will be presented for the fatigue design and development of high quality and high strength AM materials, based on the combination of the 3D defect analysis, the statistics of extremes on defects, and the area parameter model.

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Fatigue Design 2019

FD19-84

The peak stress method combined with 3D finite element models to assess the fatigue strength of complex welded structures

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The Peak Stress Method (PSM) is an engineering, FE-oriented application of the notch stress intensity factor (NSIF) approach to fatigue design of welded joints. The method uses the singular linear elastic peak stresses from FE analyses with coarse meshes. 3D modelling of complex welded structures is increasingly adopted in industrial applications and 3D tetra elements are particularly efficient to mesh geometries of complex shape. Based on this trend, in the present contribution the PSM is presented in conjunction with tetra elements implemented in Ansys. All loading modes, i.e. mode I, II and III are taken into account. As compared to previous steps of development of the method, in this paper mode I is calibrated for 120° and mode III for 90° as well as 120° sharp notch opening angles. Afterwards, an applicative example has been considered, which is relevant to a large-scale steel welded structure, having overall size on the order of meters. Two 3D FE models, having global size of tetra elements equal to 5 and 1.66 mm, have been solved by taking advantage of HPC, being the global number of degrees of freedom equal to 10 and 140 millions, respectively. The NSIFs values estimated at the toe and root sides according to the PSM have been compared with those calculated by adopting a shell-to-solid technique.

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Fatigue Design 2019

FD19-73

Fatigue design of additive layer manufacturing materials from computed tomography image

Yves Nadot[1], Carole Nadot-Martin[1], Lionel Ridosz[2]

[1]*Institut Prime ENSMA, Poitiers, France.* [2]*Zodiac Aerospace, Plaisir, France*

A modelling strategy is proposed to evaluate the influence of defect morphology on the fatigue limit of additively manufactured Al alloys by: (a, b, c) obtaining an X-ray micro-computed tomography (µ-CT) 3D image of the material, (d) computing the Equivalent Inertia Ellipse of each individual pore, (e) modelling the influence of the defect on the fatigue limit through the DSG approach and, (f) 3D mapping the criticality of each individual defect. The Methodology is validated through fatigue tests conducted on AlSi10Mg alloy manufactured by selective laser melting.

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Fatigue Design 2019

FD19-123

Crack growth arrester using gourd-shaped-insert-plate

Yoichi Yamashita[1], Takao Murakami[1], Youjirou Akizuki[2]

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In accordance with aging infrastructure systems such as steel bridges, fatigue of metals becomes serious risks. Countermeasures against them are required, because fatigue crack may lead the structure to catastrophic failure. "Crack growth arrest or retardation system" using gourd-shaped-insert-plate has been developed as a versatile and high performance construction method against fatigue crack, by using the arrester to close fatigue crack and reduce crack tip opening displacement and stress concentration at the fatigue crack tip. Arrester was applied to CT (Compact Tension) specimen and also mockup of steel bridge deck, in order to validate performance of the system. Fatigue crack growth rate of the specimen with arrester was 2~10 times lower than that without arrester, and threshold stress intensity factor range was about 10~20MPa√m higher than that without arrester by using only few insert-plates. Also, the arrester was applied to the fatigue crack in a mockup of steel bridge deck. Without arrester, fatigue crack extended in accordance with the increase of loading cycles, on the other hand, fatigue crack growth was arrested after application of the arrester in the mockup of steel bridge deck. And to enable quantitative fatigue life assessment in fatigue design, fracture mechanics based-crack closure model with spring elements for the arrester has been verified with good life prediction accuracy for the above tests.

S01
Additive Manufacturing

Chairmen:

Y. Murakami & C. Reynaud

Y. Nadot & R. Hauteville

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Fatigue Design 2019

FD19-2

Relationship between defect size and fatigue limit in Ti-6Al-4V with artificial defects

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Rotating bending fatigue tests were conducted using conventionally-melted Ti-6Al-4V. The fatigue specimens had four artificial drilled-hole defects with different sizes. Fatigue-fractured and run-out samples were investigated in detail to figure out whether fatigue cracks initiated at artificial holes or not. The fatigue limits of the specimens were identified by the crack initiation, and the relationship between fatigue limits and defect sizes was defined as a design curve. When the defect size was small, fatigue limit could be predicted by the √area method proposed by Murakami. Defect size became larger, fatigue limit was related to the fatigue crack propagation threshold, ΔK_{th}. It was proved that the proposed relationship could be used for the fatigue limit prediction of additively-manufactured Ti-6Al-4V with defects. Furthermore, the proposed Murakami-type fatigue limit prediction curve was extended to the very high cycle fatigue regime, where fatigue limit was defined at 10^8 number of cycles.

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Fatigue Design 2019

FD19-117

Fast fatigue characterization by infrared thermography for additive manufacturing

Corentin Douellou[1], Xavier Balandraud[1], Emmanuel Duc[1], Benoit Verquin[2], Fabien Lefebvre[2]

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[2]Cetim, Senlis, France

High cooling rates and strong temperature gradients occurring during additive manufacturing (AM) by during laser beam melting (SLM) are known to affect mechanical performances of the produced parts, and particularly fatigue properties. More generally, these performances strongly depend on process parameters such as laser power, scan speed, laser spot size, etc. A fatigue analysis was performed in this study, involving infrared (IR) thermography to assess heat sources associated with fatigue damage. In particular, mechanical dissipation (also named intrinsic dissipation) was measured thanks to suitable acquisition parameters. The study aims to evaluate the opportunities offered by such a calorific analysis for the fatigue analysis of metals elaborated by SLM AM. For this purpose, several metals and process strategies were compared. Comparison with conventional fatigue testing and investigations on failure mechanisms (SEM micrographs, porosity analysis) were conducted to determine the capability of the proposed calorific approach to compare close manufacturing strategies.

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Fatigue Design 2019

FD19-39

Effect of surface roughness on fatigue strength of Ti-6Al-4V alloy manufactured by additive manufacturing

Masanori Nakatani[1], Hiroshige Masuo[2], Yuzo Tanaka[1], Yukitaka Murakami[1,3]

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This study focuses on the effects of surface roughness on the fatigue strength of Ti-6Al-4V alloy manufactured by additive manufacturing (AM); Electron Beam Melting (EBM) and Direct Metal Laser Sintering (DMLS) methods. Hot Isostatic Pressing (HIP) was applied to some series of polished specimens and as-built specimens to eliminate internal defects. Fatigue limit was evaluated by rotating bending fatigue tests. Although HIP increased the fatigue limits slightly, the fatigue limits of as-built specimens with HIP were only about 30% of the ideal fatigue limit expected from the hardness. On the other hand, the polished specimens with HIP had the fatigue limit close to the ideal upper bound. The observation of fracture surface showed multi cracks initiation from surface roughness. Thus, surface roughness has crucial influence on fatigue strength of AM component. The surface morphology of as-build specimen is three dimensionally complex. The method of quantitative evaluation for three dimensionally complex surface roughness has not been established in existing researches. In the present study, the method of evaluation of surface roughness as an equivalent defect size will be developed for fatigue strength prediction of AM components. The critical size of surface roughness which does not influence on fatigue strength will be made clear based on the developed method.

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Fatigue Design 2019

FD19-5

Influence on the fatigue behavior of additively manufactured aluminum structures

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The development of additively manufactured structures and products should preferential be performed virtual from the firsts sketch to the printed component. In order to get a high quality product that can be used for safety components under cyclic loading the fatigue assessment including the structure optimization with respect to the exploitation of the lightweight design potentials must be done numerically. Therefor the local component-related material behavior has to be available and considered. During the AM process multiple influences on the cyclic material behavior, caused for instance by the lightning strategy or surface conditions, lead with the orientation of the loading to the building direction to mutual interaction. Caused by industrial needs of low development time and numerical effort, the requirements on a digital twin for the fatigue assessment are growing and only accomplishable with an adjusted numerical concept with optimized material parameters.

In this work, the influences of the manufacturing process on the cyclic stress-strain behavior as well as on the fatigue life will be discussed. Therefore, load and strain controlled fatigue test are performed and the results are summarized in order to establish a better understanding on the fatigue behavior of additively manufactured components and parts.

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Fatigue Design 2019

FD19-53

Machining influence on the fatigue resistance of Inconel 718 fabricated by Selective Laser Melting (SLM)

Sasidharan Periane[1], Arnaud Duchosal[1], Sébastien Vaudreuil[2], Hicham Chibane[3], Antoine Morandeau[4], Rene Leroy[1]

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Selective laser melting (SLM) is one of the most used additive manufacturing processes, using which complex parts can be built with high dimensional accuracy in a flexible manner with less material usage. The aerospace industry relies on SLM technique to manufacture components like turbine and compressor blades which has a high demand in its dimensional tolerance.

Inconel 718 which is a nickel based super alloy used in steam turbine, jet engines where it is subjected to high thermomechanical loads. Inconel 718 is the most preferred alloy in the above applications due to its highest strength-to-weight ratio, its excellent resistance to fatigue, creep and corrosion. Inconel 718 is mainly strengthened by the precipitates which were formed during the heat treatment process by the combination of elements like Nb, Ti and Al along with the base element Ni.

In this paper evaluation of the fatigue strength (using 4 points bending fatigue test) of Inconel 718 machined by three different machining condition such as dry, MQL (Minimum Quantity Lubrication) and emulsion. The depth of deformation (from coarsened grain to normal grain size) from machined surface varies for all the three cutting conditions. This change in the depth of deformation influences the fatigue life of the sample to sustain for more or lesser number of fatigue cycles before fracture. The fatigue crack failure is compared to each process of machining to determine the best machining condition for Inconel 718.

Keywords: Inconel 718, SLM, Machining, MQL, fatigue cycles

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Fatigue Design 2019

FD19-56

Fatigue assessment of additively manufactured metallic structures using local approaches based on finite-element simulations

Kai Schnabel, Jörg Baumgartner, Benjamin Möller

Fraunhofer Institute for Structural Durability and System Reliability LBF, Darmstadt, Germany

Additive manufacturing technologies are in a process of changing from the state of rapid prototyping to a state of serial production of safety-relevant metal components. It is therefore essential to be able to reliable assess the fatigue strength of these structures and components already within the design phase.

For the fatigue strength assessment of metallic components, which are manufactured in classical processes, there is a range of assessment approaches in which the influence of e.g. mechanical and geometric properties on the fatigue strength can be taken into account. The question arises, which possible adjustments needed to apply these concepts to additively manufactured metallic structures.

In order to get an understanding of the fatigue behavior of additively manufactured components, notched and unnotched specimens manufactured by *Laser Powder Bed Fusion* (LPBF) built in different building directions are investigated. Selected fatigue assessment concepts are applied to additive manufactured structures to examine the potential of these concepts for an industrial application. As a basis for the concepts, finite-element models set up taking different properties like surface roughness in the root of the notch and different scanning strategies used for the core and the contour of these structures into account. A proposal is made for modelling the anisotropic material behavior of this type of structures, resulting from the orientation of a component related to the printing direction. Finally, the numerical results are compared with experimental results.

Thus, it is possible to give recommendations for the fatigue assessment of selected additively manufactured metallic structures.

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Fatigue Design 2019

FD19-57

Fatigue improvement by shot peening and laser peening on additive manufacturing Ti-6Al-4V and 316L

Valentin Loury-Malherbe[1], Steve Jenkins[2], David Davies[2], Jochen Fuhr[3], Steve McArthur[4], Lloyd Hackel[5], Jon R Rankin[5], Alexander Rubenchick[6], Wayne E King[7]

[1]Metal Improvement Company, Amilly, France. [2]Leonardo Helicopters, Yeovil, United Kingdom. [3]Curtiss-Wright Surface Technologies, Feuchthwangen, Germany. [4]Metal Improvement Company, Newbury, United Kingdom. [5]Curtiss-Wright Surface Technologies, Livermore, United Kingdom. [6]NIF and Photon Sciences Directorate, Livermore, United Kingdom. [7]Physical and Life Sciences Directorate, Livermore, United Kingdom

Fatigue life improvement by shot peening (SP) and laser peening (LP) on metals is already well known. However, we are short of information about results on manufacturing (AM) parts, which are characterized by bad surface finishing, micro-porosities and structural defects. In this paper, we study the effects of SP and LP on AM Ti-6Al-4V and 316L.

We detail residual stress profiles, surface roughness, micrographics of fractures surface, fatigue results. Different surface preparations are compared: raw AM, machined, SP, LP, superfinishing. Fatigue results exhibits very important improvement with minimum +45% fatigue limit increase, but it is mandatory to get deep enough residual compressible stress to balance the detrimental effect of surface defects.

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Fatigue Design 2019

FD19-90

Influence of porosity and post-treatment on fatigue life of SLM 316L

Alexandre Damiens, Hervé Bonnefoy, Isabelle Titeux-Peth

Université de Reims Champagne-Ardennes, Reims, France

The Selective Laser Melting process involves multiple factors that are detrimental to fatigue life. It is crucial to select optimal processing parameters to avoid internal porosity, source of early failure through crack initiation mechanisms. Surface condition, especially high roughness values, may also be a critical factor for crack initiation. Influence of surface condition must be studied in the industrial context, where parts may not be completely machined before implementation.

This project is led in collaboration with industrial partner Manquillet Parizel. A SLM Solutions 280HL machine was used for sample production, located within Platinium3D, an additive manufacturing research platform located in Charleville-Mézières, France.

This work first focused on finding optimal parameters for producing low-porosity 316L parts by the SLM process. Samples were examined using X-Ray computed tomography.

Fatigue samples were then produced and submitted to various surface treatments (machining, polishing, …) while some were left as-built. They were then tested in high-cycle fatigue and S-N curves produced for each sample type. Results were injected into the Basquin equation for predicting fatigue parameters of SLM 316L.

This study indicates that high-cycle fatigue life of SLM 316L is generally inferior to wrought 316L, with as-built samples exhibiting lower fatigue limits. This was explained by surface roughness acting as crack initiation sites. Microstructural studies are still underway to confirm these results.

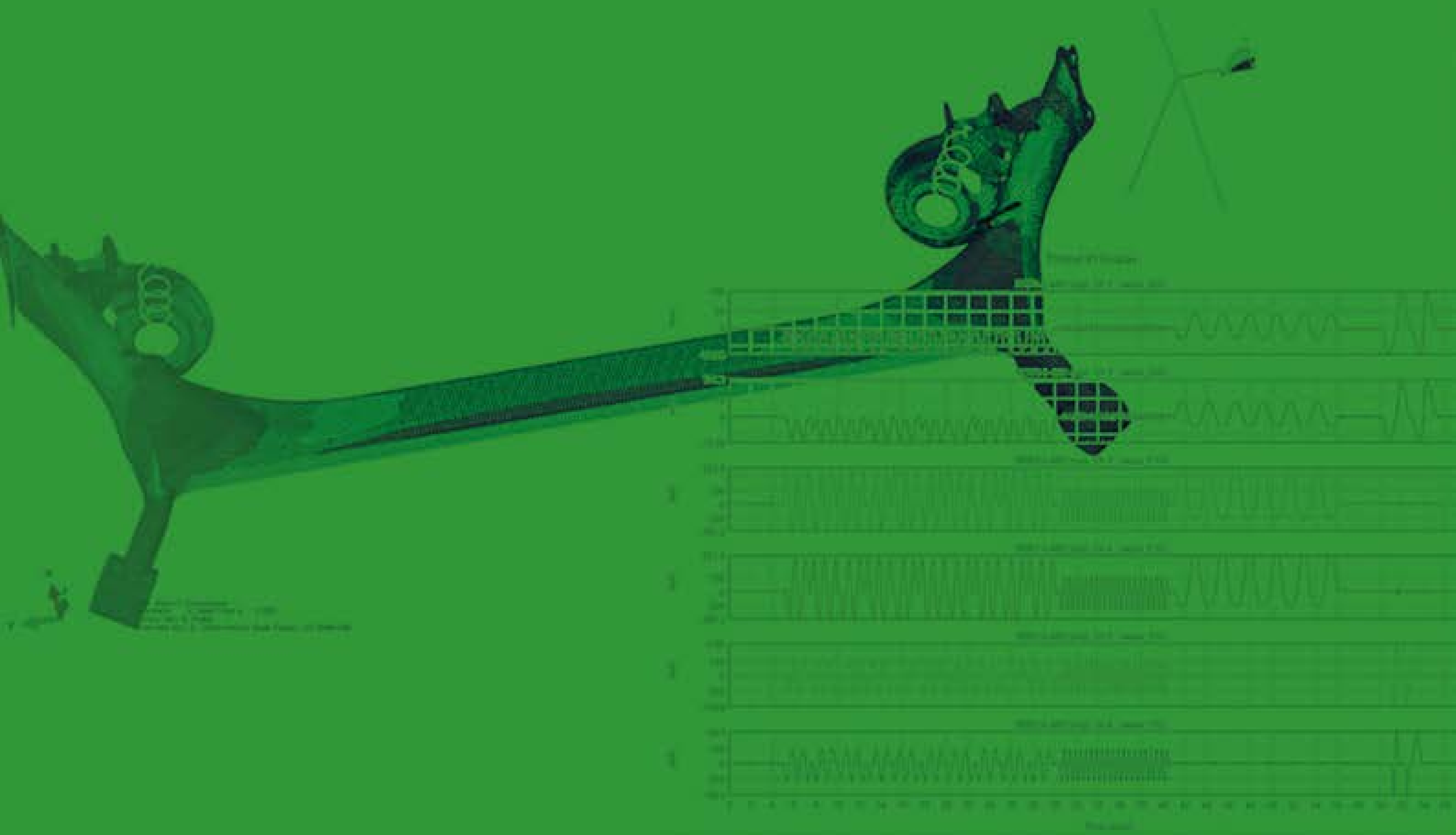
S02

Fatigue under severe environmental conditions (corrosion, low temperature,…) & Complex loading

Chairmen:

Y. Goth & T. Palin Luc

F. Morel & X. Hermite



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Fatigue Design 2019

FD19-42

Micro-scale frictional behavior of a bearing steel (JIS SUJ2) in cyclic sliding motion

Yuya Tanaka[1], Hisao Matsunaga[2,3,4], Masahiro Endo[4,5], Shigeaki Moriyama[4,5]

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Application of fracture mechanics has recently been emphasized to establish the mechanics-based evaluation of the rolling contact fatigue strength for designing mechanical elements such as bearing, rail/wheel, gear, etc. Flaking that is a typical rolling contact failure mode is intimately related to the shear-mode (modes II and III) fatigue crack growth, which is significantly affected by the interaction of opposing crack faces. Understanding the tribological properties on the crack faces being in the reciprocating sliding contact is therefore essential for the material design as well as the mechanical design of many components associated with rolling contact fatigue. The present study carried out a ring-on-ring test by making use of a combined tension-torsion fatigue testing machine to investigate the micro-scale frictional phenomena under the non-lubricated condition. The material investigated was a heat-treated high carbon-chromium bearing steel (JIS SUJ2) with a Vickers hardness of 753. The tests were conducted up to 10^4 cycles under the various conditions of mean contact pressures of 10-100 MPa, relative displacement amplitudes of 10-100 μm, sinusoidal frequencies of 0.1-10 Hz, and surface roughness values, R_a, of 0.2-1.7. The time variations of the tangential force, contact load and the relative displacement between contact surfaces were periodically monitored at a predetermined number of cycles during testing. The relationship between tangential force and relative displacement showed a square-shaped hysteresis loop. The coefficient of kinetic friction depended slightly on the relative displacement amplitude and the test frequency, while it was approximately independent of the contact pressure and the surface roughness.

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Fatigue Design 2019

FD19-30

Tensile and fatigue properties of 17-4 PH martensitic stainless steels in presence of hydrogen

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Clarification of the mechanism of hydrogen embrittlement in high-strength steels is of great importance in terms of practical use and related fatigue design. The effects of hydrogen on tensile and fatigue properties of 17-4PH stainless steels have been investigated with two grades: H900 and H1150, having an ultimate tensile strength (UTS) of 1352 MPa and 1013 MPa, respectively. Smooth, round-bar specimens were used for the tensile test and circumferentially-notched specimens at a stress concentration factor of 6.6 were used for the fatigue test. Acceleration of fatigue crack growth (FCG) rate in presence of hydrogen was evaluated from the reduction in the fatigue life of the circumferentially-notched specimen. The specimens were pre-charged in high-pressure hydrogen gas at pressures of 35 MPa and 100 MPa and a temperature of 270°C for 200 h. All the tests were performed in air at room temperature. Concerning the tensile test, the UTS was not degraded by hydrogen; however, the reduction in area (RA) was strongly degraded by hydrogen. Concerning the fatigue test, the fatigue life of the H-charged specimens was degraded by hydrogen, i.e., the FCG rate was accelerated by hydrogen. The hydrogen-accelerated FCG rate was complicatedly affected by stress levels, test frequencies, and the UTS of the material. The fatigue limit, different from the fatigue life which was reduced, was not degraded by hydrogen. Mechanisms responsible of the degradation of the tensile and fatigue properties in presence of hydrogen were investigated in regard to fracture-surface morphologies.

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Fatigue Design 2019

FD19-63

Effect of high-pressure H_2 gas on tensile and fatigue properties of stainless steel SUS316L by means of the internal high-pressure H_2 gas method

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For prohibiting a global warming, fuel-cell systems without carbon dioxide emissions are a one of the promising technique. In case of a fuel-cell vehicle (FCV), high-pressure H_2 gas is indispensable for a long running range. Although there are lot of paper for studying a hydrogen embrittlement (HE), there are few paper referred to the effect of high-pressure H_2 on the HE phenomenon.

In this study, an effect of high-pressure H_2 gas on tensile & fatigue properties of stainless steel SUS316L were investigated by means of the *internal high-pressure H_2 gas technique.* Main findings of this study are as follows;

1 - Although there are almost no hydrogen embrittlement effect on the 0.2 % proof stress and tensile strength, elongation and reduction of area decrease in H_2 gas environment,

2 - For case of low Ni_{eq} material, fatigue life and fatigue limit decrease in H_2 gas environment,

3 - For case of low Ni_{eq} material, not a few a’ martensitic phase generated on the fatigue fractured specimen.

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Fatigue Design 2019

FD19-46

Preventing stress corrosion cracking of spent nuclear fuel dry storage canisters

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Dry cask storage of spent fuel at nuclear plant sites is being used as a temporary approach until an interim or permanent dry storage site(s) is available. The dry storage casks are used once the fuel has sufficiently cooled in the spent fuel pool storage. However for storage in humid environments the corrosive nature of the moist air with entrained chlorides can make the welded regions of the casks susceptible to pitting and chloride induced stress corrosion cracking (CISCC). In this report we provide measurements of residual stress and CISCC tests of welded 316L stainless steel panels showing that high energy laser peening provides deep (>5 mm) depths of plastic compression and cracking does not initiate or propagate in laser peened regions. The work includes stress measurements vs. depth using a slitting technique and 2-dimensional residual stress measurements by Hill Engineering using a Contour method. Finally we provide detailed finite element stress analysis (FEA) comparing the strain response difference between test panels and casks. Our analysis shows that the 4 mm depth of stress measured in unconstrained test panels is indicative of actual stress in the confined cask geometry that is approximately 2 mm deeper. Following qualification testing and system configuration, a high energy laser peening process has been deployed to ensure that spent nuclear fuel dry storage casks are free from chlorine stress corrosion cracking.

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Fatigue Design 2019

FD19-69

Effect of hydrogen on fatigue limit of SCM435 low-alloy steel

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Regarding the design of high-pressure equipment, "the design by rule" approach is the most common. For the design of high-pressure hydrogen containment systems, if hydrogen reduces the fatigue limit, the risk of fatigue failure may arise. The objective is to gain a better understanding of the effect of hydrogen on the fatigue limit. The material was low-alloy steel. The material was adjusted to be sensitive to hydrogen embrittlement by heat treatment. The Vickers hardness of the material was HV600. There are two situations that fatigue limit is achieved, i.e., non-propagating cracks are present or absent in the unbroken specimen at fatigue limit. Therefore, smooth specimen and deep notched one were used to characterize the effect of hydrogen on the fatigue limit determined by both mechanisms using the same material. Tension and compression fatigue tests were performed at a loading frequency of 20 Hz in air and in 0.1 MPa hydrogen gas. A staircase method was adopted to determine the fatigue limit. For the smooth specimen, the fatigue limit in hydrogen gas was higher than that in air. This material showed severe hydrogen embrittlement during the SSRT, however, the fatigue limit was not decreased by hydrogen. For the deep-notched specimen, the fatigue limit in hydrogen gas was the same as that in air. When considering the result of the smooth specimen, it could be considered that hydrogen affected the fatigue limit. It was found that hydrogen did not affect crack initiation, but affected the threshold of propagation of small cracks.

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Fatigue Design 2019

FD19-100

Multiaxial fatigue of steels with small defects

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In this work the authors propose a new methodology to estimate threshold loading conditions for naturally defective steels under complex stress states. In this setting, multiaxial stress based fatigue models based on the critical plane approach are coupled with Murakami $\sqrt{area}$ parameter. Murakami (2002) proposed a model that relates the parameter $\sqrt{area}$ of a small artificial defect and the hardness of the material (*Hv*) with the nominal fatigue limit for this material either under uniaxial (σ_w) or under torsional (τ_w) loading. This model has been extended to estimate the fatigue limit of naturally defective materials, such as steels with non-metallic inclusions. Therefore, uniaxial and torsional fatigue limits usually required to calibrate the multiaxial criteria will be calculated by Murakami's model. The advantage of using Murakami's model to calibrate them is that it is considerably cheaper and faster to determine these limits compared to traditional methods. To assess the new methodology, multiaxial fatigue data under combined push-pull and torsion loading generated by the authors will be used. Multiaxial fatigue data available on the literature will also be considered to allow comparisons. A preliminary analysis shows good agreement between data and the proposed model.

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Fatigue Design 2019

FD19-10

Fatigue assessment of metallic structures under variable amplitude loading

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Many types of mechanical structures (cars, air-planes, trains...) and civil engineering structures (bridges, wind turbines, offshore structures...) are subjected to random in-service loading. Normally the load effects in these structures are composed of different stress ranges and mean stresses which are within the elastic limit of the material.

One main problem with fatigue assessment under variable amplitude loading is the performes of fatigue life regarding load sequence effects. In this study a model deals with the problem of fatigue life assessment under variable amplitude loading composed of differing stress ranges and mean stresses which are within the elastic limit of the material take into-account the load sequence effects is developed.

Computing of the stress range and the mean stress, in specific time based on the preceding load histories, consider load sequence effects. Using Palmgren-Miner damage rule and the new computed stress range and mean stress lead to predict the fatigue life. An evaluation of the model using data of five different metals availbe in the literature has been investigated. The results showed that the proposed model describes the effect of the load sequence in elastic loading well.

S03
Composite & Elastomer

Chairmen:

L. Gornet & R. Chantalat

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Fatigue Design 2019

FD19-107

Fatigue dimensioning of short-fibre reinforced thermoplastics at Hutchinson: from material characterization to prediction on parts

Khalid Aazizou[1], Victor Fabre[2]

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Over the last years, Hutchinson came to maturity in fatigue characterization and dimensioning of short glass fibre-reinforced thermoplastic parts for automotive antivibration applications. Today, short glass fibrereinforced thermoplastics are materials to challenge coming emission regulations in automotive sector compare to metal parts. Different targets like weight saving, mechanical performance, high volume production can be overcome with a tailored application of short glass fibre-reinforced thermoplastics. An accurate prediction of mechanical behaviour of parts using finite element numerical simulations, is a challenging topic of current R&I. In this talk are illustrated the different approaches and characterization procedures established to take up those challenges, from material characterization till final application on industrial parts.

Reinforced thermoplastics, and especially short glass fibres reinforced polyamides, due to their high stiffness and impact resistance even at average temperature combined to a low density, had been chosen as an alternative solution to some metallic automotive or aeronautic parts. More precisely, those kinds of materials can be used close to the engine. These new materials make it necessary to revisit constitutive modelling to account for specific behaviour of anisotropic heterogeneous composite, in particular the non-linear time dependent behaviour they exhibit. Reinforced thermoplastic automotive components are submitted to several kind of mechanical loadings, and in particular to cyclic sollicitations. Moreover, those parts experience variable environmental conditions in terms of temperature and humidity, with great influence on fatigue properties.

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Fatigue Design 2019

FD19-50

Static and dynamic behavior of PU foams with multilayer coatings

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In the present paper an overview on static and dynamic behavior of functional polymeric foams is presented. In particular, A PU (Poly Urethane) open cells foam was cut to obtain specimens.

Different layers of coating were applied to the foam: two samples were coated with one layer (1PU) and 4 layers (4PU) of PUD (polyurethane dispersion) respectively, while 4 samples, after being coated with 1 layer PU, were coated with 1 layer (1MW), 2 layers (2MW), 3 layers (3MW) 4 layers (4MW) of CNT (carbon nanotube).

The tests aim at characterizing the materials behavior to calibrate the material constitutive models for numerical simulations.

More in detail, experimental analysis entails at investigating the effect of foams coating on static and dynamic parameters when frequency and compression amplitude is varied from linear to non linear elastic behaviour.

Experimental procedures are defined according to International Standards. The following parameters were calculated by means of processing resulting data, for different number of cycles: the area of the hysteresis cycle, the dissipated energy per cycle, the secant modulus of the cycle, the stiffness degradation (rigidity loss) and the loss factor.

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Fatigue Design 2019

FD19-9

Fatigue testing of GFRP materials for the application in automotive leaf springs

Christian Hopmann, Fabian Becker

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Due to the high specific properties, fiber reinforced plastics are ideal candidates for the substitution of steel parts in the automotive sector enabling high weight savings and increasing the efficiency of automobiles. One application are composite leaf springs made of glass fiber reinforced plastic. Because of the simple bending load case, the fiber direction can be aligned with the loading direction. The parts are loaded under stochastic loads originating from different driving maneuvers. For this fatigue load case, a high number of component tests are required.

The aim of the research presented (in a cooperation between IKV and Ford) is to develop a simplified testing program that is able to reproduce the damage and the fatigue behavior of a road load history in shorter testing time. For this purpose, three point bending experiments on unidirectional specimens made of glass fiber reinforced epoxy pre-preg material are performed. However, since the loading of the real component has an additional transverse stress in the region of the clamping group, the results on specimen level are not transferable to component level. For this purpose, a special clamping group is developed on specimen level to enable a better prediction of fatigue life and transferability of the results of the fatigue tests from specimen level to component level. This results in a more realistic representation of the leaf spring stress state in the fatigue experiments. With the results of this research, higher safety in the design of this component and less testing time is achieved.

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Fatigue Design 2019

FD19-96

Fatigue life prediction of injection moulded short glass fiber reinforced plastics

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Short glass fiber reinforced plastics (SFRP) are increasingly employed in load-bearing structural parts and it is essential to be able to predict their long-term performance. Fatigue life depends strongly on design, fiber orientation, and loading conditions (load magnitude, load ratio, frequency), making it extremely challenging to accurately compute the lifetime for SFRP parts.

The first challenge is to properly understand and model the mechanisms that lead to failure. In general, the long-term performance of thermoplastics is limited by three failure mechanisms: I) plasticity-controlled failure, related to accumulation of plastic strain, II) slow crack growth, controlled by crack propagation, and III) molecular degradation. Here the focus is on the first two mechanisms.

This work presents a framework that combines experimental and numerical efforts to predict fatigue life of SFRP parts. This includes characterization of the failure mechanisms on simple injection molded (IM) tensile bars, samples milled from IM plaques to study anisotropy, and different test geometries to include multiple stress states. The effect of load ratio is considered for all and accounted for. Finally, the dependence of lifetime on stress gradient is identified and deployed to correct FEA lifetime prediction. The resulting models are applied on a demonstrator part, where the predicted lifetime is compared with experimental results.

Challenges are the accurate prediction of the glass fiber orientation in injection moulding and incorporating a suitable criterion for stress concentrations. Nevertheless, even with the complexity in modelling, current approach provides a substantial improvement in the predictability of the lifetime of complex parts.

S04
Damage tolerance and fatigue life

Chairmen

J. Rudolph & J. Delgado

M. Risbet & M. Marzin

S. Courtin & I. Huther

R. Chantalat & C. Peyrac

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Fatigue Design 2019

FD19-24

Improved fatigue life of the newly developed Fe-15Mn-10Cr-8Ni-4Si seismic damping alloy

Fumiyoshi Yoshinaka, Takahiro Sawaguchi, Nikulin Ilya, Susumu Takamori, Nobuo Nagashima

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An Fe-15Mn-10Cr-8Ni-4Si was recently developed for the use as a seismic damping alloy. The fatigue property of the alloy was investigated across wide strain and stress ranges. The fatigue life of the alloy at high strain levels, including extremely high strain amplitude of 10%, was significantly longer than those of common steels. The superior fatigue resistance against high strain loadings is an advantage in the application of the alloy for a seismic damper, which exhibits damping effect through cyclic elasto-plastic deformations. The mechanism of the fatigue fracture was investigated from the view point of the microstructure. The fracture surface observation showed that the crack propagates microstructure-sensitively. The microstructure after the fatigue fracture was observed and analyzed using SEM-EBSD. The EBSD analysis revealed that the deformation-induced ε-martensite was developed from the parent γ-austenite during fatigue loadings. The plausible mechanism of the improvement of fatigue life of the alloy is that the reversible γ<->ε martensite transformations during fatigue loadings suppress the accumulation of fatigue damage.

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Fatigue Design 2019

FD19-41

Anisotropic fatigue crack propagation behavior of an open-die forged high strength AA7010-T7652 aluminum alloy

Tobias Strohmann, **Eric Breitbarth**, **Guillermo Requena**

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The damage tolerance of high strength aluminum alloys plays a major role in the design of aircraft structural components. Their microstructure is one of the key factors that determine fatigue crack propagation (FCP) behavior.

The FCP of a high strength aluminum alloy AA7010-T7652, derived from an open-die forging process, was investigated in three different orientations (L-T, T-L and 45°), in a load range of 5-30 MPa√m. The microstructure of the base material, its texture, fracture surfaces and secondary fatigue cracks were analyzed by 2D microscopy (SEM and EBSD) and X-ray computer tomography.

The results show that the fracture mechanisms change as a function of FCP rate da/dN. The grain structure in the L-T, T-L and 45° orientations can be clearly identified on the fracture surfaces for da/dNop, shows differences of up to 50 % between the investigated orientations. Furthermore, the influence of spatial distribution and morphology of Fe-rich primary phases on FCP is investigated. The elongated shape of these particles along the L-axis results in earlier overall fracture in the T-L and 45° specimens, while it causes the formation of secondary cracks and, consequently, a decrease of FCP rate in the L-T oriented specimen. The results underline the necessity to characterize three dimensionally the microstructure to predict microstructure-sensitive FCP of this high strength aluminum alloy.

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Fatigue Design 2019

FD19-36

Discussion on crack growth behavior in large-scale fatigue tests of carbon and low-alloy steel plates based on fracture surface observation

Masahiro Takanashi[1], Hiroshi Ueda[1], Toshiyuki Saito[2], Takuya Ogawa[2], Kentaro Hayashi[3]

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[3]The Kansai Electric Power Co., Inc., Mikata-gun, Japan

It has been often discussed that design fatigue curves for nuclear power plants represented by the ASME boiler and pressure vessel codes are too conservative. To address the issue in Japan, the Design Fatigue Curve (DFC) Phase 1 and Phase 2 subcommittees were organized under the Atomic Energy Research Committee in the Japan Welding Engineering Society and have proposed new design fatigue curves and fatigue analysis methods for carbon, low-alloy, and austenitic stainless steels.

To investigate the correlation between the fatigue life obtained by the DFC best-fit curves and that of actual component, the authors carried out fully-reversed four-point bending fatigue tests for large-scale specimens of carbon steel and low-alloy steel plates with 90mm thickness and 150mm width. The comparison revealed that the fatigue lives given by the best-fit curve corresponded to the 1.5-4.0-mm-deep crack initiation lives in large-scale specimens.

In the center part of the large-scale specimen, a shallow and dull notch (stress concentration factor was approximately 1.3) was installed to limit the fatigue crack initiation site. During the fatigue test, the notch root was periodically observed with the replica, and after the crack grew sufficiently, the beach mark was introduced to track the crack propagation behavior. The crack propagation rates of carbon and low-alloy steels which is based on CT specimen data are specified in fitness-for-service codes like the JSME SNA1. A crack propagation analysis for the large-scale specimen is carried out using the crack propagation law obtained from CT specimens and the analysis results are compared with the experimental ones.

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Fatigue Design 2019

FD19-11

Discussion of fracture surface using beach marks on fatigue test data with large scale piping

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[3]The Kansai Electric Power Co, Osaka, Japan

Design Fatigue Curve (DFC) Phase 1 subcommittee and Phase 2 subcommittee were established in the Atomic Energy Research Committee in the Japan Welding Engineering Society. DFC 1 and DFC 2 subcommittees were proposed new design fatigue curves for carbon steels & low alloy steels and austenitic stainless steels and a new design fatigue evaluation method. And a Japanese utility project performed large scale fatigue tests using austenitic stainless steel piping (SUS316L, NPS 8 & Schedule 160) to obtain not only basic data but also fatigue data of mean stress effect.

We reported that the results of the large-scale fatigue piping tests show good agreement with the best-fit curve developed by the DFC 1 and DFC 2 subcommittees and the size effect can be considered as negligible. The effect of mean stress, it was confirmed that it can be accurately evaluated by the Smith-Watson-Topper approach.

In this paper, the beach marks introduced during the large-scale fatigue piping tests, crack growth analysis was carried out using JSME S NA1 crack propagation equation of austenitic stainless steel and evaluated by fracture surface results.

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Fatigue Design 2019

FD19-13

Fatigue analysis of cast iron components considering the influence of casting skin

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The assessment of the fatigue strength of castings with remaining casting skin still constitutes a challenge. Until now only the roughness of the casting skin will be considered by a reduction factor. This reduction factor however neglects the influence of discontinuities like inhomogeneous microstructures, imperfections, pores etc. In this work casting skin represents the rim zone of the casting, consistent of surface roughness and a deviating microstructure.

To assess the influence of the casting skin on the fatigue strength, stress and strain controlled fatigue tests on EN-GJS-400-15 and EN-GJS-700-2 specimens with deviating casting skin were investigated. The cyclic behavior of the rim zone microstructure was determined via cyclic axial strain tests with $R_\varepsilon = -1$ on small-scale flat specimens extracted from within the rim zone. For the integration of the results from the axial strain tests and the influence of the surface roughness on the fatigue strength, cyclic bending tests under alternating ($R_\sigma = -1$) and tensional pulsating load ($R_\sigma = 0$) were performed. The conclusions gained from this work shall be transferred in a fatigue assessment concept for remaining casting skin cast components.

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Fatigue Design 2019

FD19-77

Outline of the recent consolidated revision of EN13445-3, clause 18 and related annexes: detailed assessment of fatigue life

Jürgen Rudolph[1], Guy Baylac[2], Ralf Trieglaff[3], Rüdiger Gawlick[4], Michael Krämer[5], Yves Simonet[6], Manuela Triay[7]

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The European Pressure Vessel Standard EN 13445 provides in its part 3 (Design) a simplified method for fatigue assessment (Clause 17) and a detailed method of fatigue assessment (Clause 18). This major and comprehensive revision has been developed within the framework of the European working group CEN/TC 54/WG 53 – Design methods and constitutes a crucial step towards a modern and user-friendly engineering fatigue assessment method. The overall structure and amendments of Clause 18 are to be presented. All these amendments aim at a significant increase in user friendliness and clear guidelines for application.

The following items are to be mentioned in that context:

- Fatigue assessment of welded components based on structural stress and structural hot-spot stress approaches
- Detailed guidelines for determining relevant stresses and stress ranges
- Cycle counting proposals in the context of the fatigue assessment method including a critical plane approach.

The fatigue assessment of welded components is separated from the fatigue assessment of un-welded parts.

Stress analyses for clause 18 are usually based on detailed finite element analyses (FEA). As an essential amendment for the user the determination of structural stress ranges for the fatigue assessment of welds is further detailed in a new appropriate annex.

The cycle counting issue is comprehensively treated in the context of different design and operation situations (design transients, operational stress-time-histories). The description is detailed towards a critical plane approach.

Detailed proposals for implementation in an algorithmic programming framework are given making the described methods ready to use.

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Fatigue Design 2019

FD19-92

Life extension approach focusing on industrial and railway applications

Anne Coulon, Nicolas Vincent

Vibratec, Ecully, France

Using its expertise in fatigue analysis, Vibratec has developed an approach to evaluate remaining life aiming to ensure asset durability and optimize operation to extend service life. Remaining life provides visibility of the structure's future life to anticipate difficulties and guarantee long-term quality of service. Analysis of this parameter is an important part of asset management for structures designed to last for decades, like railway transportation.

The approach presented for evaluating remaining life is based on a coupled digital and experimental fatigue analysis. The sensitive areas were previously determined by Finite Element Analysis according to standard fatigue loads. The current status of structural mechanical integrity is studied by nondestructive examination (NDT, magnetoscopy, visual observation…). Then, operational measurements are performed to identify the real operational load, to evaluate and tune the Finite Element Model. Using the final reliable Finite Element Model, the future life of the structure is simulated. Different operation road maps can be evaluated to ensure the structural durability and extend asset service life.

To conclude the paper, the method is then applied to quantitatively assess bogie and car body remaining life of railway networks. Operation and maintenance road maps serve as guides to reach service life objectives. Structural modifiaction can also be evaluated to optimize life duration. Structural modification can also be evaluated to optimize life duration. This analysis provides support for investment teams, helping them optimize their asset management strategy.

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Fatigue Design 2019

FD19-59

Influence of surface irregularities on the low-cycle fatigue strength of an austenitic stainless steel

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Given the stringent requirements of high levels of safety in nuclear components, stakeholders of French nuclear industry must anticipate the presence of residual surface imperfections in these components. Such imperfections could be introduced during manufacturing or maintenance operations. The incidence of surface irregularities on the fatigue strength of metallic components has already been extensively studied but mainly in the high-cycle fatigue domain. However, nuclear components are generally loaded under low-cycle fatigue and large-scale plasticity conditions. The present work aims at assessing the impact of a surface irregularity on the fatigue life of a type 304L austenitic stainless steel. A special attention is paid in the quantification of the characteristic stages of fatigue life, namely crack initiation, micro-propagation and propagation. Fatigue tests were conducted under total axial strain control in air at ambient temperature. Surface irregularities were introduced on polished cylindrical samples. The direct current potential drop method has been used to monitor the crack propagation and to derive crack growth rate data. A Finite Element numerical simulation has been implemented and experimental markings have been conducted to calibrate the potential variation as a function of crack growth. Fatigue test results demonstrated a significant impact of the surface irregularity on the fatigue lifetime, depending on both irregularity depth and applied strain amplitude. The strain intensity factor range $\Delta K\varepsilon$ has been used as an efficient driving force parameter to represent fatigue crack growth rates evolutions under large-scale yielding for various experimental conditions.

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Fatigue Design 2019

FD19-86

Defect tolerance of high-strength steels in the HCF and VHCF regime

Bernd Schönbauer[1], Keiji Yanase[2,3], Tero Frondelius[4,5], Juha Kuoppala[6,5], Jukka Kömi[7], Masahiro Endo[2,3], Herwig Mayer[1]

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With increase in strength and hardness, steels become more susceptible to fatigue crack initiation at small defects such as scratches, punch marks, insufficient surface finish and environmentally induced surface flaws (e.g. corrosion pits). But also non-metallic inclusions as inherent defects become critical and failure may initiate in the interior of the material after a high number of load cycles.

High cycle fatigue (HCF) and very high cycle fatigue (VHCF) properties of two high-strength steels are investigated with focus on the influence of non-metallic inclusions and artificial small defects as drilled holes. The testing materials are precipitation-hardening chromium-nickel-copper stainless steel 17-4PH with a hardness of $HV = 352$ and a nano-bainitic ultra-high strength steel with $HV = 720$. Fatigue tests are performed at different mean loads using ultrasonic testing equipment. The defect tolerance is evaluated using fracture mechanics approaches. It is found that the $\sqrt{area}$ parameter model – which accounts for the size dependency of the threshold stress intensity factor range for small cracks or defects – can be well applied to predict the fatigue strength in the presence of defects with a maximum size of 80 µm. For larger defects, the experimentally determined fatigue limits can be correlated to the threshold stress intensity factor for long cracks. The applicability of fracture mechanics is found to be limited to defects with a certain notch root radius, ρ. For 17-4PH steel, defects with $\rho > 50$ µm cannot be treated as effective cracks.

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Fatigue Design 2019

FD19-6

Prediction of S-N curves at various stress ratios for structural materials

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Predictive models in the past for stress ratio effect on S-N fatigue life have been evolved since the 19th century not only with limited verifications but beyond the theoretical limit. At the same time, they have employed weak S-N curve models for the development, involving inefficiency for applications. Thus, there has been a gap in the development of predictive models between S-N curve behaviour and stress ratio effect. In this paper, an efficient procedure is proposed for predicting S-N curves at different stress ratios. The characteristics of the constant fatigue life (CFL) diagram were clarified for the theoretical capability and limitation, and the dependence of the experimental fatigue behaviour. The Kim and Zhang S-N curve model was dovetailed with the linear CFL lines of the four segments for predicting S-N curves at various stress ratios. With the benefits of damage parameters in the Kim and Zhang model, analytical expressions were derived for theoretical predictions. The theoretical predictions were found to be in agreement with the experimental results.

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Fatigue Design 2019

FD19-116

Fatigue assessment of CFRP structures for automotive applications

Sara Eliasson[1,2], Svenja Wanner[1,2], Zuheir Barsoum[1], Per Wennhage[1]

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There is an increase in the use of fiber reinforced polymer materials in the vehicle industry due to the material's significance in designing lightweight vehicle structures and components. For these structures and components structural mechanical properties are important to characterize, particularly the fatigue properties. An approach on setting up a systematical fatigue testing procedure to find an optimal specimen design for the provided lab environment is proposed. It is found that the tab configuration and tab material have a large impact on the test results. The proposed test procedure results in fatigue failure of the CFRP material rather than tab failure. The final method has resulted in successfully testing parallel-side-coupon specimens under tension-tension fatigue testing, with a load ratio of 0.1 and with a frequency of 5 Hz.

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Fatigue Design 2019

FD19-182

Tensile fatigue properties estimation of a woven carbon fiber thermoplastic matrix composite material by self-heating monitoring

Laurent Gornet[1], Laura Muller[2], Jean-Michel Roche[2], Antoine Hurmane[2], Catherine Peyrac[3]

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Heat transfer concerns the conversion, and exchange of thermal energy between materials and the environment. Spontaneous heat transfer always occurs from a region of high temperature to another region of lower temperature. Self-heating tests, based on heat transfer monitoring are an alternative approach to classic fatigue tests in order to estimate the fatigue limit of materials. This new procedure is based on the monitoring of the self-heating of the studied material under short cyclic loading blocks. The aim is to correlate a change of the heat transfer in the material connected with fatigue damage mechanisms. Acoustic emission monitoring and microscopic damage inspection could be used to confirm the accuracy of the self-heating test method. In this presentation, self-heating experimental tests are applied to a balanced 2D-woven carbon/thermoplastic composite material. The thermoplastic matrix is a semi-crystalline polymer, the polyamide 6.6, also called PA66. This resin has the particularity to be very sensitive to moisture absorption. In addition, quasi-static tensile tests are also performed to characterize the mechanical properties of material, as well as to monitor the evolution of the temperature field. The heat transfer in the material under tensile static loads and during self-heating tests is successfully compared. The fatigue limit of woven carbon thermoplastic composite materials could be connected to heat transfer properties. It appears that during a quasi-static tensile test the minimum value of the temperature variation is linked, to the self-heating test result. Finite Element simulations are also conducted to better understand experimental tests. Heat transfer such as thermal conduction, thermal convection and transfer of energy by damage mechanisms is simulated during a tensile test with the finite element code Cast3M CEA. Homogeneous woven mechanical and conduction properties are computed by periodic homogenization technics realized on the woven Representative Volume Element. For rigorous evaluation of mechanical composite properties a double scale homogenization method is used. The first homogenization is performed for the tow (fibers and matrix) while the second one is on the tows and matrix RVE. In order to predict the Wöhler curves the question will be: which method is most relevant to precisely understand the fatigue phenomena of woven composite material.

S05
Experimental and numerical design and validation methods

Chairmen:

- A. Araujo & C. Peyrac
- Y. Papuga & A. Bignonnet
- Y. Yamazaki & A. Galtier
- C. Nadot & G. Servanton

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Fatigue Design 2019

FD19-88

Influence of mean stress on inclusion-initiated fracture under axial and torsional VHCF loading of spring steel

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The influence of mean stress on inclusion-initiated fracture under axial and torsional very high cycle fatigue (VHCF) loading of a high-strength spring steel is studied. For this purpose, size and content of non-metallic inclusions in the investigated material are intentionally increased. Ultrasonic axial and torsional loading fatigue tests are performed at load ratios R = -1, R = 0.1 and R = 0.35 on shot peened specimens. With increasing load ratio, S-N curves are shifted towards lower stress amplitudes for both types of loading. Fracture surfaces are investigated by using scanning electron microscopy. Under axial loading, VHCF cracks solely initiated at internal aluminate-inclusions independent of R-ratio. Under torsional loading, a change of crack initiation site is observed when superimposing mean stresses. At R=-1, cracks initiated exclusively at the surface whereas at R = 0.1 and R = 0.35 failure occurred from internal aluminate- or MnS-inclusions. Fracture mechanics principles are used to evaluate the detrimental effect of crack initiation site at different R-ratios indicating a strong influence of inclusion type and size on cyclic strength and fatigue lifetime.

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Fatigue Design 2019

FD19-1

Fatigue strength assessment for components and subsystems of a lightweight, space saving city car with electric drive

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This conference contribution describes the concept of experimental strength and fatigue assessment for a newly developed space and resource efficient urban vehicle with electric drive. Within this concept tests on component and subassembly level are considered.

The new car for urban traffic was developed in the european joint project "Urban EV" with a strong focus on lightweight design. It features a rear axle which can be folded in order to save parking space in urban space.

In the contribution fatigue tests on component level are introduced for the control arm of the rear axle whereas on subsystem level a module of a wheel suspension of the rear axle is considered. The tests are carried out under constant amplitude and variable amplitude loads respectively. Partly environmental influence is be simulated.

It is sketched in which way a synthetic load program is applied to deduct load collectives with variable amplitudes for the load simulations.

Experimentally measured strains at one specimen of control arm are used to validate the test results. The local strain concept is applied for damage assessment.

The wheel suspension module of the rear axle on subsystem level is subjected to two-channel loads of variable amplitude. Under application of linear damage calculation the test results are analysed and the need of optimisation at the structure for load transmission is roughly quantified. The local strain concept is again applied to validate the tests.

Concluding an appraisal of the fatigue strength of the control arm and the wheel suspension module is given.

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Fatigue Design 2019

FD19-102

Fatigue testing of large-scale steel structures in resonance with directional loading control

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Offshore structures such as jacket and monopile foundations for wind towers and platforms for oil and gas are large steel structures that are subjected to severe fatigue loading conditions. When developing constructions using novel welding techniques, high-strength steel grades or specific bolted assemblies there is a need for validation testing of large-scale components. Conventionally, such fatigue tests are carried out on servo-hydraulic test which are time-consuming.

Alternatively, fatigue tests can be performed in resonant bending by a cyclic excitation force with frequency close to the first eigenfrequency of the test specimen. In this paper a new test setup is presented suitable for testing large-scale steel components in resonance with control of the loading direction by two counter-rotating excentric masses.

A wide range of loading conditions can be applied with a frequency from 20 to 40 Hz. The test specimen, that can weigh up to 25 ton, is supported in the nodes of its natural wave-form, so that no dynamic forces are transmitted to the setup.

The working principles of the test setup are illustrated based on test results of a 711 mm diameter x 25.4 mm wall thickness steel pipe, a welded X-node representative for a welding detail of an offshore jacket foundation structure and a large-scale H-beam. Crack initiation is detected using acoustic emission while crack growth is monitored by local strain gauge measurements as well as the global stiffness reduction of the test specimen. Finally, the beach marking method is used to visualise crack fronts for post-mortem analysis.

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Fatigue Design 2019

FD19-15

Fatigue design of safety relevant steel components considering local damage evolution

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Ever growing demands for weight reduction, cost savings and increased product reliability have driven the development of a huge variety of new steel grades. In comparison with classical heat treatable steels, precipitation hardened ferritic-pearlitic steels provide many advantages, which allow a reliable light weight design and considerable cost reductions during the production process at the same time. The material properties are calibrated by a defined cooling subsequent to the forging, using the heat still stored in the component and avoiding an additional heat treatment. Depending on the local logarithmic strain and the temperature gradient, also the cyclic stress-strain and the fatigue behaviour will be inhomogeneously distributed across the component volume. Assuming homogeneous material properties may in this case lead to a misevaluation of the local stress-strain state and considerable miscalculations of the fatigue life. In order to exploit the full potential of the material, the gradients in the local material properties have to be considered during the fatigue design. The presented work therefore focusses on a possible method for the numerical assessment of the local damage evolution of an axle stub made of a precipitation hardened ferritic-pearlitic steel with an inhomogeneous property distribution. Based on an experimental investigation of the influence of logarithmic strain and the cooling rate on the local cyclic stress-strain and the fatigue behaviour, forging and cooling simulations will be used in order to assign the local material properties to a finite element model for the evaluation of the local damage evolution and the resulting fatigue life.

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Fatigue Design 2019

FD19-20

Correlation between rotating bending fatigue limit and static strength of Mg-Al-Zn alloys

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In order to investigate the correlation between fatigue limit and static strength of extruded Mg-Al-Zn alloys, rotating bending fatigue tests with three types of Mg-Al-Zn alloy, AZ31, AZ61 and AZ80, were carried out. And static tensile test and compression test with these alloys were performed also. On the other hand, in order to clarify the correlation between them, more than 200 past literature research on fatigue property of various Mg alloys were surveyed. As a result of past literature research, it was found that there was a proportional relationship between fatigue limit and static strength. The fatigue limit and the static strength obtained by the experiment of this study agree well with the proportional relation obtained as a result of the literature survey. In particular, considering the super long life fatigue range up to 108 cycles or more, the fatigue limit of AZ 31 and AZ 61 was found to be almost equal to their compressive 0.2% proof stress. However, it was found that the fatigue limit of AZ80 is lower than the compressive 0.2% proof stress, and when it is considered that the compressive 0.2% proof stress and the fatigue limit are equal, it becomes a prediction of the dangerous side.

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Fatigue Design 2019

FD19-40

Effect of defects and hydrogen on the fatigue limit of Ni-based superalloy 718

Kevinsanny[1], Saburo Okazaki[2,3], Osamu Takakuwa[2,4,5], Yuhei Ogawa[1,6], Koichi Okita[7], Yusuke Funakoshi[7], Junichiro Yamabe[8,5], Saburo Matsuoka[9], Hisao Matsunaga[4,2,10]

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Tension-compression fatigue tests were performed on two types of Ni-based superalloy 718 with different microstructures in which small artificial defects of various sizes and shapes were introduced. Tests were also performed on hydrogen charged specimens with defects, that contained solute hydrogen content of 26.3 and 91.0 mass ppm. The susceptibility of the fatigue strength to the defects, especially in the non-charged specimen, varied significantly with the microstructure morphology, i.e., a smaller grain size made the alloy more susceptible to defects. The fatigue limit as a small crack threshold was successfully predicted using the √area parameter model. The evaluation of the fatigue limit was classified into the following three stages depending on the defect size: (i) harmless defect regime, (ii) small crack regime and (iii) large crack regime. Such a classification enabled a comprehensive evaluation of the fatigue limit in a wide range of defect size, considering (a) defect size over a range of small crack to large crack and (b) characteristics of matrix represented by grain size and hardness. In addition, the effect of defect and hydrogen on the fatigue strength will be discussed comprehensively based on a series of experimental results.

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Fatigue Design 2019

FD19-52

Comparison of several methods for the notch effect quantification on specimens from 2124-T851 aluminum alloy

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The report summarizes several approaches on implementing the notch effect into the fatigue life estimate in high-cycle fatigue region in case of uniaxial fatigue experiments of notched bar specimens. Results of own experiments on specimens prepared from 2124-T851 aluminum alloy (five different notch geometries) are used for the subsequent analyses. The nominal solution derived from the stress concentration factor is compared with the stress gradient approach and the critical distance approach. The way of setting the critical distance is discussed. The impact of the FE-mesh quality on results of the stress gradient approach is evaluated.

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Fatigue Design 2019

FD19-31

Low cycle fatigue of welded very and ultra-high strength steels

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Higher, wider, further... so are the requirements for structural engineering of the present time. To achieve these objectives in modern steel lightweight construction, the development of high-strength steels plays a crucial role. Steel grades with yield strengths up to 1300 N/mm² provide the necessary high strength. Combined with good toughness and weldability they enable higher load capacity and at the same time a lower weight of the construction. So, the efficiency of the structure can be increased by the use of high-strength steels.

For the fatigue design the static strength of very or ultra-high strength steels cannot be used according to current standards and regulations. Particularly in crane construction, fatigue is governed by the load cycle range below 50,000 and high single loads. This raises the question of whether the higher static strength of ultra-high strength steels in the low-cycle fatigue range comes into play and how far this can be accounted for.

Within this paper, the low-cycle fatigue behavior of modern very high strength and ultra-high strength steels with nominal strengths up to 1100 N/mm² in welded condition will be described and the application limit of elastic design rules will be defined.

Design recommendations will be given based on the nominal stress approach as well as the structural and notch stress approach. Thus, welded details made of high-strength steels can be designed for low-cycle fatigue applications. Furthermore, a more accurate assessment can be done, allowing for an economical application of high-strength fine-grain structural steels.

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Fatigue Design 2019

FD19-66

Elastic-plastic strain analysis at mooring chains pit site

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Continuous operation of offshore facilities is directly dependent on the integrity of their mooring systems that keep these facilities in position during operations. A mooring line is as strong as its weakest element, and a single line failure increases the load level on the adjacent lines that could cause operation shutdown and risking human life and environment. Mooring chains are broadly used as the major elements of mooring lines to anchor offshore vessels at sea. The chains are made of high strength steels and exposed to corrosive environment and cyclic service loads. To account for the corrosion effect, offshore industry guidelines provide basic approaches to estimate the material loss and the chain bar diameter reduction by assuming a uniform corrosion and wear per year. Corrosion pits, however, act as stress raisers at the chain link surface and facilitate crack initiation process, and as a result, reduce the chain fatigue life. In this context, a strain evolution analysis at the mooring chains pit site is numerically conducted herein. An elastic-plastic material model is adopted to account for plastic deformation around corrosion pits of various sizes and shapes as well as the residual stresses sourced from the chains proof load test. Additionally, the effects of mooring line mean tension and load amplitude on the amount of plastic deformation around the modeled pits are studied. The plastic straining at the pit site is shown to be influenced by the applied load, the pit aspect ratio and its location on the chain link.

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Fatigue Design 2019

FD19-108

Study of fatigue of tough pitch copper wire brazed to beryllium copper strip

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This paper is an overview of fatigue failure of a tough pitch copper wire brazed to a silver plated beryllium copper strip using Sil-Fos filler materials. This paper debates the effect of the brazing manufacturing process (temperature, pressure and filler material flow in the joint around the copper wire) on the fatigue lifetime of the copper wire. Examination of the fracture surface of copper wire showed a hydrogen embrittlement effect which is triggered by the brazing process environment. Finite element analysis conducted to determine the effect of the wire forming radii of copper wire when brazed to beryllium copper strip and subjected to cycling thermal and centrifugal force.

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Fatigue Design 2019

FD19-72

Numerical simulation of cyclic plasticity in mechanical components under low cycle fatigue loading: accelerated material models

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[2]University of Ferrara, Department of Engineering, Ferrara, Italy

Numerical simulation of components subjected to low-cycle fatigue loading requires an accurate modeling of the material cyclic plasticity behavior. Combined models allow capturing simultaneously the monotonic hardening and cyclic hardening/softening phenomena that occur in reality. In principle, durability assessment of components under cyclic loads can be performed only if the material behavior is simulated until complete stabilization. As materials stabilize approximately at half number of cycles to failure, it follows that in case of small plastic strains a huge number of cycles must be considered, and an unfeasible simulation time is required. Several alternative techniques have thus been proposed. Probably the most common approach is that of using the stabilized stress-strain curve already from the first cycle. Nevertheless, neglecting the evolution of material behavior from its initial state up to stabilization could lead to relevant errors. An accelerated method is based on increasing the value of parameter that controls speed of stabilization in the combined model. With this approach, the number of cycles to reach stabilization can be reduced considerably, without affecting the overall mechanical behavior. The aim of this work is to compare different acceleration techniques and to present a simple design rule that can be adopted to set up accelerated models, particularly when relatively small plastic strains occur. For this purpose, a notched mechanical component is addressed as a case study. A plane model can thus be used as a reference, as it permits a FE analysis with a combined model to be performed until complete stabilization.

S06

Fatigue of assemblies (mechanical, welded, adhesive-bonding, multimaterials,…)

Chairmen:

Z. Barsoum & L. Huther

H.P. Lieurade & M. Lukic

J.F. Flavenot & D. Spring

G. Meneghetti & G. Elbel

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Fatigue Design 2019

FD19-115

Evaluation of HFMI as a life extension technique for welded bridge details

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In this current study, HFMI technique is used to study the possibility to extend the fatigue life of pre-fatigued flange gusset welds typically found in girder bridges. The results from the study are also compared with results found in the literature for other more conventional techniques for retrofitting, e.g. cut-outs. The study also aims to investigate if the IIW HFMI recommendations [1] could be applied for existing steel structures and that equal fatigue strength improvement could be claimed for prefatigued structures. Furthermore, new recommendations for structural hot spot stress type B are suggested for HFMI treated welds, applicable to flange guest welds. The results indicate that the HFMI could be used for welded bridge details rehabilitation as a competing technology with conventional cut-out. Furthermore, the results indicate that the IIW recommendations for HFMI fatigue strength improvement could also be applied for pre-fatigued welded details.

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Fatigue Design 2019

FD19-109

Fatigue reinforcement during repainting for two motorway bridges

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Important work of innovative character which leads to successful conclusion to improve the durability of bridge with two independent decks of a French motorway carrying heavy traffics for 40 years. Each of these decks is supported by 5 steel beams insuring an important intrinsic redundancy to the structure. The three spans are of 37m - 66m - 37m.

The structures of the bridges were recently strengthened to extend their fatigue resistance:

1 - Addition of a continuous welded steel plate inclined outside of the edge girders to increase the safety at the Ultimate Limit State (ULS) and the robustness in fatigue of the lower steel flanges. The inclined additional plate supported by the webs and the free bottom flanges.

2 - Metal improvement with TIG dressing refusion of the welded cross-beams connection gussets were performed.

3 - Sticking of carbon fibres with high elastic modulus of 400 000 MPa on lower steel flanges of the main beams at the extremities of the welded existing cover-plates..

The TIG improvement method was available from several companies. the joints are butt welded. As there is no risk of crack propagation at the root, it is appropriate to use TIG dressing to remelt the foots of the welded joints. The quality of this method will be discussed, as well as the opportunity of some other improvement methods as High Frequency Mechanical Impact.

These Improvements, had to take place during the repainting works. An innovative option of mixed complete-partial sandblasting methods was adopted.

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Fatigue Design 2019

FD19-54

Enhancements of a stress-based approach for fatigue life estimation of multi-material connections joined by self-piercing rivets and adhesive

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Due to the continuously reduced emission targets from legislation, lightweight constructions are getting more and more important for car manufactures. One way to reduce weight is the use of multi-material design for the body in white where new joining technologies, such as self-piercing rivets (SPRs) need to be considered instead of spot welding. Since both spot welds and SPRs are local circular joints, it appears reasonable to adapt and modify existing methods for spot welds to estimate the fatigue life of SPRs. These established methods typically use calculated radial stresses at the joint from inner forces (derived from FEM) and compare them to a S-N curve. Instead of comparing to a regression of calculated stress values, the presented method uses measured material specific S-N curves for this purpose. These curves contain the stresses of the materials at a notch, oriented on the rivet diameters. A modification of parameters in the stress calculation leads to a significant reduction of scatter in the comparison of simulated and tested fatigue life values. In addition to this method, an approach for the estimation of fatigue life of adhesively bonded joints was adapted. This method considers an effective stress value, which is evaluated either on a critical distance to the notch or is calculated as average over a defined path. Additional requirements during the development of the new method were the reduction of tests and a small complexity of the required FE-models to enable fast and still accurate fatigue life estimation on full vehicle level.

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Fatigue Design 2019

FD19-81

Fatigue design of weld part in non-combustible magnesium alloy based on Fracture mechanics

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Fatigue design of weld part in non- combustible magnesium ally has been studied. Specimens for fatigue test were produced by MIG welding and TIG welding with different welding conditions. According to result of fatigue strength tests, all weld specimens tested in the present study were broken at the weld prat, and a weld defect was found as a fatigue fracture origin. Fatigue life was well arranged by stress intensity factor calculated with a size of weld defect played as a fracture origin and applied stress. Therefore, it is speculated that fatigue strength of weld part is depending on a size of weld defect and threshold stress intensity factor at the weld part. Size of weld defect and value of threshold stress intensity factor were possibly changed by welding process and welding condition. Therefore, relationship between heat input during welding process and threshold stress intensity factor was studied by conducting fatigue crack growth test at the weld part. The value of threshold stress intensity factor range increased with increase in heat input of welding process. However, values for threshold stress intensity factor range almost coincided when the crack growth curves were arranged by effective stress intensity factor range. Difference in threshold stress intensity factor range due to difference in heat input of welding process was mainly induced by change in crack closure effect. Fatigue design method taking effect of crack closure depending on mechanical property of weld part into account was proposed.

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Fatigue Design 2019

FD19-68

Weld bead removal retrofitting against fatigue cracking in steel girder web penetration

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Fatigue cracking in steel girder web penetration details is so dangerous that it can break steel girders completely. One-meter-long crack was detected in Yamazoe Bridge in 2006. Since a number of highway bridges have such web penetration details in Japan, it is of urgent importance to grasp these fatigue strength properties and develop effective retrofitting methods.

In previous reports, we investigated fatigue cracking behavior through fatigue tests using small girder specimens with web penetration details and effects of large attachment retrofitting methods against fatigue cracking in web penetration details through fatigue tests using a large girder specimen with web penetration details in which cross beam lower flanges are connected to lower surface of a slot by welding. However these methods cannot prevent fatigue crack initiation perfectly.

In this study, we investigate effects of weld bead removal and small angle steel attachment retrofitting method against fatigue cracking in web penetration details through fatigue tests using a large girder specimen.

As a result, it has been verified that weld bead removal and small angle steel attachment method can prevent fatigue crack initiation in the web penetration details with a slot perfectly.

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Fatigue Design 2019

FD19-75

High cycle fatigue strength evaluation of welded joints in handling equipment

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This study falls within the scope of the fatigue design of handling machines manufactured by the Manitou Group , which are usually composed of a chassis and a boom. These welded assemblies are subjected to fatigue loading conditions and include highly stressed zones acting as crack initiation sites. In view of the geometrical complexity of these structures, the degree of conservatism incorporated in design methods base on the usual international standards is difficult to evaluate. Alternative design approaches based on the structural stress are being developed and used by other companies such as PSA and LOHR.

The present work has a two-fold goal of experimentally assessing the fatigue response of the structures in question and building a numerical approach to take into account the local stress distribution and the effect of the loading modes.

The proposed numerical approach is based on shell finite element modelling of the assembly and an equivalent stiffness matrix for welds. This makes it possible to describe the local mechanical behavior of seam welds with the computational cost of a shell element based model. Once the local stresses are known, an equivalent stress is calculated by taking into account the gradient effect and size effect along the seam weld.

A vast experimental campaign is in progress using four elementary welded assemblies as well as complete chassis structures tested under real service conditions. Stereo digital image correlation is used to detect crack initiation and to capture the local mechanical behavior at the surface of the seam welds.

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Fatigue Design 2019

FD19-60

Design criterion for fatigue strengthening of riveted bridge girders

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Existing codes for the fatigue design of riveted members are not capable of considering the effect of stress ratio on the constant amplitude fatigue limit (CAFL). However, an effective solution for prevention of fatigue failure in riveted members is the application of prestressed retrofitting systems, which results in a reduced stress ratio. In this study, a simple fatigue design criterion, which can take into account the effect of stress ratio, is proposed for riveted members. The applied method is based on the constant life diagram (CLD) methodology. The accuracy of the proposed design criterion has been verified using existing test data in the literature. In addition, a procedure is presented for the fatigue design of the riveted members strengthened with prestressed and non-prestressed retrofitting systems subjected to constant and variable amplitude loadings. The proposed design procedure is then used in a numerical example to determine the prestressing force and the section modulus required for prevention of fatigue cracking in both the prestressed and non-prestressed retrofitting systems.

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Fatigue Design 2019

FD19-78

Improvement of the fatigue strength of welds for lightweighted chassis application made of advanced high strength steels

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The objective is to promote Advanced High Strength Steels of ArcelorMittal (Tensile Strength over 800MPa) and then contributes to the future vehicles lightening target. One of the practices used by carmakers and OEMs for mass saving consists in replacing current steel grades by thinner gauge ones having higher mechanical properties. Regarding stiffness and static behaviour, internal studies of steel solutions led by ArcelorMittal for chassis and suspension parts have shown that weight reduction of components is reachable by using AHSS in place of standard products. On the parent material, the fatigue strength increases with higher mechanical properties. In this context, the fatigue of Gas Metal Arc Welded (GMAW) assemblies could become a problem. On the one hand, for a same loading and a reduced thickness, the local stresses in the vicinity of the weld are higher and, on the other hand, there is no difference between steel grades in term of fatigue strength. The stress concentration induced by the geometry of welds (notch effect) explains this well-known behaviour. Therefore, solutions to improve the fatigue strength of weldment were investigated and validated on GMAW lap specimens. Then several demonstrators, representative of typical geometries, were proposed in order to valid post-treatments versus different modes of loading and provide realistic and demonstrative results. Today, we are able to quantify the improvement in fatigue resistance according to the type of post-treatment applied and to quantify the cost of such solutions. Examples of weight saving are proposed and quoted based on chassis part steel solution.

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Fatigue Design 2019

FD19-82

Use of the peak stress method to assess the fatigue life of large welded steel structures

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A precise life assessment from weld seams from large welded steel structures is very important in order to be able to optimize these structures. The local stress approaches with fictitious notch radius have been proved to be necessary to achieve the desired precision in some cases. Unfortunately, these methods are very time and resources consuming making it impossible to be applied systematically on large steel structures.

The Peak Stress Method (PSM) suggested by Prof. Meneghetti could be an alternative since its precision seems to be good and that the method is much easier to apply.

This paper shows the results of the tests that have been done on PSM applied to large steel structures from hydraulic excavators. Comparisons have been made in terms of precision and speed with the fictitious notch radius method.

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Fatigue Design 2019

FD19-87

Definition of nominal stress-based FAT classes of complex welded steel structures using the Peak Stress Method

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The purpose of this paper is to report some industrial applications of a local approach called Peak Stress Method (PSM) in fatigue strength assessment of a number of complex welded steel joints adopted in amusement park structures, particularly in roller coasters. This method is an application of the N-SIFs approach and it is based on the singular linear elastic peak stresses calculated from FE analyses with coarse free meshes, which makes it useful for industrial applications. For fatigue strength assessment of large structures, companies often use FE beam models and compares nominal stresses with fatigue strength values (FAT classes) available in design standards.Roller coasters present many types of complex welded joints that differ in (i) technological parameters, e.g. weld penetration, and (ii) geometrical parameters, e.g. track pipes number, shape and number of connection elements between track pipes (tie beam, cross beam, lattice structures, etc.). Due to complex geometries and limited number of FAT classes available in design standards, finding appropriate FAT classes consistent to real geometries is frequently troublesome. To overcome this problem, in this paper some applications of the PSM are proposed to assess the fatigue strength and to define FAT classes in terms of nominal stress starting from the master design curve of the PSM. The advantage is to perform FE analysis with beam elements having reference FAT classes derived from a robust local approach and consistent with real geometries.

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Fatigue Design 2019

FD19-91

Programme for maintenance and evolution of Eurocodes - Drafting of the future EN 1993-1-9 on fatigue of Steel structures

Mladen Lukic

CTICM, Saint-Aubin, France. CHEC, Arcueil, France

A four-phase six-year programme dedicated to maintenance and evolution of structural Eurocodes has entered its fourth and final phase. The main objectives for all the phases have been «reduction of nationally-determined parametres» and «ease of use». The new versions of the standards are about to be finalized by the designated CEN Project Teams and their publication and mandatory use in construction is expected for 2024.

The work on drafting a new version of EN 1993-1-9 belongs to Phase 3. The five-member Project Team responsible for drafting the standard started thus its work in autumn 2018. The Project Team has based its work on several grounds:

- Results of the CEN Systematic Review on EN 1993-1-9
- Particularities in National annexes of EN 1993-1-9
- Proposals by all 43 official experts, members of CEN/TC 250/SC 3/WG 9 on EN 1993-1-9, and many others, membres of ECCS/TC6 on Fatigue and fracture, including:
  - harmonization with other EN standards
  - integration of new experimental results
  - clarified unified fatigue data analysis
  - integration of execution quality
  - enlargement in order to follow modern design and execution practices.

The aim of the programme is to obtain harmonized and user-friendly design rules able to cover standard cases in steel construction, representing about 80% of all cases. For more complex problems, the new Eurocodes will present a necessary basis for the research of an adapted solution.

This paper is exploring all the modifications on EN 1993-1-9 «Fatigue» proposed and integrated in its latest draft.

S07

Reliability–based approaches and probabilistic methods

Chairmen:

F. Khim & M. Facchinetti

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Fatigue Design 2019

FD19-18

Probabilistic fatigue and reliability simulation

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The fatigue design of mechanical systems has historically followed a *'deterministic'* process. That means, for a given set of inputs they will return a consistent set of fatigue life results with no scatter. In practice, the designer will apply a safety factor to each input parameter to account for the uncertainty.

In comparison, a *'Probabilistic Fatigue Simulation'* method is *'stochastic'* in nature. This design process helps to avoid poor in-service reliability whilst reducing over-design.
This paper address in detail the three stages of *Probabilistic Fatigue and Reliability Simulation*:

1. Uncertainty Quantification (UQ) of input parameters
2. Stochastic fatigue simulation of individual components
3. Reliability simulation of the entire system

In order to take advantage of *Probabilistic Fatigue Simulation*, uncertainties in the input and the analysis model must be properly calculated. Two types of input uncertainties are considered:

1. Reducible uncertainties (or epistemic uncertainties)
2. Irreducible uncertainties (or aleatoric uncertainties)

Stochastic simulation is performed using a *'Monte Carlo'* simulation. Also, statistical sampling techniques known as *'Design of Experiments (DOE)'* are discussed for optimizing the size of the design space matrix. Two broad areas are discussed:

1. Exploring the extremities of design space
2. Exploring the statistical variability of design space

Reliability analysis of the simulated failures is performed using a Weibull analysis. A case study is presented to demonstrate how reliability analysis is used to:

1. Optimize the design to achieve the target reliability
2. Identify potential cost savings by identifying the most influential uncertainties
3. Provide an optimized maintenance schedule

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Fatigue Design 2019

FD19-124

Test reduction strategies for reliability demonstrations

Xavier Hermite, Fabien Lefebvre

Cetim, Senlis, France

Reliability demonstration always includes experimental approaches, which are expensive in terms of costs and duration.

Failure Modes and their effects analysis allows a prioritization of the tests to perform by assessing the criticality of the failure modes.

Accelerated testing methods combined with design of experiment and progressive results analysis can highlight the weaknesses of the product.

By that way, experimental strategy can be defined to converge to the reliability objectives with the most efficient number of tests.

Integrating experience feedback in the test protocol might also improve the test strategy, and Bayesian methodology can also be used to specify the tests needed to demonstrate the reliability target.

This paper aims to present a methodology of test reduction, which has been applied on real industrial cases in whole or in part. However, since results cannot be disclosed, no real application will be presented in the paper.

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Fatigue Design 2019

FD19-98

Comparison of different strategies for the quantitative identification of the fatigue scatter and its uncertainties: simulation-based investigation on classical and advanced staircase procedures and comparison with the use of the self-heating method

Vincent Roué[1,2], Cédric Doudard[1], Sylvain Calloch[1], Adriana Mattiello[2], Quentin Pujol D'Andrebo[2]

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The determination of the fatigue scatter is a well-known challenge. In this study, a simulated based investigation is performed to quantify the number of specimens needed to correctly estimate the fatigue scatter with classical fatigue tests.

First, two different staircase procedures are evaluated: the classical one, already well studied in the literature, and a variant with the reuse of unbroken specimens. In this advanced method all the specimens are reloaded at higher stress amplitude up to their failures in order to extract more information from the same number of specimens. A large number of simulations are then performed for different sample sizes in order to quantify the median response and the scatter in results of these fatigue determination methods on the fatigue scattering parameter. The uncertainties are compared as a function of the number of specimens. Different assumptions are needed to perform the simulations: one of them is the shape of the fatigue properties distribution. The two-parameter Weibull distribution is assumed. The analysis of the staircases is performed with the maximum likelihood method with only censored data. The uncertainties on the fatigue scatter parameter are still important, even with a large sample size, but are significantly reduced with the reuse of unbroken specimens.

These results are then compared to the self-heating method and the two-scale probabilistic model used to describe the involved dissipative mechanisms. Indeed, the assumptions made during the modelling leads to a Weibull model. With this method, the fatigue properties can be determined with only one specimen.

S08

Thermal and Thermo-mechanical fatigue

Chairmen:

L. Remy & F. Guilloret

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Fatigue Design 2019

FD19-104

Concrete example of a multiphysical approach to a fatigue problem applied to thermal failure

Yvon Goth, Elodie Crapeau, Tayeb Aiouaz, Jacques Saindrenan

Cetim, Senlis, France

The work presents a numerical approach dedicated to assess for the lifetime of a metallic structure submitted to periodic thermal loads. The thermal loads are due to a gas at high temperature flowing around the structure.

As the shape of the structure is complex, the use of CFD computation has been needed to get the heat transfer coefficients. The short time steps required in a CFD study being incompatible with the large computing times associated to the thermal inertia of the structure, a two-step approach has been defined to get the periodic temperature field preliminary to the thermomecanical stress study and the fatigue analysis.

The full process from the definition of thermal loads to the assessment of the lifetime of the structure is described by application to a concrete example. The modeling hypothesis and the chaining of software used is reviewed.

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Fatigue Design 2019

FD19-12

High temperature fatigue properties of oxide-dispersion-strengthened platinum-10% rhodium alloy

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In high-quality glass manufacturing processes, platinum alloys are widely used for parts in contact with molten glass. Since these platinum alloys are used at very high temperature and are subjected to various mechanical loads, oxide dispersion strengthened platinum alloys has been applied for the purpose of extending the life. However, there are few data on mechanical properties of these alloys for practical conditions, and it is currently difficult to predict their life time accurately. In this study, various tests were carried out to clarify the high temperature bending fatigue properties of the oxide dispersion strengthened platinum - 10% rhodium alloy. As a result of bending fatigue test with higher axial stress at 1400 degree C, it was clarified that the number of cycles to failure varies depending on the test frequency, and time dependence appears strongly. In addition, when the axial stress was low, fracture occurred due to crack propagation in the grain, but it was clarified that intergranular fracture occurred as axial stress increases because the influence of creep became stronger.

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Fatigue Design 2019

FD19-28

Damage operator based thermo-mechanical fatigue prediction of a steam turbine shaft

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The paper is an overview of the work conducted in order to investigate thermo-mechanical fatigue endurance of a steam turbine shaft under various startup and shutdown conditions. Experimental campaign to calibrate the so-called Damage Operator Approach (DOA) proposed by Nagode et al. is introduced. Validation tests that employ the online axial and torsion strain control provided by the digital image correlation are introduced. Correlation of experimentally and numerically determined specimen lifetimes is shown. Good agreement of the measured and computed data was observed. Application of the DOA to the problem of steam turbine shaft fatigue prediction is demonstarted.

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Fatigue Design 2019

FD19-70

Effect of temperature condition on short crack propagation in a single crystal Ni-base superalloy under thermo-mechanical fatigue

Yasuhiro Yamazaki, Maiki Miura

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Ni-base superalloys have been used with high reliability for blades and vane applications in gas turbine system used as electrical generators. Usually, they are subjected to rather complicated stress and temperature cycles due to the temperature gradients that occur during start-up and shut-down or from temperature gradients within the component during steady-state operation. The accumulation of such stress and temperature cycles leads to the possibility of failure by thermo-mechanical fatigue (TMF). Therefore, an understanding of the crack propagation characteristics under TMF conditions is essential. Notably, early growth of short cracks in order of sub-millimeter in size can provide some essential information for life and the remaining life prediction to these failures.

This study investigated the behaviors of short cracks in a single crystal Ni-base superalloy under the thermo-mechanical loading. The effect of temperature condition on the propagation behavior of short crack was discussed taking into account of crack closure.

S09

Taking into account manufacturing process in fatigue analysis (effect of microstructure, welding, residual stresses,…)

Chairmen:

X. Hermite & R. Sesana

E. Wasniewski & S. Hashimura

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Fatigue Design 2019

FD19-76

On the impact of mechanical and metallurgical characteristics on pinion bending fatigue performance

Oscar Cuevas Melo[1,2], Hind Orkhis[1], Marion Risbet[2], Julie Marteau[2], Saoussen Tria[2], Jérôme Favergeon[2], Fabien Lefebvre[3], Michel Octrue[3], Hervé Rognon[3]

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In mechanical components and most in particular in pinions, the final state of the thin layer below the surface is of crucial importance, it is defined by the type of process to which parts were subjected during the manufacturing operations. Geometrical characteristics of functional surfaces are often enhanced by processes or surface treatments such as grinding, coating or even shot peening. These finishing operations have also an impact on the near surface layer characteristics, residual stresses and the microstructure could be modified and thus have an impact on the fatigue performance.

The aim of this work is to study the relation between the finishing process of pinions and their performance to bending fatigue. The analysis of the mechanical and metallurgical characteristics of the near surface layer enabled us to understand the mechanisms leading to the bending failure. Sample pinions were machined on the same steel grade and carburized, under industrial conditions. Different gear surface treatment processes were then applied. All samples were gear ground and coated or shot peened.

The impact of each configuration was analyzed by examining residual stresses and the microstructure characteristics in the treated layer. At the same time, the impact of these processes was evaluated in regard to the bending fatigue performance. A pulsator test machine was used to apply different level of loads on the samples and evaluate the gap in bending service life between them. As a result, a connection between the gear bending performance and the mechanical and metallurgical properties was built.

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Fatigue Design 2019

FD19-89

Fatigue properties and cracking mechanisms of a 7075 aluminum alloy under axial and torsional loadings

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Surface mechanical attrition treatment (SMAT) exhibits great potential in strengthening mechanical components. SMAT is based on multidirectional impacts of materials with flying shot boosted by an ultrasonic generator. It is able to generate a superficial nanostructured layer along with a transition region beneath the treated surface. In addition, high compressive residual stresses can be generated especially in the near-surface region where the plastic deformation is highly activated. Studies presented in the literature show that SMAT is able to significantly improve the properties of various materials for example their fatigue resistance.

In this work, fatigue properties of a 7075 aluminium alloy under torsional loadings are investigated. For this purpose, reversed torsional loadings are imposed on specimens with different conditions, including untreated and SMATed states. The results of the fatigue tests are presented in the form of S-N curves. Scanning Electron Microscopy (SEM) is used to observe the fracture surfaces in order to examine the crack initiation process. The results of fatigue life are interpreted in taking into account the observed crack initiation mechanisms. Due to the fact that the fatigue data points are highly spread out, a statistical method is used to analyse the results. Basquin type power model is thus used to describe the fatigue data, and a Weibull statistical analysis of the data is performed to predict the fatigue life. In addition, P-S-N diagrams are built to compare the results obtained with different material states.

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Fatigue Design 2019

FD19-99

Fatigue behavior of gear teeth made of case hardened steel: from competing mechanisms to lifetime variability

Vincent Argoud[1,2], Franck Morel[1], Etienne Pessard[1], Daniel Bellett[1], Simon Thibault[2], Stéphane Gourdin[2]

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Jet engines gears are generally made of steel and are case-strengthened via thermochemical treatments such as carburizing or nitriding causing microstructural modifications, superficial hardening and compressive residual stresses in the surface layers. These treatments increase the resistance to cyclic loads caused by contact between teeth and by the bending loads applied to the teeth. Both of these create high stress gradients at the surface.

A large number of studies concerning the effect of thermochemical treatments on fatigue resistance have been carried out for uniaxial loads (rotating bending, tension or plane bending). Most of them were undertaken using smooth specimens, which do not correctly reproduce the stress gradient at the root of the gear teeth and a strong dependence between the loading mode and the position of the crack initiation site is observed.

The present work aims at experimentally investigating the fatigue behavior of case hardened steel with a special focus on crack initiation and growth mechanisms. A vast experimental campaign composed of two parts is undertaken. Firstly, a Single Tooth Bending Fatigue (STBF) test is carried out on gears made of 16NiCrMo13 carburized steel. The resulting Wöhler diagram shows high scatter at certain stress levels which suggests a bi-modal behavior, characterized by very different crack initiation phases. Secondly, a fatigue tests conducted on plane bending notched specimens, designed to accurately reproduce the stress gradient observed at the gear tooth root are carried out to confirm this bimodal behavior and to characterize the failure mechanisms.

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Fatigue Design 2019

FD19-120

Influence of the type of thermochemical treatment on the mechanical properties

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[3]IRT-M2P , Metz, France

Within the TTA project (dedicated to Advanced Thermochemical Treatment) managed by IRT-M2P industrial partners worked together in order to investigate the influence of the type of thermochemical treatment on the strength of gears.

During this project, special specimens were developed in order to be representative of automotive gears as far as bending tooth failure is concerned. These specimens were used to compare different treatments such as case hardening, atmospheric or low pressure carbonitriding. The influence of Nitrogen content has been quantified and the benefit of a tempering cycle demonstrated.

In addition to mechanical tests, the enriched layers were characterized in terms of retained austenite, hardness and residual stresses.

Mechanical properties that have been investigated are monotonic loading, impact resistance and fatigue strength.

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Fatigue Design 2019

FD19-22

The effect of machined surface layer on low cycle fatigue lives of austenitic stainless steel

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Low cycle fatigue tests were performed for austenitic stainless steel, SUS316L, in order to investigate the effect of machined surface layer. In order to change the machined surface layer, round bar specimens were machined by different condition of turning. Then, fatigue tests were carried out for the specimens machined by different conditions. In addition, in order to separate the effect of surface shape and material property variations, we prepared the specimens, whose machined surface layers were removed completely or partly by polishing. Fatigue test results show that plastic deformation caused by machining as well as residual stress had small influence on fatigue lives. On the other hand, scratches reduced the fatigue lives. If there were scratches on specimen surface, many cracks initiated from the valley of scratches in a row. The cracks grew rapidly to be a semicircular crack almost as large as the scratch in early stage of fatigue life. But, fatigue lives of a specimen which had few small scratches was similar to that of a specimen whose scratches were removed. Finally, fatigue crack propagations were predicted based on elasto-plastic fracture mechanics. We can predict safety side fatigue lives assuming scratch length with the aspect ratio of 1.

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Fatigue Design 2019

FD19-37

Discussion of effect of disk grinding surface finish on fatigue strength of the nuclear component material

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Disk grinding is often used to repair the scratches of the surface of the component and also used to weld toe finish to mitigate unexpected stress concentration.

This study investigates the effect of disk grinding surface finish on fatigue strength of the nuclear component materials. In order to achieve this objective, fully reversed tension-compression strain-controlled fatigue tests of disk grinding finished austenitic stainless steel SUS316L plate are conducted at RT, in air. Two types of disk grinding directions, which are parallel and perpendicular to the cyclic loading direction, are considered in this study, and fatigue test results are compared to S-N curves obtained by emery polishing and lathe machining finished specimens. It is found that the disk grinding surface finish decreases fatigue strength of materials and, in some cases, the fatigue strength of disk grinding finished materials is smaller than that of lathe machining finished specimens of maximum height roughness Rz is more than 100 micrometers. To find out the mechanism of fatigue strength reduction due to the disk grinding, metallographic observation and some measurements such as roughness, hardness and residual stress of the surface are carried out. In addition, this study discusses the effect of stress concentration and configuration of the micro scratches introduced to the surface of the material by disk grinding are discussed.

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Fatigue Design 2019

FD19-47

Fatigue resistance of light alloy sheets subjected to an environmetally friendly chemical milling process: metallurgical and chemical aspects

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Component lightening is a key issue for automotive and aerospace industries. Lightening processes on design profile are not always possible by means of mechanical machining processes. In these cases chemical milling processes can be used, usually by acid etching. The effect of chemical milling on fatigue behavior is related on many factors, such as chemical surface composition and surface roughness. Chemical milling can also be used to achieve a controlled surface roughness, which is in particular interesting for additively manufactured components, where surface finish still remains a parameter difficult to be controlled and repeated. The environmental aspects related to acid processing are still an important issue.

In the present paper an overview on chemical milling for component lightening is presented with focus of the effects of such treatment on the mechanical and chemical resistance of materials. Furthermore, a new environmetally friendly chemically etching procedure for aluminum alloys, called Green Etching, is outlined.

Finally, the results of an experimental campaign on an aluminium alloy is presented. In particular fatigue tests results on specimen subjected or not subjected to Green Etching are presented, and related to processing parameters and chemical, profilometric and metallographic analyses. Wettability and surface tension investigations results concerning the same process, as well as preliminary results of tests performed on AM specimens, are also presented.

S10
Contact fatigue

Chairmen:

L. Amar & R. Jacques

S. Fouvry & G. Thoquenne

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Fatigue Design 2019

FD19-111

An experimental and numerical multi-scale approach to predict the fretting-fatigue life of overhead conductors

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Overhead conductors used for long range electrical transport have a wire rope structure, and their mechanical behavior remains a key point for any Transmission System Operator (TSO). These conductors endure aeolian vibrations, tensile loads and clamping efforts that induce fretting fatigue damage between contacting wires in the clamping assembly. The aim of this research is to predict the distribution of fretting fatigue failures in the conductor-clamp system by coupling a multi-scale numerical analysis with experimental investigations. The global model gives a macroscopic representation of a clamped conductor and the structural effects induced by wind vibrations. The purpose of this model is to give the spatial distribution of normal and tangential loads for every contacts between neighboring wires depending on the clamping effort, tensile loading and oscillating amplitude. Then, specific contacts can be selected from this distribution in order to be simulated using a local model. This numerical zoom focuses on a contact between two aluminum wires, and is suitable with implicit calculations. The Crossland criterion was used, associated with a non-local fatigue stress approach to address the stress gradient effects thus to predict the crack nucleation risk. Crack propagation was simulated using Z-crack SIF simulations. These different simulations are compared versus mono contact fretting fatigue experiments. A rather good correlation is observed, however two aspects need to be deepened in the future developments: first a more precise description of the cyclic plastic response of the material and secondly a better consideration of the anisotropic fatigue properties of the aluminum wire.

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Fatigue Design 2019

FD19-29

Effect of wheel size and tread braking on subsurface crack initiation of heavy haul car wheel

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Subsurface cracks initiating from internal defects are one of main rolling contact fatigue damages of heavy haul car wheels. Finite element analyses of the wheels are performed to evaluate effect of the wheel size and tread braking on subsurface crack initiations. Critical defect sizes for the subsurface crack initiations are calculated from the results of finite element analyses and fatigue tests of wheel steel based on the multiaxial fatigue evaluation model. The critical defect sizes of 38 and 36 inch wheels are almost equivalent in service conditions according to AAR standard. On the other hand, 33 inch wheel has larger critical defect size than 38 and 36 inch wheels. 33 inch wheel has smaller stresses at the subsurface because it has a smaller wheel load than the other wheels. Stop braking with normal brake energy has less effective to the critical defect size, whereas drag braking at constant brake energy for long duration decreases the critical defect size due to an increase of tensile residual stress. Therefore, the subsurface cracks are more likely to initiate for larger wheels with drag braking.

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Fatigue Design 2019

FD19-64

Characteristics of shear-mode fatigue crack growth behaviors in roll steels

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Nowadays, rolling is one of the most important industrial processes because a greater volume of material is worked by rolling than any other techniques. Further, given the substantial industrial demand for rolled steel sheet products, the increase in productivity with simultaneous cost reduction is an important issue for the steel plants. Therefore, a great effort has been made to enhance the productivity and reliability of rolling mills by improvement of the facilities and the rolling process. In practice, a roll is one of the crucial components, and the life of rolls is determined by the regular maintenance and the planned discard. The roll life might be significantly shortened by cracks mostly caused by rolling incidents such as cobble. If the cracks penetrate deep into the roll inside, the damage could be fatal for the roll, in the worst case they may lead to roll spalling that causes interruption of rolling operation or damages of other rolls like back up rolls as well. Since the crack propagation is associated with shear-mode fatigue crack growth, the investigation of such crack growth behavior can give us a clue for the development of prospective material against spalling. Accordingly, in this study, aiming for such material development, a series of torsional fatigue tests are conducted by using the roll steels with different microstructures. Shear-mode fatigue crack growth behaviors and their characteristics are reported and discussed.

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Fatigue Design 2019

FD19-95

Experimental study of the fatigue performance of overhead pure aluminium cables

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University of Brasilia, Brasilia, Brazil

This work presents an experimental comparative study to evaluate the fatigue performance of two overhead cables made of different types of pure aluminium. A battery of eighteen fatigue tests were carried out on two cables, named Orchid and AA 1120 823 MCM, made of pure aluminium, i.e. AA 1350 and AA 1120, respectively. Fatigue of cables is a main cause of failure resulting to aeolian vibration. Through wind, the cable is subjected to three types of loading which are the clamping force, the bending stress and the mean stress due to the cable stretching load. This stretching load is expressed in term of *H/w* parameter which is the ratio between the horizontal stretching load *H* and the linear weigh of the cable *w*. The CIGRÉ organization has suggested the use of the *H/w* as a parameter of power line cable design against fatigue due to aeolian vibration. Fatigue tests were conducted for cable/suspension clamp systems and two S-N curves were generated at the same *H/w* value of 1820 m. One curve was obtained for each cable. The generated S-N curves proved that the 1120 cable could sustain a higher number of cycles before fatigue failure than the 1350 for the considered value of *H/w*. Additionally, a failure map was raised to determine the morphology of wire break. The microscopic analysis showed that the cracks were nucleated in the fretted marks. Data presented in this study will be helpful for the fatigue design of overhead cables against aeolian vibration.

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Fatigue Design 2019

FD19-43

Recent advances in spline couplings reliability

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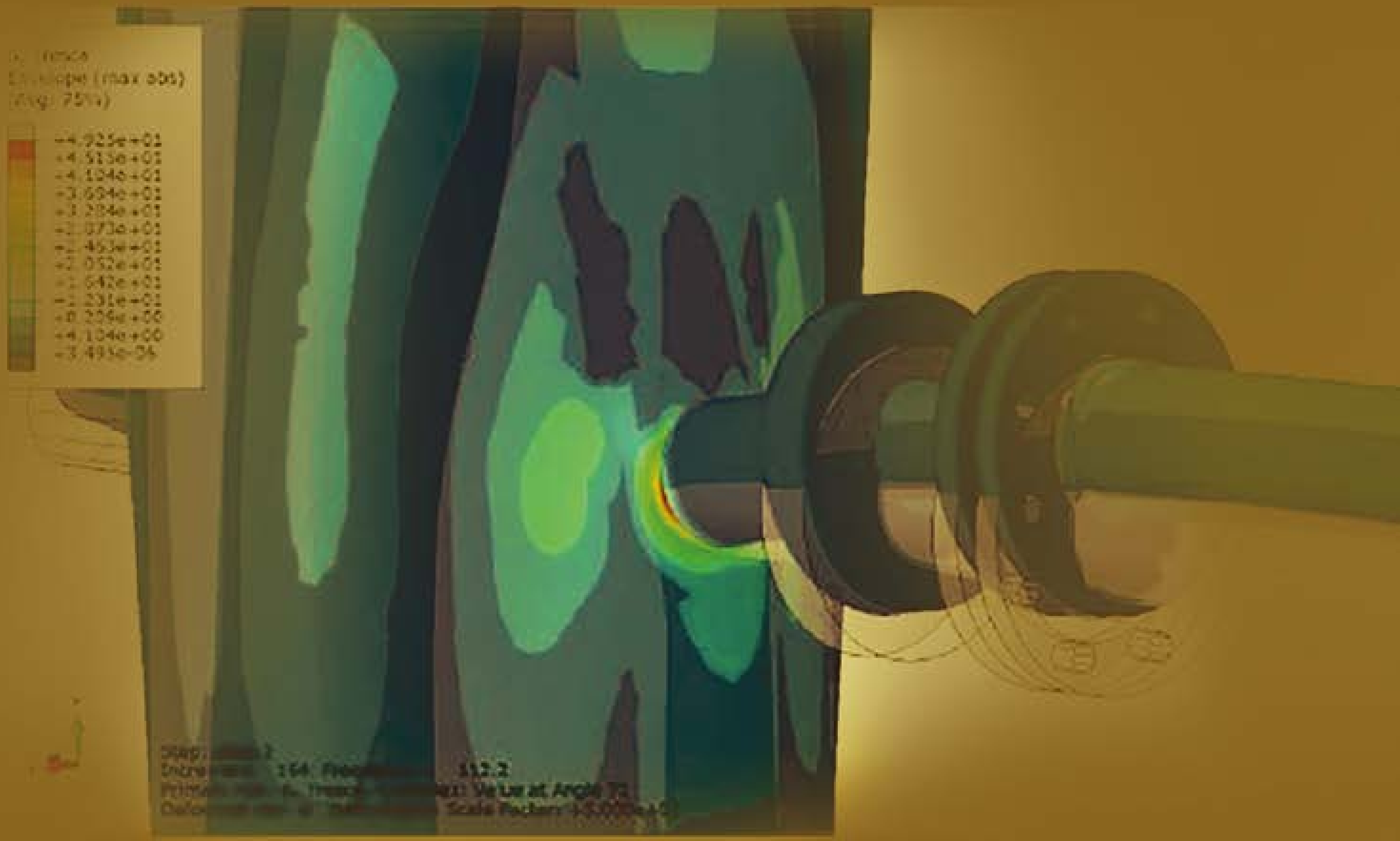
Spline couplings are widely used mechanical components to transmit torque between rotating parts. Although they are well known components, critical issues such as wear damage and unshaven loads affect them especially when working in misaligned conditions. Wear damage appears on engaging teeth bringing to component failures. The main way to reduce wear damage is to lubricate the engaging teeth of to apply surface coatings. In this, work wear damage on spline coupling has been investigated and a compound made of grease added with graphene has been tested against standard lubricants (oil) in order to find out if it may improve wear strength. Experimental tests have been performed by means of a dedicated test rig, designed to perform tests with misaligned spline couplings.

Preliminary results shows that graphene improve grease performance reducing the coefficient of friction (bringing to a reduction of unshaven overloads).

S11
Vibration Fatigue

Chairmen:

H. Rognon & M. Berger



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Fatigue Design 2019

FD19-21

Random vibration fatigue of welded structures: applications in the automotive industry

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The automotive industry is facing its most significant transformation since the first Ford factory. The rise of electrical vehicles alongside autonomous driving and additive manufacturing increase demand for lightweight vehicles, which requires proper numerical analysis tools in place in order to keep the costs low and to achieve durability targets. Vibration in heavy and light-duty vehicles poses many challenges in the design phase mainly due to the uncertainties associated with the loads and material properties. Therefore stochastic methods have attracted the attention of engineers responsible for the fatigue assessment of truck chassis and their welded attachments. In order to address the mesh scale sensitivity in the finite element method, Dong et al created the Battelle Structural Stress Method, an elegant alternative to the Volvo nodal force/moment method which was named Verity. For fatigue life evaluation of welds Verity is used in conjunction with a master SN curve developed by the same authors. The present paper proposes a frequency domain variant of the Verity Method to be used in random vibration fatigue applications along with Dirlik and T&B methods. Frequency domain approaches enjoy the statistical advantage of using probability density functions instead of rainflow cycle counters, which offers computational benefits in multi-channel long history scenarios. This paper thoroughly describes the proposal and shows an example of its application to a brake chamber support attached to the rear axle of a light-duty truck. Verity is used in the both the time and frequency domains and the fatigue results are compared.

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Fatigue Design 2019

FD19-7

A new modeling framework for fatigue damage of structural components under random-on-random spectrum

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Time and frequency domains based fatigue damage prediction approaches have been developed over past decades to predict fatigue performance of mechanical structures subjected to random loads. Frequency domain approaches are increasingly being adapted to provide fatigue assessment of mechanical components subjected to random loads due to computational efficiency and cost savings. Current frequency domain damage models only deal with stationary random loadings where Power Spectral Density (PSD) of random loadings does not change in time. However, many machine components, such as jet engines and tracked vehicles are subjected to evolutionary PSD i.e. random-on-random loadings under real service loads. A new fatigue damage modeling framework is proposed to predict fatigue damage of structures under complex evolutionary PSD where the topology of PSD function changes with time. The proposed modeling approach is based on the underlying concept that the evolutionary PSD response of a structure can be decomposed into a finite number of discrete PSDs. Each PSD can be split into narrow frequency bands so that each of narrowbands can be associated with Rayleigh distribution of stress cycles. Fatigue damage can then be predicted by summing up damages for each individual band and each discrete PSD function on the basis of a damage accumulation rule. The proposed modeling approach is numerically and experimentally validated by a finite element method and experiments using three simplified structures made of 5052-H32 aluminum alloy. The proposed approach provides a more efficient and accurate modeling technique, and account for complex random loadings of structural components.

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Fatigue Design 2019

FD19-93

Adapted locati method used into accelerated fatigue test for random vibrations

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Fatigue experiments are very important for the study of structural fatigue damage. As we all know, fatigue experiments usually consume a lot of resources and time, slowing down the research progress. The Locati method, which is applied to the frequency domain analysis method of random vibration fatigue, replaces the traditional up-down method and accelerates the progress of the fatigue experiment. This method can effectively improve efficiency and reduce test time and test piece consumption under the premise of ensuring accuracy. It is based on the material S-N curve, after one step-load fatigue test, combined with the FEM, the cumulative damage of the structure under random vibration load is quickly determined, and the life analysis is completed. The specimen was made by Aisi304 and designed to make the fatigue damage of the second-order bending mode more significant. The random vibration acceleration defined by the PSD method is used as a load and applied on the specimens through the shaker. In this process, the material properties of the structure will be optimally fitted according to the experimental results, so that the finite element model is as close as possible to the real structure for fatigue calculation. Finally, an experiment will be used to verify the accuracy of this method. The method has now been validated under Gaussian distributed signals. At the same time, the structure is required to be linear.

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Fatigue Design 2019

FD19-97

Updating the master S-N curve to account for run-out data: application to piping vibrations

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In the very high-cycle fatigue regime there is a well-known lack of data for the assessment of welded joints. This lack of data has led to Codes and Standards with a wide range of recommendations. Most of these recommendations are justified by experience and lack a well-documented technical basis. The difficulty in testing at very high cycles is that the tests currently take too long to be practical and are often suspended between 106 and 107 cycles. The suspended test results are thought to be of no value and are frequently discarded. However, in piping vibration applications the system may undergo more than 108 cycles per year. Since much of the experimental data in this very high-cycle regime is suspension data, we explore approaches to extract the information contained in such data and infer the behavior of the Master S-N curve in the very high-cycle regime. This paper first provides a historical background on how Codes and Standards have varied their recommendations in the very high-cycle regime, then presents a statistical approach to account for suspension data to provide a basis for extending the Master S-N curve to the very high-cycle regime for welded joints. The updated Master S-N curve is then applied to a series of examples related to the problem of piping vibrations.

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Fatigue Design 2019

FD19-4

Fatigue response of high-strength steel bolted connections under in-plane shear and out-of-plane bending loading modes

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The use of high-strength steel (HSS) permits weight reduction in heavy-duty applications such as trucks, trailers, and agricultural machinery, where significant fatigue resistance is a requirement. Fatigue cracks are often initiated at locations of stress concentration such as the joining of mechanical parts, the most widely used methods being welding and mechanical fastening.

It is known that HSSs do not only have higher yield values but also perform better in terms of fatigue. Yet, the weld fatigue resistance does not improve with an increase in the base material property due to the stress concentrations and imperfections introduced by welding. The aim is to explore the possibilities of using conventional mechanical joining techniques for HSSs and assess the fatigue properties under typical loading modes.

Mechanical joining introduces an additional failure mechanism called fretting fatigue resulting from the oscillatory relative displacement between the surfaces in contact. This failure mode is reproduced by the experiments and the effects of pre-tension, hole-making procedure, washer configuration, and surface condition are analyzed for steel grades S500MC, S700MC, and S960MC. Accompanying finite-element simulations are employed to develop a deeper understanding of the underlying physics. The results might lead to various guidelines with respect to design rules and best practices for HSS bolted connections subjected to fatigue loading.

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Fatigue Design 2019

FD19-8

Practical notes for assessing the fatigue life of bodyworks of buses and trolleybuses

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When developing a new vehicle, the prescribed fatigue criteria must be fulfilled in all important structural nodes of the vehicle bodywork. Maximum stress amplitudes (stress ranges) must be lower than permissible values when the vehicle crosses significant road unevenness. The development stages are:

1. Projecting and design of vehicle;
2. Investigation of vehicle function sample on test stand;
3. Measurement of vehicle prototype.

The permissible value of the maximum stress amplitude can be the same value as fatigue limit, but mostly is defined for prescribed service life with the aid of the linear cumulative damage rule.

In case the prescribed condition is not fulfilled, it is necessary to recommend a modification of the vehicle bodywork. It is possible to divide the modifications of the structure into three groups:

1. Local reinforcements or changes of design of individual critical bodywork nodes;
2. Additions of structural elements makes skeleton much stiffer in neighbourhood of critical bodywork areas;
3. Fundamental change in the design of the bodywork.

In any case, it is necessary to know the fatigue properties for various structural and technological variants of the body sections. These properties can be determined in advance by laboratory fatigue tests.

The paper will describe the assessment of fatigue life in successive phases of vehicle development and will present the results of fatigue tests of several variants of welded nodes used in body construction.

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Fatigue Design 2019

FD19-10

Fatigue assessment of metallic structures under variable amplitude loading

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Many types of mechanical structures (cars, air-planes, trains...) and civil engineering structures (bridges, wind turbines, offshore structures...) are subjected to random in-service loading. Normally the load effects in these structures are composed of different stress ranges and mean stresses which are within the elastic limit of the material.

One main problem with fatigue assessment under variable amplitude loading is the performes of fatigue life regarding load sequence effects. In this study a model deals with the problem of fatigue life assessment under variable amplitude loading composed of differing stress ranges and mean stresses which are within the elastic limit of the material take into-account the load sequence effects is developed.

Computing of the stress range and the mean stress, in specific time based on the preceding load histories, consider load sequence effects. Using Palmgren-Miner damage rule and the new computed stress range and mean stress lead to predict the fatigue life. An evaluation of the model using data of five different metals availbe in the literature has been investigated. The results showed that the proposed model describes the effect of the load sequence in elastic loading well.

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Fatigue Design 2019

FD19-19

Fatigue simulation of welds using the total-life method

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"Fatigue is the progressive weakening of a material caused by cyclic or otherwise varying loads, even though the resulting stresses are well within the static strength limits"

Fatigue cracks initiate and grow as part of a two-stage process, with Stage 1 - crack initiation, and Stage 2 - crack growth. Historically, crack initiation has typically used a strain-life (EN) model, whereas crack growth has used either a *Linear Elastic Fracture Mechanics (LEFM)* or an *Elastic-Plastic Fracture Mechanics (EPFM)* model.

The *Total-Life* model combines aspects of both models into a unified model for fatigue life estimation. The model can produce fatigue life estimates that are considerably more accurate than the classical approaches. This is particularly apparent with welded structures and lightweight structures.

The *Total-Life* model described in this paper is based on the work of Glinka and Mikheevskiy [1]. The paper presents a contextual overview with a detailed review of the mathematical model. The paper describes how the *Total-Life* method has been implemented in a CAE environment, including required inputs for FE modelling, material properties, residual stresses, and applied loading.

A case study is provided illustrating how the model was applied to an engineered weld. Recently the SAE Fatigue Design and Evaluation committee evaluated and validated the *Total-Life* method. By combining crack initiation with crack growth, and including Glinka's cyclic crack-tip multiaxial plasticity model, the new *Total-Life* technology was shown to estimate fatigue life to within a factor of 2 through simulation alone.

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Fatigue Design 2019

FD19-23

Effects of clamp force on fatigue strength of aluminum alloy bolts

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[3]Nagaoka University of Technology, Nagaoka, Japan

In order to achieve weight reduction in transport equipment, it is necessary to replace steel with nonferrous materials not only for structural parts but also for joining elements such as bolts and nuts. It is known that the fatigue strength of high strength steel bolts has rarely been influenced by clamp force which acts as mean stress to the bolts because of local plastic deformation at the root of the first thread. However the effects of clamp force on fatigue strengths for nonferrous bolts have not been sufficiently revealed yet. In this study, fatigue tests for aluminum alloy A5056 and A6056 bolts have been conducted to reveal the influence of clamp force on fatigue strength. Hexagon head bolts M8 made of A5056 and A6056 were used. For the internal screw parts for the A5056 bolts, A5056 nuts were used. For the internal screw parts for the A6056 bolts, internal screw parts made of die cast material ADC12 considering actual usage were used. Results showed that the fatigue strength for A5056 bolts decreased with an increase in the mean stress. However the fatigue strength for A6056 bolts did not decrease if the mean stress was greater than 6 kN although it decreased if the mean load was less than 6 kN. In order to reveal the reasons the behaviors of these fatigue strengths were different, elasto-plastic analyses were conducted. Results of FE analyses showed that the causes were reduction of mean stress due to local plastic deformation at the fracture portions.

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Fatigue Design 2019

FD19-25

Effect of stress ratio on the fatigue fracture mechanism of adhesive single-lap joints: in case of GF/PP plates and an acrylic-based structural adhesive

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Applications of bonding technology have been expanded for lightweight structures and multi-material designs; however, the strength estimation and design method for bonded structures have not been fully established. New design concept and standard related to strength and reliability are required from industries.

In this work, fatigue tests under different stress ratio conditions and fracture surface observations were carried out to investigate the influence of the stress ratio on the fracture mechanism of adhesively bonded structures. Tested material was a glass-fiber-reinforced polypropylene composite plate, and adhesive was an acrylic-based structural adhesive. With single-lap joint specimens, fatigue tests were conducted using uniaxial electro-hydraulic fatigue testing system; frequency was $f = 10$ Hz, and stress ratios were $R = -1, -0.5, 0.1, 0.5, 0.7$, and 0.9. The effects of mean load were observed under higher stress ratio conditions, and fatigue strength at 10^7 (10 million) cycles dramatically deceased when the stress ratio was larger than 0.5. Fracture surface observations revealed correlation between the fatigue properties and fracture mechanism.

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Fatigue Design 2019

FD19-32

Design recommendations for fatigue-loaded hollow section K-joints with gap

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KoRoH GmbH – CCTH Center of Competence for Tubes and Hollow Sections, Karlsruhe, Germany

The K-joint with gap made of hollow sections is the most common joint type for lattice girders as used for jack-up rigs, wind energy converters, bridges, crane structures, agricultural machinery or amusement rides. The existing and approved rules for the fatigue design of hollow section joints have origin in the CIDECT Design Recommendations, which are based on experimental investigations made in the 1990s and earlier. Since then, a lot has changed in the development of materials, manufacturing and computer-aided design. So, for example for high strength steels as well as for sections with large thickness only little information about the fatigue behavior is available. In addition, there is often still great uncertainty in the design of hollow section joints. Preliminary investigations have shown, that in several cases this could lead to very conservative and uneconomic design on the one hand, or to unsafe constructions on the other hand.

This paper will present conclusions of recent research, based on fatigue tests and numerical investigations as well. The nominal stress method as well as the structural stress method is considered. Drawbacks and opportunities of existing design recommendations will be exemplified. Further instructions for fatigue resistant constructions will be worked out to enable a safe and economic design of such joints and girders.

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Fatigue Design 2019

FD19-44

Derivation of a new fatigue class for top flange to web junctions of runway beams

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The replacement of German codes DIN 18800 and DIN 4132 by introduction of the Eurocodes due to the European harmonization in the technical approved area for steel construction led to a significantly more conservative classification regarding fatigue failure category details, especially for flange to web connections of runway beams in heavy smeltery cranes compared to former design experiences. Actually these changes would lead to a doubling of the cross-sectional thicknesses, which e.g. also can result in web plates with extreme thicknesses of 80 mm. Execution as well as monitoring of such flange to web connections using full penetration tee-butt welds are quite critical and could no longer be realized economically.

Encouraged by the operators of such constructions and crane installations from the metallurgical industry, the aim was therefore to devise an amendment to the correspondent actual fatigue classification in the Eurocode. The basis for these efforts are crane runway girders designed according to the "old standard" and their damage behavior for the notch detail "concentrated wheel load" at the upper neck seam. Some of these carriers have been in use for decades and usually show no damage for this connection - if the design is suitable according to previous standards.

The investigations were accompanied by numerical simulations. The results are closing the experimental gap that has been existing and that so far has been bridged by experience and interpretation of single test results, justifying a modification of the rules in EC3-1-9 table 8.10.

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Fatigue Design 2019

FD19-51

Investigations on the fatigue behaviour of end plate connections with prestressed bolts

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In many areas of our infrastructure, as for instance the construction crane runway beams, fatigue design of steel structures is a major issue. An important detail in practice, but insufficiently classified in the DIN EN 1993-1-9 detail catalogue, is the end plate connection with prestressed bolts. Detailed numerical simulations are often necessary for the fatigue check of the weld at the T-stub. The knowledge of the true bolt force required in the detail catalogue can usually also only be taken into account using finite element simulations. For these reasons, the detail 'end plate connection with different weld configurations and prestressed bolts' containing the two critical design cases mentioned above has been investigated. The analysed details comprise butt as well as fillet welds and connections with extended and non-extended end plate connections.

A literature review of existing investigations on end plate connections and bolt force models is given. Moreover, the test program on three fatigue tests series is presented. After conducting experimental investigations on small as well as large scale specimens detailed numerical simulations have been realised. In order to assess the fatigue resistance of the welded connection, the effective notch stress concept has been used. Additionally, fatigue resistances of prestressed bolts have been investigated by recalculating the bolt force progress. After the verification of the numerical models, a parametric study has been conducted by varying geometric characteristics in order to give general statements about bolt force and weld stress curves of end plate connections with prestressed bolts.

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Fatigue Design 2019

FD19-55

Evaluation of dimensional accuracy and mechanical behavior of 3D printed reinforced polyamide parts

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This paper aims to evaluate the mechanical behavior, dimensional accuracy and total cost of fused deposition modeling (FDM) produced reinforced polyamide (PA) parts; glass reinforced PA and Kevlar reinforced PA. First of all, the standard specimens are printed by varying three parameters, namely the layer thickness, the print speed and the extrusion temperature. Then, the weight and main dimensions of the obtained samples are measured before the mechanical characterization by tensile test. The results showed the effect of extrusion temperature and layer thickness on material properties is more significant than the impact of print speed. The influence of evaluated factors on the dimensional accuracy and total cost is also observed. Furthermore, a design of experiments (DOE) test protocol was applied to determine the effect of the controlled printing variables on the material properties of 3D printed matrix PA parts. Overall, this experimental investigation showed the advantage of reinforcement in enhancing mechanical performance and achieving better geometrical tolerance in comparison to FDM printed neat polymer components.

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Influencing factors on the fatigue strength of selectively laser melted structures

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This research focusses on influencing factors on the fatigue strength of selectively laser melted (SLM) aluminum and steel structures. One main effect is detected as the surface condition. Therefore, miscellaneous test series involving the as-built surface as well as machined and polished surface topographies are experimentally investigated. In addition, the impact of different post-treatments on the fatigue strength is researched. The microstructure of selected samples is studied utilizing SEM images of micrographs whereby microstructural features are assessed. Additionally, the axial residual stresses at the surface of selected specimen are measured using X-ray diffraction, with the aim to assess influencing factors on the fatigue strength more properly. The fatigue characteristic is evaluated by tension-compression high cycle fatigue tests under a load stress ratio of R=-1. Subsequently to the testing, a fracture surface analysis for each tested specimen is carried out in order to study the failure mechanism and evaluate the fatigue crack-initiating imperfection. The results revealed that for specimens that possess an as-built surface, the high cycle fatigue strength is significantly influenced by surface related characteristics. It is also found that the microstructure affects the fatigue behavior as well.

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Fatigue Design 2019

FD19-79

Macroscopic modelling of cyclic plastic response of 304L austenitic stainless steel

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The main of this paper is modeling of ratcheting-fatigue phenomena, the phenomenological macroscopic behavior modelling Chaboche model which gives very good prediction of ratcheting under uniaxial and multiaxial loading by the evolution of a hysteresis loop with a progressive cycle. The fatigue assessment of material is tests by stress and/or strain controlled. The ratcheting phenomenon is tests under non-symmetric stress cycles; the cyclic hardening/softening behavior of metals under strain control has also been investigated

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FD19-90

Influence of porosity and post-treatment on fatigue life of SLM 316L

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The Selective Laser Melting process involves multiple factors that are detrimental to fatigue life. It is crucial to select optimal processing parameters to avoid internal porosity, source of early failure through crack initiation mechanisms. Surface condition, especially high roughness values, may also be a critical factor for crack initiation. Influence of surface condition must be studied in the industrial context, where parts may not be completely machined before implementation.

This project is led in collaboration with industrial partner Manquillet Parizel. A SLM Solutions 280HL machine was used for sample production, located within Platinium3D, an additive manufacturing research platform located in Charleville-Mézières, France.

This work first focused on finding optimal parameters for producing low-porosity 316L parts by the SLM process. Samples were examined using X-Ray computed tomography.

Fatigue samples were then produced and submitted to various surface treatments (machining, polishing, …) while some were left as-built. They were then tested in high-cycle fatigue and S-N curves produced for each sample type. Results were injected into the Basquin equation for predicting fatigue parameters of SLM 316L.

This study indicates that high-cycle fatigue life of SLM 316L is generally inferior to wrought 316L, with as-built samples exhibiting lower fatigue limits. This was explained by surface roughness acting as crack initiation sites. Microstructural studies are still underway to confirm these results.

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Based on the virtual experiment study of the impact of load sequence on the calculation process of random vibration fatigue damage

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In the traditional fatigue calculation method, it usually does not consider the impact of the load sequence, such as the peak-to-valley method and the rain flow counting method. However, in the actual fatigue process research, the proper amount of load can improve the resistance of the material to the fatigue process. The larger load will affect the health of the structure and accelerate the whole fatigue damage process. This phenomenon will vary slightly depending on the material. It will have a large impact on the accuracy of vibration fatigue damage and life estimation. This paper discusses the impact of this phenomenon on damage calculations from an experimental perspective. The specimens were made of Aisi304 and AlT6. They were designed to make the fatigue damage of the first-order bending mode more significant. The random vibration acceleration defined by the PSD method is used as a load and applied on the specimens through the shaker. During the test, the sequence of step-load would be changed as specifically designed. Through the test, the change trend of the specimens' life, the damage in same specific frequency range under each step load were recorded, and the load threshold of the material could be obtained through data analysis. Establishing a structural random vibration damage model based on this threshold will improve the accuracy of the life assessment of the structure under random vibration loads.

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Probabilistic fatigue software platform (ProbFat) for optimizing life-cycle decisions

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Fatigue is inherently uncertain. Thus, the use of technology for prediction of fatigue damage for ensuring long-term reliability of equipment must embrace such uncertainty. The proposed probabilistic fatigue software platform (ProbFat) accomplishes just that. The stochastic engine behind ProbFat is a Bayesian Decision Network (BDN) that assesses risk to identify the optimal life-cycle strategy for maximizing overall return (i.e. return = benefit – cost). Benefit is a measure of profitability (e.g. annualized profit) and cost is a measure of expense (e.g. inspection, repair, replacement, failure, et cetera). To optimize benefit the BDN must incorporate all aspects of LCM including: (i) design and construction, (ii) monitoring, inspecting, and maintenance scheduling, (iii) identification of damage, (iv) assessment of observed damage, and (v) decision strategies to either run, repair, rerate, replace, or retire the component(s) of interest. BDNs are structured as graphical cause-effect relationships, represented by probabilistic nodes with directional links. Populating conditional probabilities associated with nodes is accomplished through assessment of laboratory and site-specific data, contributions from subject matter experts and simulations from in-house deterministic and stochastic fatigue models. In this paper, two industry examples are used to demonstrate the effectiveness of ProbFat: (i) low cycle thermo-mechanical fatigue of a coke drum, and (ii) very-high cycle vibration fatigue of a piping system. For both applications the fatigue methods available in API 579-1/ASME FFS-1 are utilized for deterministic/probabilistic prediction of fatigue damage accumulation and remaining life. Methods available in API RBI are used for inspection planning and maintenance scheduling.

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Forensic engineering investigation of fatigue failures in machineries

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MatCor, Singapore

A fatigue failure in machineries occurs progressively over time in service under cyclic stress loading, which could be insidious in nature. A knowledge of the fatigue damage mechanisms found in machineries can be used as an effective tool during statutory inspections to mitigate the risk of a sudden catastrophic collapse during usage.

Machineries generally can be operated safely in service, well within design limits, but if disrupted by deviations such as mechanical damage or corrosion, the stress level in the system or component may be adversely altered and worst, result in failure initiation. A deviation or flaw in the operation or design of the machineries could also be the cause of failure initiation from the start. It is also crucial for proper inspection and maintenance be carried out during the course of service life to detect the onset of any potential failure and arrest the issues. An improper or inadequate addressing of the issues may lead to further problems.

In some cases, the fatigue failures may be associated with multiple contributory factors. An engineering investigation will help to establish the mode and cause of the failures for managing the risks of future failure occurrences.

This paper presents a compilation of fatigue failures found in different types of machineries. Several influential factors, such as damage, corrosion, operation, design, maintenance (repairs) and inspection are considered. The forensic engineering investigation process and effects of some of the contributory factors on the fatigue damage are investigated and discussed in detail.

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Fatigue Design 2019

FD19-110

Repair of fatigue cracks on motorwaybridges

Jacques Berthellemy

The roads represent an important heritage of the society. Even more than corrosion, the fatigue is the principal aging processes that affects their durability.

The case of continuous four spans steel-concrete motorway composite box girder bridges will be presented. They were built in the late 1980's after 1987. Bottom flange stiffeners were not designed continuous, as recommended before in France for fatigue, but the bridge was experimentally "calculated" regarding fatigue. However details 1 and 2 were not correctly considered because the class of the longitudinal stiffener (detail 1) did not directly appear in the tables of the ECCS recommendations and a ''modified" stress as it is called in the Eurocodes today was not calculated to take into consideration the factor of stress concentration.

The modified stress was not calculated for detail 2 either.

In 1993, it was decided after the visit of the bridge by J. Berthellemy and D. Poineau to inspect every year the two wrong details. A pilot project with the right details for such box girder bridges was also designed in Nevers:

Detail 1 : At 16 different locations of the bottom flange, stiffeners presented cracks in 2014, i.e. 50 % of all details of type 1. The more advanced crack had cut the bottom flange of the box. The fatigue class along the cut is strongly reduced, from 125 MPa to about 40 or 50 MPa, according to the loacal radius of the cut found on the bridge, by considering the real stress concentration factor.

Detail 2 : No crack of this type existed in 2014. But 20 locations presented cracks in october 2015. Local stresses due to the bending of the concrete deck, and the effects of distortion of the box girder section should have been considered.

Repair and strengthening decisions :

Detail 1 : Repair by local welding in a first step. In a future step, the right longitudinal mechanical continuity of the stiffeners will be established.

Detail 2 : Two repair options with bolts have been tested. Option A is attached to the concrete deck and could have helped the connection devices between steel and concrete. Option B (weld + bolds after welding) will be used in current section.

An animation of the crack propagation will probably be available during the poster session (Calculated with Code_Aster and the XFEM method)

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Fatigue Design 2019

FD19-112

Modelling of fretting fatigue endurance from partial to gross slip: a "fatigue-sliding" chart approach

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The fretting fatigue (FF) appears as key damaging process in many assemblies subjected to vibrations. In this study, a finite element model is proposed to predict the fretting fatigue endurance and to formalize the competition between wear and cracking processes taking into account the debris layer entrapped within the interface. The studied interface is 35NCD16 cylinder/plane contact modelled using a 2D (plain strain) elastic assumption. As long as the contact is running under partial slip, the increase of displacement amplitude increases the tangential force and consequently decreases the fretting fatigue endurance. Above the sliding transition, the gross slip sliding condition by promoting surface wear tends to reduce the interface stressing and consequently promotes an increase of the fretting fatigue endurance. To simulate such non monotonic "U shape" endurance evolution, a combined wear and cracking FE modelling is developed taking into account the presence of a debris layer entrapped within the interface. Wear and crack nucleation parameters were previously extracted from a post processing analysis of plain fretting experiments (i.e. without fatigue stress). The comparison between the experimental fretting fatigue endurance curve and the FEM simulation is very good which confirms the necessity to take into account consider the presence of the debris layer to predict fretting fatigue failure under gross slip conditions. This approach is extended to establish an extended "fatigue-sliding" fretting fatigue map concept where cracking, failure and wear damages are defined as a function of the fatigue stress and the contact displacement amplitude.

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Fatigue Design 2019

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Influence of microstructure and heat-treatments on the fatigue behavior of fully pearlitic steels

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For the design of huge suspension bridges, it is of utmost importance to apply the optimum steel grade in order to minimize weight and reduce construction costs. Cold-drawn pearlitic steel wires are a very good option because they exhibit an excellent combination of high strength and good ductility required for wire strands, ropes and cables for suspension bridges. The pearlite structure consist of alternating lamellae of ferrite and cementite. The tensile strength of pearlitic steels is mainly determined and optimized by the drawing parameters (drawing reduction, temperature), which influence the pearlite lamellae spacing. However, such structures are typically exposed to several damage mechanisms such as fatigue and corrosion damage, which lead to a progressive material degradation of their components. Therefore, an accurate assessment of pearlitic steel fatigue resistance is essential to increase safety and long-term reliability of its applications. This study aims at investigating the influence of the microstructure and heat-treatments on the fatigue behavior of fully pearlitic eutectoid steels, in particular fatigue crack initiation and propagation, and stress to strain response. Heat treatments were performed to produce microstructures with different pearlite interlamellar spacing in fatigue specimens. The fatigue tests were conducted at room temperature under total strain control ranging from $\Delta\varepsilon t$=0.6% to 1.2%. First results showed that the pearlite lamellae spacing has significant influence on fatigue crack growth behavior. The results are discussed in light of the microstructural changes and fractographic observations of the failed specimens. In addition, the effect of ageing on fatigue properties has been also discussed.

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Fatigue Design 2019

FD19-119

Fatigue damage and failure analysis of honeycomb sandwich

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Fatigue behavior of sandwich structures with honeycomb core and GFRP skins is studied and failure mode is investigated through tomographic observations. The first S/N curves are presented. The second part discusses the failure modes observed during fatigue tests and responsible for stiffness decrease during fatigue tests.

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Fatigue Design 2019

FD19-121

Investigation on damage mechanisms in both continuous and short fibre reinforced thermoplastic

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In the automotive sector, structural components made of reinforced thermoplastic are increasingly replacing metallic parts with a primary goal of weight reduction. Most of these structural components are subjected to thermo-mechanical fatigue loadings and to develop optimal designs, engineers need accurate models and failure criterion. This requires the understanding of the microscale damage mechanisms and their link to macroscopic results. In this paper, the behaviour of reinforced polyamide 6,6, mix of short and continuous glass fibres, is studied at different scales with monotonic and low cycle fatigue loadings. In order to propose a physically based micro-mechanic fatigue damage model, the first part of this paper deals with X-ray microtomography observations for virgin and damage samples. The second part is dedicated to the macroscopic scale where an unified fatigue criterion is sought in order to predict fatigue resistance with a FEM modelling. This criterion have to take into account the fibre orientation and the stress triaxiality level.

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Multiscale analysis of fretting wear mechanisms of metallic materials

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Fretting is a common wear mechanism of mechanical components characterized by motion with a low amplitude. It can result in cable breaks, actuator blockages, bearing destruction (false Brinelling effect) and splined shaft loosings and electrical contact faults ... For parts subject to cyclic stresses, fretting favors crack initiation by fatigue (fretting fatigue). We observe the generation of fine particles often oxidized (fretting corrosion) around the contact zone.

To find solutions to reduce fretting wear, numerous studies have been carried out. Indeed, depending on the concerned application, lubrication technologies by using surface treatment have been particularly studied. Fretting wear is strongly influenced not only by the amplitude, frequency and trajectory of the movement, pressure and contact geometry, but also by different parameters such as the material, the roughness and the surrounding environment (grease, humidity). Therefore, for all conditions, it is difficult to evaluate the effectiveness of each solution likely to have a risk of fretting.

Moreover, according to a statistic study carried out by the Cetim on 560 cases of wear damage, 29% of mechanical component damage is caused by fretting, just behind galling (35%). This high percentage is mainly due to the lack of knowledge about the fretting wear mechanisms and the lack of reliable data expressed by design offices and maintenance services as regards the understanding of the fretting behavior of materials and surface treatments.

To reduce fretting industrial failure cases and to propose a representative friction test for various mechanical applications, Cetim has previously worked on the realization of fretting tests according to ASTM G-204. This test was performed by using a ball-on-plate configuration and frequency and amplitude domains representative of the mechanical applications. Thus, after having generate fretting wear tracks on stainless steel specimens by performing this previous fretting test method (ASTM G204), the present work aims to obtain a better understanding of the fretting wear mechanisms by carrying out a multi-scale and multi-technique approach. This latter approach is partly based on the realization of measurements of friction coefficient as function of time during the tribological test and analyses of the worn surfaces by using roughness measurements and scanning electronic microscopic (SEM) observations coupled to energy-dispersive X-ray spectroscopy analysis (EDS). For this purpose, the fretting wear behavior of various material couples such as 316L/ Nitronic 50, 316L/ Nitronic 60 and 316L/ Uranus 45N are confronted.

Whatever the material couple, it is shown that the friction coefficient evolution is characterized by three different stages which depend on time. In addition, the Nitronic 60 presents a much higher wear volume compared to the three other materials which present equivalent wear volumes. Currently, efforts are devoted to performing microstructural analyses of the impact of fretting wear on the subsurface for theses material couples. More precisely, to improve the analysis of the correlation between the microscopic and macroscopic tribological behaviour of these stainless steels, additional experimental techniques should be used such as electron backscatter diffraction (EBSD) and nano-indendation.

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Fatigue Design 2019

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Microstructure evolution of pearlitic steel at early states of wear under rolling contact fatigue

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Understanding of wheel/rail contact effect on pearlitic microstructure of rails is an important concern for maintenance of railway network. In this study, a new testing machine is used to reproduce wheel/rail contact on R260 steel rails. Different conditions of initial surface preparation and rolling/sliding ratio have been applied with a number of cycles from 1000 to 3000. Consequences of oxidation layer formation previous to test and effects of a 0.5% sliding are investigated. Effects on local variations of mechanical properties and microstructure of material is measured. Results from micro-hardness indicate that strain hardening is concentrated in the first 200 µm under the contact surface. Scanning electron microscopy shows that pearlitic colonies are elongated and cementite lamellae are reoriented. The fragmentation of colonies is highlighted by electron backscatter diffraction (EBSD) analysis.

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Prediction of stresses, at high temperature, generating Liquid Metal Embrittlement (LME) on Advanced High Strength Steels (AHSS) during Resistance Spot Welding (RSW)

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Resistance Spot Welding (RSW) is commonly used to fasten together metal sheets in automotive industry. The body in white, which is the safety structure of a vehicle, is assembled by means up to 6000 spots welds. During resistance spot welding of zinc-coated Advanced High Strength Steel sheets, cracks may occur in the Heat Affected Zone (HAZ). This phenomenon, called Liquid Metal Embrittlement (LME) takes place when liquid zinc of coating penetrates into steel grain boundaries, at high temperature. Mechanical stresses during welding plays a significant role to propagate these cracks.

Consequently, a prediction of stress levels during resistance spot welding (at high temperature) is very useful to reduce and/or avoid LME phenomenon. Therefore, a methodology to predict mechanical stresses at high temperature by means of Sysweld® numerical tools is proposed in this work.

Authors

Notes

X-Raybot, stress evaluation system by x-ray diffraction:

X-Raybot is a 6-axis collaborative robot device dedicated to stress (or retained austenite) evaluation by X-ray diffraction. It uses an air cooled miniaturized X-ray tube that avoids the flexible water pipes existing in classical apparatus. Three anodes are currently available: Cr, Mn and Cu, thus permitting measurements on most materials (ferritic and austenitic steels, aluminum, copper, nickel base, titanium alloys,…). The silicon microstrip position sensitive detector (1280 channels) employed to record the diffraction peaks is at least five times more efficient than classical scintillators or proportional counters. Its large angular range (more than 30 degrees) permits analyzing the broadened peaks obtained in case of thermomechanical surface treatments like carburizing or carbo-nitriding. Different detector positions are predefined that allow to reach diffraction angles from 119 to 171 degrees. A laser-camera triangulation system permits to adjust the measurement point. It not only controls the precise position of the robot versus the analyzed surface, but also its orientations.

This device has been developed in collaboration with Cetim.

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