fatigue design 2015

ABSTRACTS BOOK

6th edition

of the International conference on fatigue design

18 & 19 November 2015 Senlis France

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Introduction Message

On behalf of the Fatigue Design 2015 International Scientific Committee and Organizing Committee, we would like to welcome you all to the 6th edition of Fatigue Design 2015 taking place at Cetim, Senlis, France on November 18 & 19 2015.

Since 2005, and every two years, the conference takes place at Senlis, the Royal City, 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.

The 6th Fatigue Design 2015 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.

For the first time, the organizing committee has decided to dedicate the conference to the scientific community from a specific country.

In respect to the USA advance research works in the area of fatigue and fracture mechanics in the last decade, for Fatigue design 2015, the USA has been proposed as the "partner country" for this conference. More than 25% of conference speakers are coming from the USA including 3 plenary key speakers.

Cetim and his partners organizing the Fatigue Design International Conference since 2005 to promote 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 6th edition of the Fatigue Design International conference is organized by Cetim and its partners on 18 & 19, November 2015 at Senlis, France in close collaboration with Elsevier editor for the proceedings publication through Elsevier 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.

This edition of the conference will cover the following scientific and technical topics:
• 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...),
- Fatigue of Shape Memory Alloys.

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.

"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: 90 oral presentations are performed with 50% by industry.

We do 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 review, 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.

Mansour Afzali
Chairman
Organizing Committee
Fatigue Design 2015

Fabien Lefebvre
Co-Chaiman
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Poster Award 2015

The poster session of the 6th edition of the Fatigue Design conference includes more than 19 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 best poster will be chosen by the Poster Award Committee members with scientific and technical criteria. The Poster Award winner will receive a Certificate of Recognition and an I-Pad©.

During the 5th Fatigue Design 2013 conference, the Poster Award has been dedicated to Linamaria Gallegos Mayorga her thesis work and poster on "Fast characterization of fatigue properties of an anisotropic metallic material: application to a puddled iron from a nineteenth century French railway bridge".

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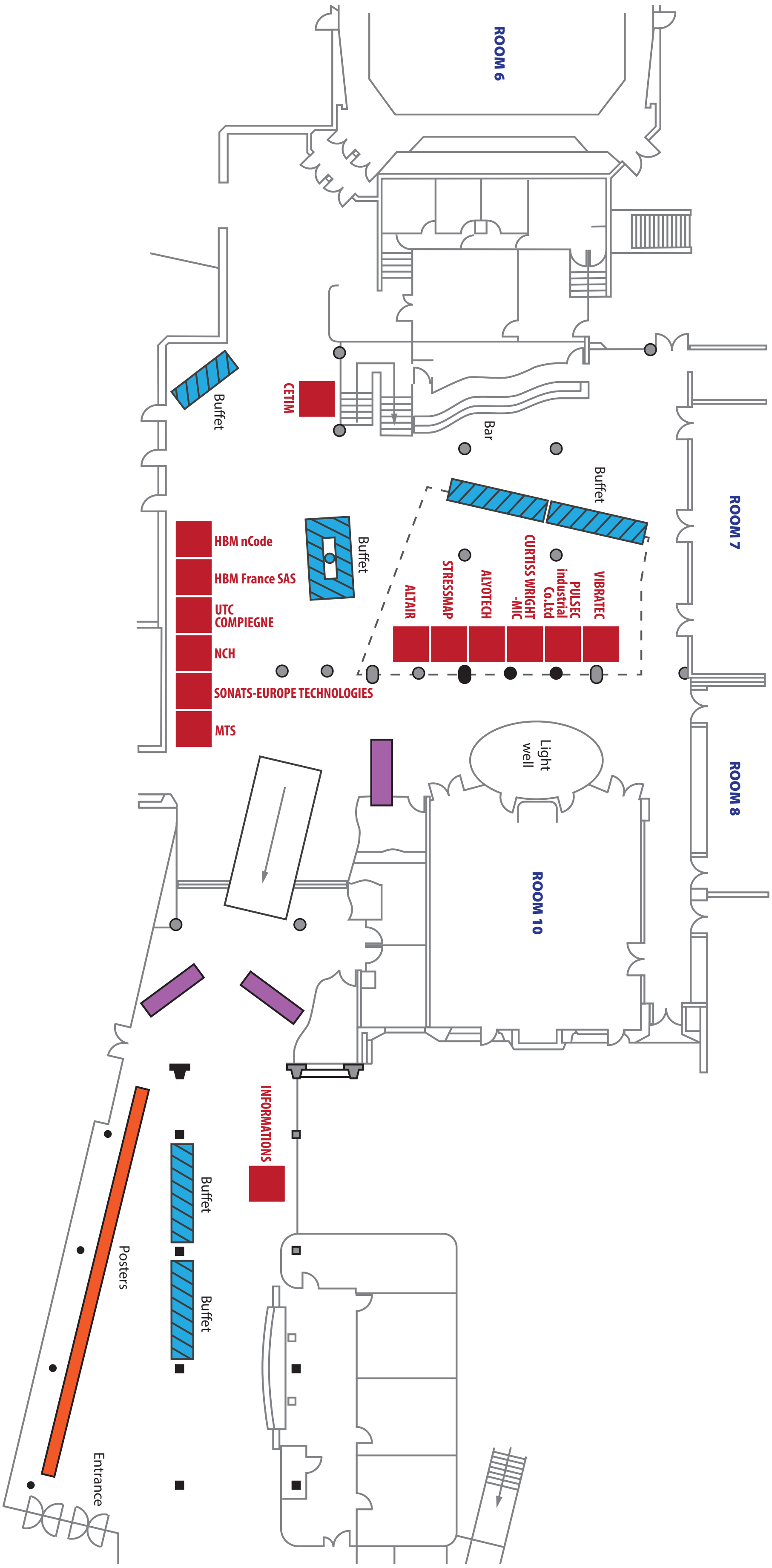
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Chairmen:

D. Osage, M. Afzali,

D. Mac Dowell, F. Lefebvre

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Procedia Engineering (2015) 1877-7058

Procedia Engineering

6th Fatigue Design Conference, Fatigue Design 2015

PLENARY SESSION
WEDNESDAY 18 NOVEMBER

FD15-003

MICROSTRUCTURE-SENSITIVE MODELING OF FATIGUE CRACK FORMATION AND EARLY GROWTH IN METALLIC POLYCRYSTALS

DAVID MCDOWELL

GEORGIA TECH, ATLANTA, GA, USA

We review developments in our group over the past decade regarding microstructure-sensitive modeling of fatigue of structural alloys. In particular, we consider sensitivity of fatigue crack formation and early growth at the scale of the grains in polycrystalline and polyphase microstructures to facilitate preliminary parametric design exploration aimed at comparing a range of microstructure morphologies for nominally the same composition.

A general methodology for stages of small crack formation and growth is introduced, including fatigue crack nucleation and early growth at the scale of grains (incubation), microstructurally small crack growth, physically small and long crack growth. Scatter in high cycle fatigue (HCF) and very high cycle fatigue (VHCF) is computationally assessed using multiple statistical volume elements and the distribution of computable mesoscopic Fatigue Indicator Parameters (FIPs). The distribution of indicated crack formation sites and relative growth in HCF are considered as a function of strain amplitude in α–β Ti alloys and Ni-base superalloys. To compare microstructures based on the criterion of a given low probability fatigue life (e.g., 1% probability) for remote applied loading conditions, extreme value statistics are used to characterize the extreme value FIPs of a large number of computational statistical volume elements for Ni-base superalloys and Ti-64 alloys.

The concept of marked correlation functions is introduced as a means to quantify the role of multiple microstructure attributes that couple to enhance the extreme value FIPs, providing a tangible means of feedback to modify microstructure to facilitate design of alloys with improved fatigue properties.

Recent work is reviewed in modeling crack formation and early 3D propagation of microstructurally small fatigue cracks in polycrystalline microstructures using mesoscopic (grain level) FIPs as surrogates for the cyclic crack tip displacement.

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Procedia Engineering (2015) 1877-7058

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PLENARY SESSION
WEDNESDAY 18 NOVEMBER

FD15-109

APPROACHES TO FATIGUE LIFE PREDICTION FOR FLOATING PRODUCTION UNITS

TIMO DE BEER, ANDREW NEWPORT, MAMOUN NACIRI, LUCILE RAMPI
SBM OFFSHORE, MONACO

The keynote will address the approach to fatigue life calculation for FPSO's (Floating Production Storage and Offloading systems), covering the differences in approach for hull, topsides and mooring areas. A contrast will be drawn between the offshore approach (welded structures, S-N basis) and mechanical industries such as automotive and aerospace (machined components), and load simulation by model tests will be presented.

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Procedia Engineering (2015) 1877-7058

Procedia Engineering

6th Fatigue Design Conference, Fatigue Design 2015

PLENARY SESSION
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FD15-026

FATIGUE BEHAVIOR AND PREDICTIVE MODELING OF SHORT FIBER THERMOPLASTIC COMPOSITES

ALI FATEMI
THE UNIVERSITY OF TOLEDO, TOLEDO, USA

Short glass fibre reinforced thermoplastics are being increasingly used, particularly in the automotive industry. The capability to be molded in complex geometries, low manufacturing cost, and high production rate are among the advantages of applications of these materials. Many components in such applications are under cyclic loading and, therefore, understanding their fatigue behaviour is essential for their failure and life estimation analyses. This presentation provides an overview of fatigue behaviour of these materials with respect to a variety of effects. These include effects of anisotropy, fibre length and orientation, stress ratio or mean stress, cycling frequency and self-heating, humidity, temperature, stress concentration, thermo-mechanical fatigue and creep-fatigue interactions, and damage mechanism. The presentation includes both experimental data, as well as predictive models for the aforementioned effects. Several commonly used glass fibre reinforced thermoplastics were chosen for this investigation using a plate type specimen geometry. The specimens were tested at room, -40 °C, 85 °C, and 125 °C temperatures, at R ratios of -1, 0.1, and 0.3, and cut in directions parallel, perpendicular, and at 45° to the mold flow direction. Similarities and differences with metal fatigue behaviour and analysis methods are also highlighted.

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FD15-066

FATIGUE TESTS FOR AUTOMOTIVE DESIGN: OPTIMIZATION OF THE TEST PROTOCOL AND IMPROVEMENT OF THE FATIGUE STRENGTH PARAMETER ESTIMATION

Matteo Luca Facchinetti[1], Fabrice Guérin[2]

[1]PSA Peugeot Citroën, Vélizy Villacoublay, France, [2]ISTIA, Angers, France

Despite of continuous improvement of numerical computations, experimental fatigue tests are still of prior concern for high safety level parts, in particular for the automotive industry. Destructive fatigue tests are required in order to prove to authorities an effective fatigue design by highlighting the weakest link and its failure mode, and possibly taking account for the manufacturing process influence. Actually, experimental tests need for expensive means (i.e. rigs and specimens) and fatigue phenomenon is expected to take long time to get a crack issue. Thus, cost and delay time reductions always call for more effective methods.

Within this framework, we address here some recent improvements dealing with, respectively:

a) the optimization of the fatigue test protocol, i.e. how the load time history is applied to the specimen in order to minimize the overall fatigue test duration;

b) the reliability of the fatigue strength estimation, i.e. how the experimental data are considered in a reliable statistical model.

The first point let us focus on a so-called Locati fatigue test protocol, whereas the second point let us make use of Maximum Likelihood and Bayesian techniques.These improvements are currently and successfully applied to chassis system parts at PSA Peugeot Citroën.

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PLENARY SESSION
THURSDAY 19 NOVEMBER

FD15-018

INTRODUCTION TO DURABILITY RELIABILITY DEMONSTRATION TEST METHODS

YUNG-LI LEE, SANDEEP MAKAM, SEAN MCKELVEY

FIAT CHRYSLER AUTOMOBILES, AUBURN HILLS, MICHIGAN, USA

A complete product design cycle should include the following three stages: target setting, product design and development, and product validation. In the first target setting stage, it is required to understand the voice of customers (VOC), define the extreme customer usage condition, acquire the duty cycle or customer usage data for the target, and castcade the VOC targets from system to component levels. In the second product design and development stage, the multi-objective design optimization in the virtual analysis domain is performed, where the analytical tools to design the product for various design criteria should have been developed and in place for analyses.

In the final product validation stage, the test methods with a limited sample size to demonstrate the reliability of product population meeting the specific design functional and performance requirements are required to be conducted. Since the test results exhibit significant statistical variations, these test methods (named the reliability demonstration test methods) are the most important mechanism to ensure a successful product launch for durability, reliability and quality. Again due to the limited sample size for testing, a specific reliability and confidence target should be predetermined to be demonstrated by these test methods.

The focus of this presentation is to provide a quick overview of various reliability demonstration test methods which depends on the failure criterion in product validation testing. For a non-repairable system the test is considered complete or suspended as the system fails, while a repairable system allows the actions to restore/renew a failed system to operational status. The commonly used reliability demonstration tests for a non-repairable system are the test-to-failure method, the test-to-bogey method, the extended bogey method, and the step-stress test method, and for a repairable system, the non-homogeneous Poisson process (NHPP).

This presentation will review the theoretical background and discuss the pros and cons of the following test methods:

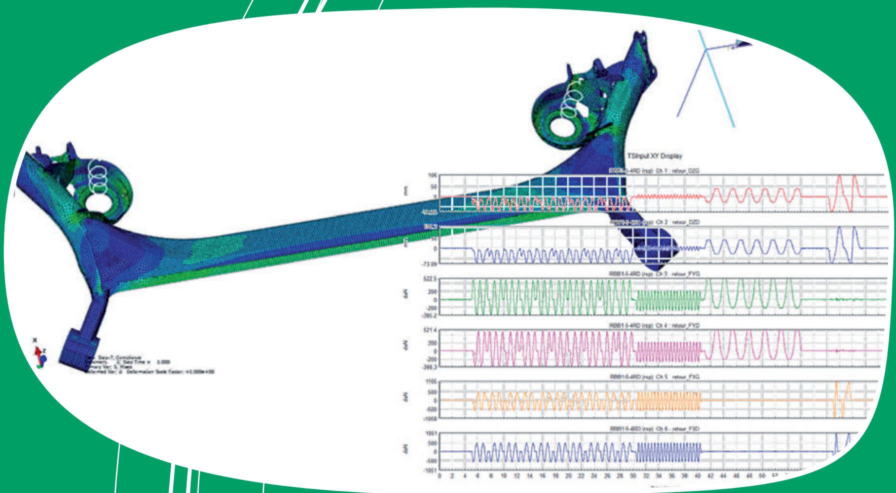
- Non-repairable system
- The test-to-failure method
- The best-to-bogey method
- The extended bogey method
- The step-stress test method
- Repairable system
- The non-homogeneous Poisson process

S01 - Complex loading

Chairmen:

A. Araujo, M. Bennebach

T. Palin Luc, D. Kujawski



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COMPLEX LOADING S01-1
THURSDAY 19 NOVEMBER

FD15-078

FORMULATION OF MULTI-AXIAL FATIGUE CRITERIA WITH LENGTH SCALE AND GRADIENT EFFECTS

HABIBOU MAITOURNAM, PATRICK LE TALLEC, ZEPENG MA

ECOLE POLYTECHNIQUE, PARIS, FRANCE

The objective of the paper is first to extend some classic high cycle fatigue criteria (as Crossland, Dang Van, Papadopoulos, ...) to take into account a sensitivity of the criteria to stress spatial variations occurring at length scale lg, and second to compare the performances of the extensions through numerical simulations of experimental fatigue tests.

After an introduction of the basic criteria and of their gradient based extensions, the criteria are tested and applied to 3 different simple situations: pure rotation, 4-point bending and cantilever rotative bending. Analytical techniques are used, for some tests, to estimate the relative error between the exact solution and the numerical simulation. The other tests are modelled with numerical methods implemented within the Cast3M Finite Element software and Matlab.

The results obtained from the different gradient formulations of the criteria are then analyzed and discussed. From instance, it is found that Dang Van and Papadopoulos criteria are the same in the case of pure rotation and 4-point bending. Crossland Criterion is slightly different. However, in the case of cantilever rotative bending these three criteria have different outcomes. And the gradient terms are very small comparing to the original criteria.

Finally, the present study develops a simple formulation of gradient multi-axial fatigue criteria extending the classical HCF criteria. In this work only cases with typical loadings have been examined. In these cases, the gradient is such that it has a beneficial effect on fatigue. An application to an industrial structure is then performed.

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COMPLEX LOADING S01-1
THURSDAY 19 NOVEMBER

FD15-044

THE CRITICAL PLANE ORIENTATION UNDER BIAXIAL FATIGUE LOADING CONDITIONS

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[2]GUANGDONG PROVINCIAL KEY LABORATORY OF ELECTRONIC INFORMATION PRODUCTS RELIABILITY TECHNOLOGY, GUANGZHOU, CHINA,
[3]EDF ENERGY R&D UK CENTRE/LOW CARBON GENERATION AND THE MODELLING AND SIMULATION CENTRE, MANCHESTER, UK,
[4]SCHOOL OF MECHANICAL, AEROSPACE AND CIVIL ENGINEERING, THE UNIVERSITY OF MANCHESTER, MANCHESTER, UK

The thermal loadings in the pipe wall of the residual heat removal systems in pressurized water reactors can be generally regarded as biaxial fatigue loadings, which may lead to multidirectional thermal fatigue cracks on the inner surface of the pipe wall. In this paper, the orientations of the critical plane defined by maximum damage under biaxial fatigue loading conditions are investigated by analytical and computational approaches.

The analytical solutions of the critical plane orientation for the Matake's and Fatemi–Socie's criteria are first derived using an elastic material law. The computational results obtained from Code_Aster are used to validate the analytical solutions. The analytical solutions of the critical plane orientation using an elastic material law appear to be consistent with the computational results obtained from Code_Aster by using an elastic material law or a Chaboche-type elastoplastic material law. An analytical derivation is performed to investigate the effect of the plasticity on the critical plane orientation by using a simple elastoplastic material law with one linear isotropic hardening term. It is concluded that for the loading path of applied biaxial stress considered in this study where the maximum and minimum stresses in both directions are reached simultaneously, the critical plane orientation is not effected by the plasticity.

Finally, the critical plane orientations are compared with the observed directions of the thermal fatigue cracks.

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COMPLEX LOADING S01-1
THURSDAY 19 NOVEMBER

FD15-116

WHERE DO YOU GET YOUR LOADS TO ASSESS COMPONENT STRENGTH AND DURABILITY?

KESHAV SUNDARESH, RAJIV RAMPALLI
ALTAIR, USA

Designing high quality, reliable products is always a prime motivation for a wide variety of Industries from home appliances to land vehicles. While it is possible to use physical testing to verify durability, it is most efficiently done by applying simulation methods integral to the development process.
In the past, our colleagues have written some interesting articles such as "Simulation Driven Automotive Closures" and "Analyzing Durability". If you try to connect the dots here, you will realize that one of the most crucial aspects for predicting durability is getting accurate component loads. The challenge is that in many situations is that these cannot be directly measured experimentally.

This article gives you an insight into how accurate component loads are generated from physical or virtual tests and the different approaches in use today for vehicle durability evaluation home appliances to land vehicles.
While it is possible to use physical testing to verify durability, it is most efficiently done by applying simulation methods integral to the development process.

Durability of Chassis Frame or Other Components

Durability is the ability of a product or a component to withstand failure due to fatigue, corrosion, wear, and creep. In most durability situations, the predominant failure mode is fatigue. Fatigue is defined as failure due to repeated cyclic loads that are well below the failure strength of the material. Therefore, avoiding premature fatigue failure is a critical element in the creation of long lasting products. Products should be validated and optimized for the dynamic loads to which they will be exposed during their operation. There is a need for durable products across all industries; this article focuses on the evaluation of the durability of the chassis of an automobile.

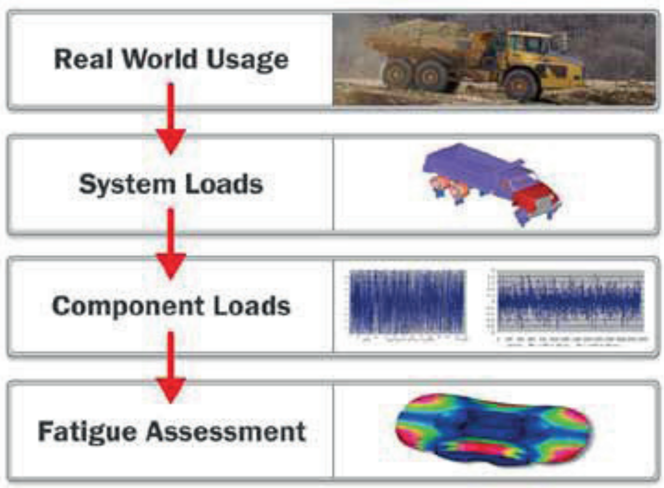

Figure 1: The typical process for measuring chassis durability

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In conventional vehicle development, the fatigue strength of the chassis and its components is evaluated through physical testing. Since a complete set of component load and stress measurements for components is hard to obtain, field-testing is augmented with laboratory measurement and simulation.

Through coupled multi-body dynamics (MBD), finite element analysis (FEA), and fatigue simulations, the need for physical testing, is not only minimized, but available test data is used to greater benefit.
Virtual durability testing is performed in two ways:

a. Semi-analytical durability evaluation
b. Analytical durability evaluation

Semi analytical durability evaluation can be condensed into five key steps:

1. Experimental measurement: The first step is to define a duty cycle for the test product. The vehicle is instrumented with wheel force transducers to capture the time history of the loads on each of the spindles. The vehicle is driven over different road conditions on the test track for varying durations and the force-time histories are collected. A duty cycle representative of real-life usage is then synthesized from the collected force-time histories.
2. MBD: The second step in the process is to perform virtual system level testing with the duty cycle to determine component load time-histories for the duty cycle. An MBD model of the vehicle is placed on an MBD model of a test rig. The duty cycle is fed as input to virtual actuators in the virtual test rig. These apply the excitation either to the tires or directly to the spindles of the vehicle model. An MBD simulation of the combined vehicle and test rig with a synthesized duty cycle is performed. Components of interest in the MBD system model are instrumented to obtain load time histories at all the attachments on the component.
3. FEA: A unit loads FE analysis of the component is then performed. Unit loads are applied in each of the six directions at each of the attachment points. The stress or strain state for the unit loads is generated.
4. Fatigue analysis: The material model for the component is defined. The unit results from FEA are scaled with the loading obtained from MBD and a fatigue analysis of the component is performed. The fatigue analysis can be quite detailed. For instance, the fatigue life of each of the individual welds on the chassis or frame can be calculated and fatigue life at all stress concentrations can be evaluated.
5. Post-processing: The MBD, FE, and fatigue results are visualized to understand the durability behavior of the component. This process is graphically illustrated in Figure 2. Semi-analytical approaches are useful because they can be done quickly and they reduce the need for physical testing. When physical prototypes are not available, a fully analytical approach is required. Analytical approaches avoid the use of physical prototypes and experimental measurement. The prototype is tested entirely in the virtual world. The role of MBD in this scenario is to mimic the proving ground tests.

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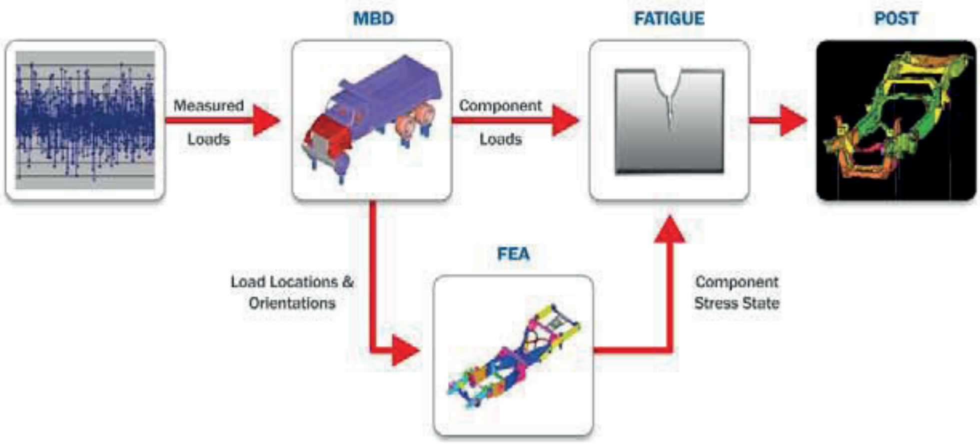

Figure 2: The semi-analytical process for chassis durability evaluation. Experimentally measured loads are provided as input to a virtual vehicle model.

Analytical durability evaluation can be condensed into four steps:

1. System level testing: An MBD model of the vehicle is built.This system is validated first. Then it is exercised in exactly the same way one would have tested a physical model, if it were available. The virtual vehicle, outfitted with a virtual driver and high fidelity tire models is driven over a virtual road, and component load histories at each of its attachments are generated.
2. FEA: A unit loads FE analysis of the component is then performed. Unit loads are applied in each of the six directions at each of the attachment points. The stress or strain state for the unit loads is generated. This step is the same as for semi-analytical approaches.
3. Fatigue analysis: The material model for the component is defined. The unit results from FEA are scaled with the loading obtained from MBD and a fatigue analysis of the component is performed. This step is the same as for semi-analytical approaches.
4. Post-processing: The MBD, FE, and fatigue results are visualized to understand the durability behavior of the component. This step is the same as for semi-analytical approaches. This approach is summarized in Figure 3. Analytical durability evaluation is more compute-intensive than semi-analytical approaches. Furthermore, it is hard to validate results against real experiments since physical prototypes are not available. For these two reasons, fully analytical approaches were not very common. Today, however, with the development of new computer validation techniques and faster computer systems, this approach is gaining acceptance.

The analytical approach may be used in other scenarios as well. The durability evaluation of automobile doors is an example, as illustrated in the “Simulation-Driven Automotive Closures” article. This approach is general; it also can be applied to other products.

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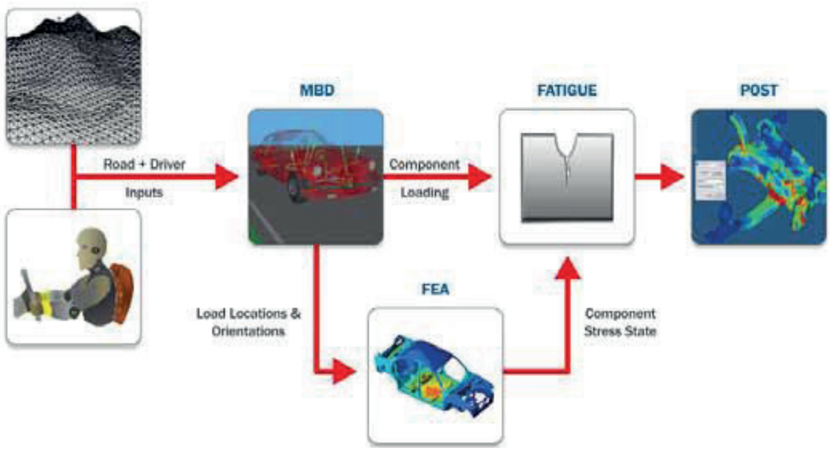

Figure 3: The analytical process for chassis durability evaluation. A virtual car is driven on a virtual proving ground. Component load histories from the simulation are used to assess their fatigue life

Summary

Simulation methods and physical testing have become an integral parts of the development process to enable organizations to create high-quality products and significantly speed their time to market. Both virtual and physical methods have evolved tremendously in the past few decades because of advances in hardware and software technology. HyperWorks offers a comprehensive set of tools for multi-body dynamics, finite element analysis and fatigue that can be used to virtually test and improve Industrial applications.

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COMPLEX LOADING S01-2
THURSDAY 19 NOVEMBER

FD15-004

FAMOS 4 WIND – A METHOD FOR THE FATIGUE MONITORING OF WIND ENERGY PLANTS

STEFFEN BERGHOLZ[1], JÜRGEN RUDOLPH[1], ADRIAN WILLUWEIT[1], GERRIT HAAKE[2]

[1]AREVA GMBH, ERLANGEN, GERMANY, [2]AREVA WIND GMBH, BREMERHAVEN, GERMANY

Modern state-of-the-art fatigue monitoring approaches gain in importance in the context of renewables such as wind power plants. Fatigue is of utmost importance in terms of potential damage mechanisms and in the perspective of scheduled plant lifetime periods of 20 years. A qualified fatigue monitoring approach considering the real loads provides:

- the best possible knowledge of the state of the plant (protection of investment)
- the basis for long term operation projects and
- the basis for a load ranking within a wind park in case of partial load operation. It is the aim to ensure a constant damage accumulation across the wind park. AREVA disposes of a long tradition in the development of fatigue and structural health monitoring solutions.

The methodology established for power plant applications is transferred to mechanical loading conditions of components of wind energy plants. The core challenge is the identification and qualified processing of realistic load-time histories. The related methodological requirements will be explained in detail. In terms of components of wind energy plants the wind loads are producing inner structural loads (forces and moments). Hence, the main target is gaining knowledge about the histories of these inner load series. The approach is based on a modern standard acceleration measurement at specific positions on the wind turbine tower. The entire fatigue monitoring process can be described by the following workflow:

1. Measurement of the tower acceleration with modern acceleration measurement equipment;
2. Evaluation of displacement histories based on the acceleration measurements using double integration functions;
3. Calculation of internal loads histories based on the equation of motion and the knowledge of towers stiffness;
4. Scaling and superposition of elementary (unit) stress responses based on the internal load histories for getting component stress histories and
5. Evaluation of fatigue accumulation based on stress histories using classic methods of damage calculation on the basis of the Palmgren-Miner rule.

Key words: Fatigue Monitoring, Wind energy plants, Load-time histories. Fatigue lifetime management.

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Procedia Engineering (2015) 1877-7058

Procedia Engineering

6th Fatigue Design Conference, Fatigue Design 2015

COMPLEX LOADING S01-2
THURSDAY 19 NOVEMBER

FD15-020

FATIGUE OF CLIP CONNECTORS FOR OFFSHORE DRILLING RISERS UNDER THE COMBINED INFLUENCE OF A HIGH MEAN STRESS AND BIAXIAL TENSION

VIDIT GAUR[1,2], VERONIQUE DOQUET[1], EMMANUEL PERSENT[2], ELEONORE ROGUET[2]

[1]ECOLE POLYTECHNIQUE, PALAISEAU, ÎLE-DE-FRANCE, FRANCE,
[2]INSTITUT FRANÇAIS DU PETROLE ENERGIES NOUVELLES, RUEIL-MALMAISON, ÎLE-DE-FRANCE, FRANCE

The clip connectors used to join the riser tubes for deep offshore oil drilling undergo cyclic loading due to sea waves. About 90% of the service life is spent in the “connected mode” (riser tubes in tension, fixed at top and bottom) which implies a moderate amplitude but a high mean stress (R = 0.7), while 10% of the service life is spent in the “disconnected mode” (riser tubes hanging from the top platform) characterized by a larger amplitude but a lower mean stress (R = 0.2). Finite element computations have been performed using elastic-plastic constitutive equations identified from push-pull tests on the F22 steel which constitutes the clip connectors. It shows that in-phase biaxial tension prevails in the critical area of the structure.

Both the mean stress effect and the biaxiality effect need thus to be addressed for a proper design of these structures. However, most of the multiaxial fatigue criteria proposed in the literature were based on combined tension and torsion fatigue data and do not discriminate well the influence of biaxial tension from that of a mean stress. The purpose of this study is thus to investigate separately those two effects and to model both effects in a suitable fatigue criterion.

To investigate mean stress effects, stress-controlled uniaxial fatigue tests were run on cylindrical specimens of F22 steel at different R ratios (0.6, 0.25, 0, -0.5, -1) for 105 to 3.106 cycles. The fatigue lives as well as the slope of the S-N curves sharply decreased with increasing mean stress.

The Gerber parabola is found to capture the evolution of the endurance limit with the mean stress, while Walker's model gives good results for finite life. While only surface crack initiation- followed by crystallographic or intergranular growth and frequent deflections at grain or laths boundaries- is observed for fully-reversed loading, positive R ratios are found to promote internal crack initiation from defects creating “fish-eye” patterns at fatigue lives as low as 3.105 cycles. These defects are pores or chemically inhomogeneous areas, rich in oxygen and carbon that get de-bonded from the matrix. The reason why a high mean stress promoted such initiation mechanism will be discussed.

To investigate the positive biaxiality effect, stress-controlled in-phase tension and internal pressure tests are in progress on tubular specimens using a tri-axial testing machine.

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COMPLEX LOADING S01-2
THURSDAY 19 NOVEMBER

FD15-101

FATIGUE LIFE ASSESSMENT UNDER MULTIAXIAL COMPLEX LOADING

YVES NADOT, DAMIEN HALM

PPRIME/ENSMA, FUTUROSCOPE, FRANCE

This paper aims at comparing two different modeling to assess the fatigue life of steel under complex multiaxial fatigue spectrum. The first model is based on a multiaxial fatigue criterion able to describe out of phase loading plus non linear damage rule. The second one is based on an incremental mesoscale plasticity/damage modeling applied directly on the spectrum studied. Experimental results on a 1045 steel are obtained under tension/torsion loading for the out of phase + variable loading representative of automotive suspension loading type (Fig. 1).

It is shown that the criterion + non linear damage rule is able to describe the experimental result but the identification of the non linearity of the damage is a function of the spectrum. The incremental approach gives better results without any identification of the non linearity of the damage but computation time if very long.

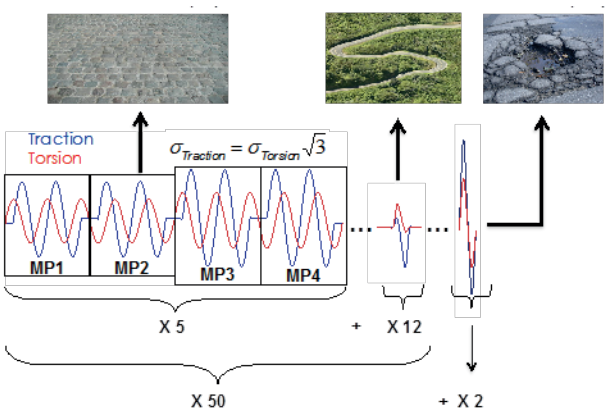

Figure 1: out of phase and variable fatigue spectrum

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COMPLEX LOADING S01-2
THURSDAY 19 NOVEMBER

FD15-093

EFFECT OF STATIC AND INTERMITTENT SHEAR STRESS ON THE FATIGUE STRENGTH OF NOTCHED COMPONENTS UNDER COMBINED ROTATING BENDING AND TORSION.

MOHAMED BENNEBACH[1], *THIERRY PALIN-LUC*[2]

[1]*CETIM, SENLIS, FRANCE,* [2]*ARTS ET MÉTIERS, BORDEAUX, FRANCE*

In power transmission machinery or crane industries, shafts are designed using specific standards; that may not correctly cover the large panel of materials and loadings involved in these sectors, making it necessary to use safety factors leading to over-conservative life predictions and non-optimized designs.

Shafts are key components, usually experiencing alternated normal stresses combined with static and fluctuating (intermittent) shear stresses.

In high cycle multiaxial fatigue, it is admitted that mean shear stress has no significant effect on the fatigue strength of smooth specimens if the maximum shear stress does not exceed ~80% of the material yield limit. Under combined rotating bending and torsion the situation is unclear, especially in presence of notches.

In this paper the effect of a static and intermittent shear stress on the fatigue strength of two steel grades, 30NiCrMo8 and 42CrMo4, is studied on notched specimens with bending stress concentration factors K_t=2 and K_t=3. It is shown that mean shear stress has little effect on the rotating bending endurance limit, the maximum decrease is about 5%, whereas this decrease is more pronounced for intermittent shear (varying in blocks), reaching up to 30% for the sharpest notch.

Results of several fatigue models are discussed with regard to the cyclic plastic strains at the notch tip (calculated by FEM).

S02 - Composite and elastomers

Chairmen:

A. Fatemi, L. Juras

L. Gornet, N. Leray

S. Castagnet, C. Peyrac

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COMPOSITE AND ELASTOMERS S02-1
WEDNESDAY 18 NOVEMBER

FD15-102

FATIGUE LIFE ASSESSMENT OF THERMOPLASTICS (WITH AND WITHOUT REINFORCEMENT)

SYLVIE CASTAGNET, CAROLE NADOT-MARTIN, SONG THAN THAO NGUYEN

DEPARTMENT OF MECHANICS AND PHYSICS OF MATERIALS - PPRIME INSTITUTE,
FUTUROSCOPE-CHASSENEUIL CEDEX, FRANCE

The automotive industry needs to reduce the weight of vehicles for environmental and economic purposes. To this aim, short-fiber reinforced thermoplastics are used for the design of mechanical structures. In this paper, a specific methodology for multiaxial fatigue life assessment of injection-molded components (called ‘Through Process Modelling’ (TPM)) is proposed. It takes into account the variable fiber orientation due to the injection process in the estimate of local mechanical fields from which the input equivalent quantity required by a fatigue criterion is computed.

Results obtained at room temperature for standard and injection-molded notched samples are successfully compared to a large experimental multiaxial fatigue data base involving three materials and established through collaborations with LBF laboratory (Germany) and Polytechnic Institute of Milan (Italy). Then, the application of the TPM to an industrial component is discussed. At last, ameliorations to increase the performance of the TPM at room temperature and to extend it to higher temperatures are discussed.

The second part concerns pure thermoplastics. In this case, even at room temperature, the employment of fatigue criteria raise the question of the stabilization of the cycle over which the mechanical parameters should be computed. The challenge is not only to predict the ratcheting strain but also the stabilized loop itself (or approximation of it) and the relevant energetic contributions, within a formalism as simple as possible to be used for structure simulations.

The study is conducted in polyethylene, with a special interest paid on the viscoelastic contribution. A challenge is to accurately capture the long term scale of strain ratcheting and the short term scale of the cycle itself. Cyclic accommodation is experimentally investigated over the first thousand cycles of force-controlled tests at room temperature. After establishing from recovery tests that viscoelasticity mainly contributes to the ratcheting strain, a small-strain non-linear viscoelastic model is proposed in the framework of Thermodynamics of Irreversible Processes. The aim is to capture the ratcheting strain evolution and recovery kinetics, as well as the stabilized loop area and dynamic modulus.

Volume / deviatoric contribution is an open issue, because of their different contribution to thermoelastic coupling. Thermo-mechanical coupling is then examined. Tensile and shear cyclic tests are performed in collaboration with LMGC laboratory (Montpellier, France). A fully coupled thermo-viscoelastic model is implemented in Abaqus® software to compute cyclic response of tensile and shear specimens, including heat exchanges. Results are compared with the time evolution of deformation, temperature and heat sources fields experimentally obtained at the cycle scale and during cycling.

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Procedia Engineering

6th Fatigue Design Conference, Fatigue Design 2015

COMPOSITE AND ELASTOMERS S02-1
WEDNESDAY 18 NOVEMBER

FD15-054

FIBER REINFORCED PLASTIC DURABILITY: MEAN STRESS SENSITIVE MULTI-SCALE MODELING FOR STRUCTURAL PART LIFE PREDICTIONS

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The last 50 years saw the development of mechanical simulation thanks to the growth of computers. This development was originally boosted by the industrial production of metal parts. It yielded technologies subsequently applied to new materials such as fiber reinforced plastics with uneven success and consecutive suboptimal designs. Indeed, such materials exhibit much different properties than metals. In particular, their nonlinearity and anisotropy are not straightforward to take into account in simulations. Moreover their properties vary through space (within a given part) and time depending on the manufacturing process and the operating environment. This variability is actually driven by the material microstructure i.e., the amount, shape and orientation adopted by the fibers at the core of the composite. Hence the name of the game in composite material modeling – and the strategy applied by e-Xstream engineering since 11 years – consists in enriching simulations with such microstructural information. This multi-scale modeling strategy will be addressed in this paper, focusing on fiber reinforced plastic durability.

Multi-scale modeling enables accurate structural part life predictions from a limited amount of experimental data. On the one hand, it yields stresses depending on local fiber orientation, required as first input for a structural fatigue analysis. On the other hand, it provides S-N curves for local microstructure, load ratio and multiaxial stress state, necessary as second input for the fatigue analysis. Hence, its combination with local fiber orientations from injection molding simulation constitutes a fully coupled approach to lifetime estimation.

The two dependencies on microstructure, embedded in so-called material models, are calibrated on specimen measurements in few directions with respect to the injection direction, routinely performed by Solvay as long as PA66 is concerned. They are subsequently available for structural part life predictions, e.g., for a beam demonstrator employed at Solvay or an engine mount, an automotive part undergoing demanding under-the-hood environmental conditions. Hence they drive reductions in prototyping and design costs related to the structural durability of a component, one of the most expensive attributes to test.

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6th Fatigue Design Conference, Fatigue Design 2015

COMPOSITE AND ELASTOMERS S02-1
WEDNESDAY 18 NOVEMBER

FD15-112

EDGE EFFECTS AND FATIGUE DELAMINATION OF COMPOSITE LAMINATES AND BONDED ASSEMBLIES

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Scale up wind turbine blades to catch more energy is a challenge of the offshore wind turbine market, and lengthening blades is permitted by lightening them using more efficient materials or improving the design. For these reasons, composite materials are widely used in wind turbine blades because of their density and capacity to sustain fatigue. However, the use of composite regarding fatigue, which mainly drives blade design, raises the question of the accuracy of the laws used to compute fatigue life.

Today, these laws are based on Goodman and Miner formulation on the laminate which leads to the following limitations: lack of precision corrected by high safety factors, long testing campaigns, no physical description of the damage state in composite and no taking into account the loading history.

Regarding these limitations, working at the ply scale with a fatigue damage model seams promising. However, we wonder if such models are accurate enough to predict fatigue life of the blade. Indeed, unidirectional plies are used in wind turbine blades. Their on-axis behaviour is well known but they are very sensitive to multiaxial loading which leads to early damage propagation.

To answer this question of law accuracy to compute fatigue life in composite wind turbine blade, multiaxial stress state has been calculated in fatigue in an existing blade by finite element analysis, damage has been observed under critical multiaxial stress states and predictions of existing ply-to-laminate fatigue damage models have been compared under this realistic stress state.

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COMPOSITE AND ELASTOMERS S02-2
WEDNESDAY 18 NOVEMBER

FD15-079

INNOVATIONS IN TESTING MATERIAL APPLIED TO ELASTOMER CRACK PROPAGATION AND LIGHT COMPOSITE VIBRATIONAL FATIGUE.

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Means of experimentation are developed first for a specific application and are then implemented on products such as dynamic testing machines and fatigue tests rigs. Two examples illustrates this way of introducing innovative development.

First, in order to characterize elastomers resistance to tearing, a new methodology was defined and tested on fatigue test machine for crack propagation analysis. This functionality was then implemented on series products.

Second, a fatigue test machine was modified in order to characterize vibration fatigue of light composite structure at high temperature without any added mass or rigidity. Fatigue test was achieved by exciting a test beam at natural frequency with constant maximal strain.

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Procedia Engineering (2015) 1877-7058

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COMPOSITE AND ELASTOMERS S02-2
WEDNESDAY 18 NOVEMBER

FD15-086

SELF-HEATING METHOD FOR FATIGUE LIMIT DETERMINATION ON THERMOPLASTIC COMPOSITES

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To achieve weight reduction of structures, composite materials are used extensively in different industrial applications as aerospace and automotive, for example. Their high mechanical performances and good fatigue durability offer advantages compared to more traditional materials. To be able to design composite parts, it is necessary to characterize their fatigue behavior and more precisely to evaluate fatigue limit. All fatigue tests generally used for this determination take long time and are potentially very costly.

In this paper we propose to apply on thermoplastic composites, the self-heating method, which has been developed and validated initially on carbon/epoxy composite materials.

The material under consideration is a woven made of carbon fibers and PA66 matrix. Mechanical static and fatigue tests are conducted on two stacking sequences ([0°] and [+/-45°]). The results show that during self-heating tests at room temperature, the mechanisms leading to the increase in temperature are different compared with those observed in thermoset matrix composite systems. This means that a new analysis of the results must be developed to obtain the limit of fatigue. The fatigue limit obtained with this method, is successfully compared with results from classical SN curves.

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Procedia Engineering (2015) 1877-7058

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COMPOSITE AND ELASTOMERS S02-2
WEDNESDAY 18 NOVEMBER

FD15-065

COMPARISON BETWEEN THREE FATIGUE DAMAGE MODELS AND EXPERIMENTAL RESULTS FOR COMPOSITE MATERIALS SUBMITTED TO SPECTRUM LOADING

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The theme that we have treated here is about phenomenon of random fatigue of composite structures. The failure mode on which we focused in our work is that of inter-laminar fracture delamination. Next to experimental results, we have presented three models for predicting damage of structures in order to compare them to test results. The effect of the standard deviation of the predictions of the life of composites is also highlighted in the last part of the paper.

Thanks to their excellent fatigue resistance and low weight ratio, today; composite materials are of great importance in humanity life, either in civil or military fields such as aerospace, automotive, marine … and as is usual, each material reaches failure towards the end of his life which is manifested by the occurrence of fractures. Until now, researchers put their efforts into service in order to achieve accurate and general models for predicting damage of this mysterious material. On our side, we compared three fatigue damage models in order to see the most accurate and consistent with our experimental results. Throughout the work, we adopted a stationary ergodic Gaussian random loading.

First, we conducted a thorough study of the interlaminar fracture of composite laminates subjected to stochastic loads. The choice of this failure mode was inspired by the fact that this failure mode is most predominant among others; moreover, it is more dangerous because it's invisible and undetectable and occurs suddenly between the layers of material. The results of the experiments carried out with graphite epoxy composite laminates [± 45/0/90]3s, were compared to the predictions of three models namely:

- Linear damage model based on the law of Miner,
- Damage mathematical expectancy E (t),
- Stiffness degradation model,

Second time, following an analysis of the results, we found that the three models mentioned above are close to the experimental results. We see that the correlation is the best for the stiffness degradation model. On the other hand, the effects of load sequence and interaction are not taken into account in linear damage model, which can lead to some difference between the model predictions and experimental results.

Finally, we had to study the effect of standard deviation on the life of composite laminates. For this we calculated the lifetime for various values of sigma and various average amplitudes of the applied load. Interpolating the data obtained led us to an equation linking lifetime of structures to standard deviation.

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COMPOSITE AND ELASTOMERS S02-2
WEDNESDAY 18 NOVEMBER

FD15-095

FATIGUE BEHAVIOUR OF A THERMOPLASTIC COMPOSITE REINFORCED WITH WOVEN GLASS FIBRES FOR AUTOMOTIVE APPLICATION

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This work is the result of the cooperation between the DPMM laboratory (PPrime Institute) and the vehicles manufacturer Renault. This project aims to develop lightening solutions for cars using composite materials. Thus, the purpose of this study is to characterise the behaviour of a woven glass-fibre-reinforced composite with a thermoplastic matrix during a low-cycle fatigue test.

Optimization of the coupons geometry has been done in order to obtain a valid failure during fatigue tests. Thus, three different geometries have been investigated: rectangular (ASTM D3479), dumbbell and dogbone (as proposed by De Baere et al. [Pol. Test. 2011]). It is worth mentioning that for the three geometries, the gauge section is the same (equal to 20mm). The use of IR camera has allowed following the evolution of temperature cartography during fatigue tests and so, the location of stress concentration leading to the specimen failure. For rectangular specimen, the stress concentration is systematically located near the grip.

For dumbbell specimen, it is located in the fillets whereas the failure occurs in the center of the specimen for dogbone coupons. So, dogbone specimen has been chosen as the optimised geometry. Once the appropriate specimen geometry has been chosen, instrumented fatigue tests have been carried out at room temperature on 0° coupons (warp bundle in the same orientation as the loading direction). During these tests, damage mechanisms have been analysed.

Damage identification has been carried out using several methods such as acoustic emission, thermography and microscopic observations (optical microscopy, SEM, X-Ray microtomography). Acoustic emission associated to microscopic observations allowed identifying different types of damage occurring in fatigue within the material: fibre-matrix interface debonding, longitudinal fibre failures and meta-delamination. The next step of this project is to analyze the influence of fibre orientation and moisture on fatigue life. Three different orientations (0°, 90° and 45°) and three conditioning types (RH0, RH50 and RH100) will be studied.

In parallel, these tests were used for the evaluation of two different fatigue life models: a hybrid model based on the power and the exponential models proposed by Sarfaraz et al. [Comp. A. 2012], and the Epaarachchi et al. model [Comp. A. 2003] already validated in other studies [De Vasconcellos et al., Comp. B. 2014]. These models have shown good fitting to experimental data. Work is in progress to evaluate the ability of these models to predict fatigue life for this type of composites under different conditions.

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Procedia Engineering (2015) 1877-7058

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COMPOSITE AND ELASTOMERS S02-3
THURSDAY 19 NOVEMBER

FD15-110

INFLUENCE OF FIBER ORIENTATION AND MULTIAXIALITY ON THE FATIGUE STRENGTH OF UNNOTCHED SPECIMENS – LIFETIME ESTIMATION

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In components for the automotive industry, short-glass fiber reinforced thermoplastic parts are increasingly used due to their potential for economical lightweight constructions, for example, by substitution of metal components. In order to guarantee the reliability of these components, fatigue-lifetime assessment concepts are needed. The multiaxial loading and fiber orientations are important factors which effect fatigue life. Therefore, different multiaxiality criteria, together with a new concept capturing the influence of fiber orientation on fatigue strength are proposed. The fiber orientation is a result of the injection molding process that leads to local anisotropic behavior, which gives rise to multiaxial stress states.

Anisotropic material behavior is modeled by a simulation chain consisting of first, injection molding simulations, secondly, mapping and homogenization and finally, finite element analysis (FEA). In order to demonstrate the benefit of this simulation chain, the results of an isotropic FEA are compared with the anisotropic case. Finally, a combined multiaxiality fiber orientation concept is presented and applied to fatigue experiments on unnotched specimens of polyamide 6.6 reinforced with 35wt.% short glass fibers.

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Procedia Engineering (2015) 1877-7058

Procedia Engineering

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COMPOSITE AND ELASTOMERS S02-3
THURSDAY 19 NOVEMBER

FD15-064

EFFECT OF ANTIOXIDANTS ON THE FATIGUE CRACK GROWTH BEHAVIOR OF FILLED SBR COMPOUNDS

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Fatigue crack growth tests consist in measuring the propagation rate of a pre-existing flaw inserted into a sample, in opposition to the crack nucleation approach often studied. Nowadays, they are of most importance in rubber industry to improve, but also estimate, the service life of elastomeric products, such as tires or antivibration components. Such tests are performed at the LRCCP on a DMA+300 fatigue machine developed by METRAVIB, on “pure shear” samples, a classical geometry to study fatigue crack propagation in the literature.

The purpose of this work is thus to evaluate the influence of various experimental parameters on the measured crack growth behaviour but mainly the effect of the addition of antioxidants to the material formulation. Indeed, the comparison of fatigue crack growth rates measured on different SBR samples, with various amounts of 6PPD (which acts as an antioxidant), before and after a thermal ageing, helps finally to determine how the fatigue crack growth behaviour is affected by this kind of chemical compound.

Finally, we should expect from those results a better understanding of the fatigue behavior of dynamically loaded parts such as tires, subjected to self-heating, and consequently to thermal ageing.

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Procedia Engineering (2015) 1877-7058

Procedia Engineering

6th Fatigue Design Conference, Fatigue Design 2015

COMPOSITE AND ELASTOMERS S02-3
THURSDAY 19 NOVEMBER

FD15-104

FRACTOGRAPHY, A POWERFUL TOOL FOR IDENTIFYING AND UNDERSTANDING FATIGUE IN COMPOSITE MATERIALS

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Fractography is a tool widely used in the academic world but a little-known technique in the industrial world. This tool can be useful at most stages of the development of composite parts: prototyping characterization, industrialization, production quality problems,... Finally when a composite part is broken during service, fractographic analysis is one of the most efficient tools for the determination of the root causes of failure. Fractography is useful for the engineer who has to determine if the failure results of a mechanical overload or of a fatigue phenomenon.

The implementation of a fractographic investigation requires to follow a methodology with different steps:

The first step is to determine the direction of propagation in the different zones of the rupture by recognition of features on the broken surface. From these results, the initiation area can often be identified. Then a long part of the work consists in seeking features of static or fatigue damage. Fractography also allows to determine what type of mechanical loading has caused the micro-damage in the initiation area. This information can be compared with the expected loading.

Sometimes, the fatigue fractographic features are localized just along manufacturing defects. In this case, a specific study is required to establish the harmfulness of these defects. The defect acceptance criteria after manufacturing are then sometimes amended.

Article will discuss these aspects through industrial examples.

S03 - Contact fatigue

Chairmen:

S. Fouvry, Y. Chen

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Procedia Engineering (2015) 1877-7058

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CONTACT FATIGUE S03
THURSDAY 19 NOVEMBER

FD15-096

PREDICTION OF PARTIAL SLIP FRETTING CRACKING USING OF A SIMPLE *CONTACT SHEAR - SLIDING SIZE* PARAMETER

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Fretting fatigue is a critical loading that appears on many structures such as the blade/disk contact of aircraft engines, wheel assemblies of train, etc ... The prediction of the crack nucleation risk is essential for safety aspects but particularly complex to achieve. Indeed the contact stresses are multiaxial and characterized by severe stress gradients. To solve such difficulty a common approach consists in computing the multiaxial fatigue analysis at a critical distance thus to correct the stress gradient effect and to achieve stable and pertinent predictions [1]. However this strategy is very expensive in FEM computations according that very fine FEM mesh size, sometime below 10 µm, need to be applied limiting its application for large 3D industrial contacts. Investigating the partial slip fretting crack nucleation boundaries of a 35NCD16 steel (plane) fretted against 52100 steel cylinders, a new semi-empirical contact loading parameter, defined as the product of the maximum shear stress generated in the interface (q_{max}) multiplied by the square-root value of the sliding size (s) of the partial slip interface (i.e. $\Phi = q_{max} \times\sqrt{s}$) is introduced (Fig. 1). Using this very simple parameter we found that all the crack nucleation data obtained for a large spectrum of contact pressures and cylinder radius, are aligned along a single vertical master curve displaying a very low dispersion even smaller than the expensive "fatigue-critical distance method". Analytical analysis of contact stresses demonstrated that the cyclic strain energy imputed in the partial slip region is function of the Φ variable which indirectly justifies the application of this basic parameter.

[1] R. Ferre, S. Fouvry, B. Berthel, J.-A. Ruiz-Sabariego "Stress gradient effect on the crack nucleation process of a Ti–6Al–4V titanium alloy under fretting loading: Comparison between non-local", International Journal of Fatigue 54 (2013) 56–67.

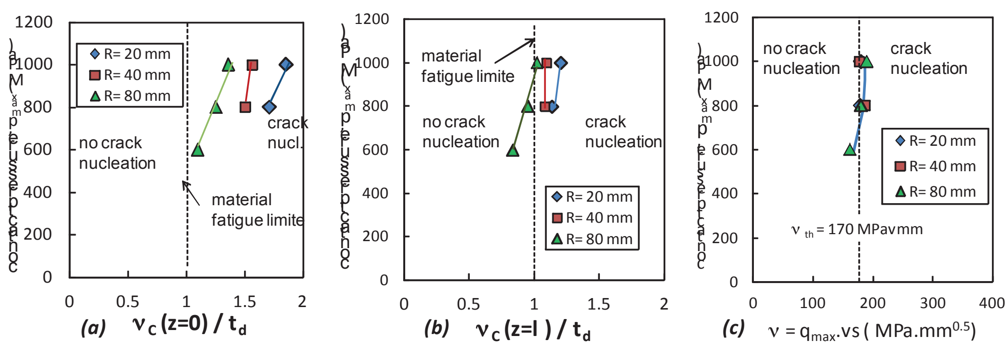

Fig. 1: Fretting crack nucleation (10µm) of the 35NCD16(plane)/52100(cylinder) contact as a function of the contact pressure for different cylinder radius : (a) Crack analysis using the hot spot Crossland's stress value (x= -a, z= 0); (b) Crack analysis using the Crossland's stress defined at the optimal critical distance (x= -a, z= □=11µm); (c) Crack analysis using the proposed *contact shear- sliding size* parameter (a: Hertzian contact radius; q_{max} :maximum surface shear in the fretted interface; s: radius of the sliding zone in the partial slip interface; τ_d= 386 MPa shear fatigue limit of the studied 35NCD16 steel).

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Procedia Engineering (2015) 1877-7058

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CONTACT FATIGUE S03
THURSDAY 19 NOVEMBER

FD15-108

A NEW EXPERIMENTAL APPROACH TO TEST OPEN GEARS FOR WINCH DRUMS

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In several applications like hoisting equipment, cranes, open gears are used to transmit power at rather low speeds (tangential velocity < 1m/s) with lubrication by grease. In consequence those applications have particularities in term of lubricating conditions and friction involved, pairing of material between pinion and gear wheel, lubricant supply, loading cycles and behaviour of materials with significant contact pressure due to lower number of cycles.

The comparison of proofed old rating methods (HENRIOT….) with ISO 6336 has shown that ISO is very conservative for through hardened steels gear wheels running with case hardened pinion specifically in the range of limited life.

This has emphasis the need to develop experimental tests, in representative conditions. In order to assess new values of allowable contact-pressure stress numbers, the authors present the concept and the realization of a new test bench in order to satisfy those requirements with the associated procedures of calibration and testing.

Analysis of experimental results and metallurgical analysis of cold working of tooth flanks are given. Fatigue result test are then compared to ISO and AGMA gear ratting method predictions.

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Procedia Engineering (2015) 1877-7058

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CONTACT FATIGUE S03
THURSDAY 19 NOVEMBER

FD15-082

EXPERIMENTAL CHARACTERIZATION OF THE MULTIDIRECTIONAL GRADIENT OF MICROSTRUCTURE PRODUCED BY ROLLING CONTACT FATIGUE BELOW THE RUNNING BAND OF WORN RAILS

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In modern railway networks, rolling contact fatigue (RCF) of rail steels is recognized as an increasing issue, which can lead to the spalling of the rail surface layer or even to the brutal rail failure. In any case, there are currently only preventive solutions such as rail grinding or renewal; consequently, it increases maintenance costs. It is established that RCF damage is caused by the rolling-sliding action of the wheel on the surface of the rail. Due to the heavy and cyclic contact loading, the microstructure undergoes severe plastic deformation which has been shown to be a major factor leading to RCF crack initiation.

The aim of this study is to increase understanding of the relationship between RCF cracking and plastic deformation of the pearlitic microstructure. Following a multi-technical and multi-scale characterization of the worn rail surface, the multidirectional gradient of mechanical properties below the running band is studied with a microstructural point of view. In order to achieve the characterization of the running band and to quantify the influence of the microstructural/mechanical gradient on the global fatigue behaviour, this experimental methodology has been based on the combination of several microstructural investigations by optical and scanning electron microscopy (FEG-SEM) in both rolling and transverse directions, microindentation performed on the gradient profile and determination of quantitative data on the pearlitic aggregates through the gradient by Electron backscatter Diffraction (EBSD).

Due to the severe plastic deformation, material experiences progressively work hardening and the pearlitic microstructure is modified. In the middle of the running band where the contact patch envelope is more frequent, the pearlitic colonies below the worn rail surface are fractured by accumulation of cyclic and severe shear strain. The resulting lamellar structure of ferrite and cementite is elongated and aligned in the direction of shear strain as the interlamellar spacing decreases. On the contrary, at both sides of the running band where the contact with wheel is rare, the surface is rougher, the pearlitic colonies remain unaffected and the lamellae are not oriented preferentially.

The understanding of the running band microstructure and the material's gradient characterization will contribute to improve the modelling of rail failure by RCF by enabling to include microstructural data.

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Procedia Engineering (2015) 1877-7058

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CONTACT FATIGUE S03
THURSDAY 19 NOVEMBER

FD15-094

HEAT SOURCES ESTIMATION AND CRACK NUCLEATION CONDITIONS IDENTIFICATION DURING A FRETTING TEST BASED ON INFRARED IMAGE PROCESSING.

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Fretting damage has been recognized as a problem in several industrial applications for years now. Fretting is a small amplitude oscillatory movement, which may occur between contact surfaces subjected to vibration or cyclic stress. In the case of partial slip regime the contact surface is split into sticking and two sliding areas. The main damage process during this regime is crack nucleation. Determination of crack nucleation conditions requires time-consuming and expensive destructive methods giving dispersive results. In this work, fretting phenomena were studied using a calorimetric approach; the goal was to determine the different heat sources accompanying the fatigue test and to develop non-destructive experimental method, based on the dissipative field, to determine crack nucleation threshold during a fretting test under partial slip conditions.

The present work was performed on a 35NiCrMo 6 low-alloyed steel, in a cylinder on flat contact configuration assuring a 2D contact configuration. An experimental set-up based on coupled kinematic-thermal measurements to assess fretting damage was used. First, infrared thermography provides thermal images which are used to separately estimate the heat sources. Secondly, speckle image correlation techniques, involving a digital CCD camera, were used to assess surface displacement fields. These kinematic fields enabled us to suppress deformations and rigid body movements on the IR images and therefore build temperature maps.

Heat sources accompanying the fretting mechanisms have at least two possible origins. On the one hand, the thermoelasticity gives coupling sources related to the thermal expansion. On the other, the irreversibility that accompanies the microstructure evolution is translated by a dissipated heat that warms the sample. Therefore, we developed an appropriate image processing method to estimate separately fields of mean dissipation per cycle d_1 and fields of thermoelastic source amplitude s_{the} (cf. Figure 1 (a)). Finally, we develop a method to determine the crack risk domain under fretting loading by detecting earlier micro-plastic phenomena through the analyze of the dissipative field (cf. Figure 1 (b)).

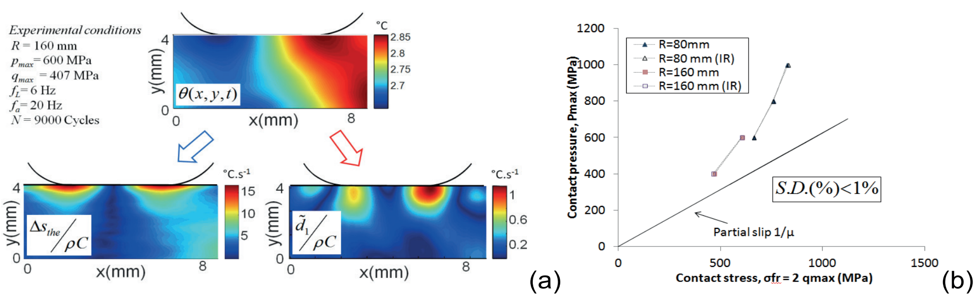

Figure 1: (a) pattern of heat sources estimated during a fretting test; (b) comparison between crack thresholds obtained by destructive and analyze of the dissipative field.

We can observe that both heat sources are: (i) in good agreement with supposed stress field (s_{the}) and damage localization (d_1); (ii) not in the same order of magnitude ($s_{the} >> d_1$). Finally a close correlation is found between crack thresholds obtained by a destructive method and the method based on dissipative fields.

S04 - Damage tolerance and fatigue life

Chairmen:

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Procedia Engineering (2015) 1877-7058

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6th Fatigue Design Conference, Fatigue Design 2015

DAMAGE TOLERANCE AND FATIGUE LIFE S04-1
WEDNESDAY 18 NOVEMBER

FD15-100

FATIGUE LIFE ASSESSMENT OF CAST AL STRUCTURAL COMPONENT

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The evaluation of fatigue life of cast components needs the knowledge of several parameters to be accurate. Fatigue data have been obtained from structural tests on real components submitted to constant amplitude loading. The location of the failure is identified and a fatigue criterion methodology is used to simulate the fatigue life of the component. The following parameters need to be taken into account for an accurate simulation of the fatigue life:

- Measurement of local deformation to validate the FE model of the component.
- Verification of the microstructure (including defect size) in the initiation area.
- Evaluation of the influence of the stress gradient.
- Evaluation of surface residual stresses.

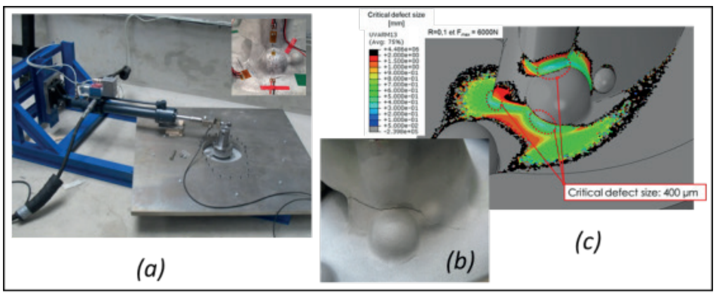

Figure 1: fatigue test on structural components

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Procedia Engineering (2015) 1877-7058

Procedia Engineering

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DAMAGE TOLERANCE AND FATIGUE LIFE S04-1
WEDNESDAY 18 NOVEMBER

FD15-084

COMPARATIVE FATIGUE RESISTANCE OF OVERHEAD CONDUCTORS MADE OF ALUMINIUM AND ALUMINIUM ALLOY: TESTS AND ANALYSIS

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COSME ROBERTO MOREIRA DA SILVA, MAURICIO JESUS GONZALEZ

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The aim of this work was to carry out a comparative analysis on the fatigue performance of Aluminium Conductor Steel Reinforced (ACSR), whose wires in the external layers are made of Al 1350-H19 (considered as pure aluminium), and of a All Alloy Aluminium Cable (AAAC), whose wires are made of Al6201-T81. An special fretting fatigue bench, 47 m length, of the resonant type, was designed and mounted to conduct this test program. S-N curves were constructed for the ACSR and AAAC. Although the Al6201 alloy presented significantly static material properties (yield limit, fatigue strength, hardness) than the Al 1350, the fatigue tests of these conductors revealed that, under a same level of nominal stress the AAAC lasted up to 85% less than the ACSR. In stress terms, the ACSR could sustain stress levels 1.25 times larger than the AAAC for a same life.

This is somehow surprisingly considering that the fatigue resistance for metals usually scales up with their static strength. The authors concluded in their analysis that that the inversion in the fatigue performance of these Al alloys, which occurs when they are mounted in a cable configuration, may well be associated with the higher sensitivity of the Al6201 to the mechanical contact between its wires, which generates stress concentration and stress gradient.

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Procedia Engineering (2015) 1877-7058

6th Fatigue Design Conference, Fatigue Design 2015

DAMAGE TOLERANCE AND FATIGUE LIFE S04-1
WEDNESDAY 18 NOVEMBER

FD15-022

ROTOR DESIGN OPTIMISATION THROUGH LOW FATIGUE TESTING

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In order to fulfil new CO2 emission laws for cars, Valeo develops new electrical machine like starter-alternator. They are subjected to new profile damage and their electrotechnical performance needs to be improved. Nowadays component design is mostly modelled by finite element method that takes into account several properties defined by the designer. Indeed, the sizing of the rotor results from the best compromise between eletrotechnical performance of the machine and mechanical properties of the material. This rotor is made of a stack of Fe-3Si steel sheets having a thickness of 350µm.

Up to know, the mechanical limit of the rotor is set equal to the fatigue endurance of the material. Therefore, no plastification of the material is accepted. But today, to improve electrotechnical results, several zones of the rotor need to be refined. This is only possible if plastic straining is allowed in these zones. Therefore, it is proposed to use the Chaboche model for the design of the rotor and to set a new mechanical limit. Indeed, this model takes into account the plastic deformation induced by fatigue.

In low cycle fatigue, cycling of the material may be either beneficial or detrimental in terms of stress response to cyclic strain, depending on the material (influence of the chemical composition, grain size, heat treatment…). Therefore, experimental low cycle fatigue tests were made on the thin steel sheets taking into account the influence of the signal mode. From the experiments, material parameters for Chaboche model are extracted and damage mechanisms of the material are investigated.

The model is first validated on smooth samples loaded under strain control. It is secondly validated on notched samples loaded under force control. The realisation of a prototype is intended in order to valid the mechanical model in real loading conditions. Finally, an optimisation of the design of the rotor is proposed which meets both mechanical and electrotechnical requirements.

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Procedia Engineering

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DAMAGE TOLERANCE AND FATIGUE LIFE S04-2
WEDNESDAY 18 NOVEMBER

FD15-014

EXPERIMENTAL INVESTIGATION OF FATIGUE CRACK PROPAGATION IN RESIDUAL STRESS FIELDS

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This work is on the interaction of residual stresses and fatigue cracks in welded steel plates. A longitudinal deposit weld is used to create high tensile residual stresses in axial loading direction. The fatigue crack is trained to start at an artificial notch and propagates through a field of high tensile residual stresses. The fatigue crack propagation as well as the re-distribution of residual stresses are studied in detail by combined experimental methods.

The mean stress is varied as well as the residual stress state of the samples used. Samples are tested as-welded as well as stress relieved at $R=\sigma min/\sigma max=0$, $R=-1$ and $R=-3$. The materials used are a typical fine grained construction steel S355 (Re = 360 MPa) as well as a high strength quenched and tempered steel S960 ($Rp0.2$ = 960 MPa).

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DAMAGE TOLERANCE AND FATIGUE LIFE S04-2
WEDNESDAY 18 NOVEMBER

FD15-032

SELECTION AND ANALYSIS OF A DAMAGE APPROACH FOR OFFSHORE APPLICATIONS

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In almost every situation that involves fatigue, the nature of the loads to which a structure is subjected, is variable with time. These series of loading/unloading events are often defined as spectrum. In the offshore industry the main loading conditions taken into consideration in the fatigue structural design are wind, currents and waves. These factors are combined and a linear damage rule (Miner's rule) is normally used to carry out the design calculations. However this approach was reported to be (in certain situations) over or under conservative, which means that the variable amplitude (VA) loads could lead to a non-linear fatigue behaviour of the structure. There is not any specific approach which let designers describe all aspects of variable amplitude fatigue.

Because in basic design approaches adopted by the codes this factor is not considered, designers have to adapt the criteria exposed there together with a non-linear model in order to achieve an accurate description of the fatigue life. However, selection of the correct criteria (and therefore development of an accurate model) is not an easy task.

This paper has the aim of describing a series of non-linear damage models to finally selecting the most appropriate for predicting the fatigue life of a specimen subjected to offshore variable amplitude loading due to a JONSWAP spectrum. A series of fatigue tests will allow to quantify the previous selected approach. Finally, a comparison between the results from tests and from the literature aims to clarify the difference among VA fatigue histories defined as a series of blocks in comparison with a randomized spectrum.

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Procedia Engineering

6th Fatigue Design Conference, Fatigue Design 2015

DAMAGE TOLERANCE AND FATIGUE LIFE S04-2
WEDNESDAY 18 NOVEMBER

FD15-083

MAINTENANCE OF ROAD BRIDGES AND ROAD EQUIPEMENTS OPTIMIZED BY GOOD FATIGUE DESIGN

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The article will present several examples that illustrate the importance of affecting a right consideration to the fatigue question for the maintenance of a road heritage.

The eurocodes give us the possibility to design regarding the fatigue caused by the wind both sign bridges and lightning masts. If these equipements fail, the road will not be closed, but accidents may occur that will affect the transport safety. The introduction of the fatigue design rules to the sign bridges and lightning masts regarded as construction will thus increase the road safety. The article will present at least a case study.

For the Dancourt bridges, works of very innovative character were brought to a successful conclusion in order to improve the durability of the two independant bridges decks of a French motorway carrying heavy high heavy traffic since 40 years.

The structure of the bridges was recently strengthened to extend their fatigue resistance and these woks will be presented.

For bridges, the eurocodes will also be improved in the future thanks to the experience acquired with the existing constructions. The article will present two examples where the fatigue class of the detail is evaluated thanks to a FE-modelization according to the 2008 IIW Fatigue Recommendations:

- Design of the longitudinal stiffeners of steel box girder bottom flanges,

- Reevaluation of the fatigue class of butt-welded flange joints to consider the flange thickness transition zone and the local forces and stresses that occur near the welded connection to the web.

S05 - Experimental, numerical design and validation methods

Chairmen:

F. Morel, G. Thoquenne

N. Saintier, V. Chiaruttini

HT. Kang, B. Depale

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Procedia Engineering (2015) 1877-7058

Procedia Engineering

6th Fatigue Design Conference, Fatigue Design 2015

EXPERIMENTAL, NUMERICAL DESIGN & VALIDATION METHODS S05-1
WEDNESDAY 18 NOVEMBER

FD15-071

THERMAL RESPONSE OF C45 STEEL IN HIGH AND VERY HIGH CYCLE FATIGUE

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High and very high cycle fatigue regimes are rapidly reached using an ultrasonic fatigue machine working at 20 kHz. For instance, a fatigue test up to 109 cycles lasts 14 hours at 20 kHz while it lasts 100 days at 100 Hz. The heating of specimen can reach several tens of degrees at 20 kHz fatigue tests. In this work, the S-N curve and the thermal response under fatigue tests at 20 kHz were investigated on annealed C45 steel. Fatigue tests at 20 kHz demonstrate than fatigue fracture exists for number of cycles ranging from 106 to 1010 cycles. In addition, three stress amplitude domains were identifying with regard to the specimen thermal response.

These domains were correlated with fracture response. For $\Delta\sigma/2<200$ MPa, the heating was < 10°C and no fracture was observed at least up to 1010 cycles. For 200 MPa$<\Delta\sigma/2<$250 MPa, the heating reached few hundreds of degrees. Fatigue fracture took place. The crack initiated at an internal non-metallic inclusion leading to the classical fish eye observed in very high cycle fatigue. For 250 MPa$<\Delta\sigma/2$, the heating reached 800°C and a ductile fracture occurred.

This project was financially supported by the CETIM Fundation.

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Procedia Engineering (2015) 1877-7058

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EXPERIMENTAL & NUMERICAL DESIGN METHODS S05-1
WEDNESDAY 18 NOVEMBER

FD15-005

SIMULATION OF THERMAL-MECHANICAL DEFORMATION BEHAVIOUR AND LIFETIME OF A NICKEL-BASE ALLOY

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The reduction of the carbon dioxide emission due to carbon combustion in steam power plants is achieved by increase of the degrees of efficiency which are directly related to higher operating temperatures. For this purpose Nickel-base alloys with high creep, fatigue and corrosion resistance are applied. Detailed information concerning the specific material behavior at elevated temperatures is essential for the design and lifetimes under service conditions. Especially the superposition of complex thermal and mechanical loading by high temperature gradients in thick-walled components is considered as the major damaging loading condition. Generally, this thermal-mechanical fatigue behavior (TMF) is characterized by highly complex laboratory experiments.

In this paper the thermal-mechanical deformation behavior of the Nickel-base alloy Nicrofer 6025HT is calculated on the basis of a viscoplastic Chaboche-model - with respect to elastic properties, nonlinear isotropic and kinematic hardening and time-dependent material behavior [1, 2, 3]. The experimental analysis of the relevant material parameters (i.e. influences as strain rates, strain amplitudes and viscoplastic relaxation behavior) is performed by isothermal complex low-cycle fatigue testing (CLCF) at specific temperatures.

All material parameters are identified from the measured isothermal CLCF data by computational optimization using a deterministic optimization technique (Levenberg-Marquardt algorithm) [4]. Thus, the temperature dependence of each parameter is obtained. As a result isothermal and thermal-mechanical fatigue under various operating conditions can be predicted. Finally, the accuracy of the model is verified by corresponding experimental TMF testing.

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WEDNESDAY 18 NOVEMBER

FD15-073

STUDYING THE INFLUENCE OF FORMING PROCESS ON THE FATIGUE LIFE PREDICTION OF COMPLEX 304L STEEL STRUCTURE

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Primary membrane of the liquefied natural gas (LNG) carrier cargo containers is generally made of AISI 304L stainless steel. To deal with the thermal strain due to the cryogenic transport temperature of the LNG (at -163°C), corrugations are realized on the primary layer in contact of LNG. During transport phase, tankers are submitted to static and cyclic mechanical loadings, because of interactions between fluid and structure (hull bending, internal sloshing...). The aim of this study is to predict the fatigue life of such structure taking into account the effect of the forming process and using fatigue results obtained from standard specimens. The study of high cycle fatigue properties of these alloys and structures presents a crucial interest for tank designers.

Firstly, fatigue properties of the alloy have been determined on as–received and pre-hardened states, using experimental self-heating measurements associated with an energy-based fatigue criterion and a probabilistic multiscale model. Secondly, fatigue life of the formed knots has been estimated using 4-Cast numerical tool developed at Brest Laboratory of Mechanics and Systems (LBMS EA 4325).

4-Cast tool enables a post processing of finite element model results using fatigue properties obtained from standard specimens. The calculations have been realized on the final structure meshing under a mechanical loading using a Dang Van fatigue criterion. The initial non-standard state was defined after the forming process, based on the results of the material mechanical behaviour modelling previously studied. Finally, the numerical results in terms of predicted fatigue life have been compared to the experimental ones realized on the whole knots structure.

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Procedia Engineering (2015) 1877-7058

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EXPERIMENTAL & NUMERICAL DESIGN METHODS S05-2
THURSDAY 19 NOVEMBER

FD15-055

FATIGUE STRENGTH OF MARKED STEEL COMPONENTS

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Steel components have to be identifiable and traceable during the whole manufacturing chain. The choice of the identification method is not specified consistently in international rules and standards. In the European standard for the execution of steel structures EN 1090-2 it is specified that the use of durable marks may not result in producing damages and that hard stamped marks are only permitted for steel grades up to S355 and only in areas where no effect on the fatigue life is expected. In other international standards hard stamped marks are explicitly required. There are contradictions which should be resolved.

In terms of durability and liability, markings should be resistant against particular manufacturing processes such as sandblasting, hot dip galvanizing or coating. In detail these methods are scribing, hard stamping, plasma marking and needling.

Nowadays the machinery manufacturers have developed machines in which the marking process is automatically integrated in the manufacturing process of steel components so that manual layout scribing is not required anymore and components can be marked on the fly. However, the effect of the installed notch due to the marking process on the fatigue strength of the components has not been investigated yet. As a result a classification of the notched details in the European detail categories of EN 1993-1-9 is in principle not possible.

For these reasons the influence of durable marking methods on the fatigue strength of steel components needs to be clarified by experimental fatigue tests and numerical calculations which are actually performed at the Institute for Metal and Lightweight Structures of University of Duisburg-Essen. The tests should determine the influence of several identification methods on the fatigue strength of structural steel details. Within the investigations the different surface conditions unmarked, scribed, hard stamped, plasma marked and needled are researched. The experimental investigations are carried out considering three different steel plate thicknesses 15, 25 and 40 mm and two different steel grades S355J2 and S460N.

As expected the marked specimen show a decrease of the loading cycles until failure. Within this contribution the performed investigations and the results will be present.

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Procedia Engineering (2015) 1877-7058

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EXPERIMENTAL & NUMERICAL DESIGN METHODS S05-2
THURSDAY 19 NOVEMBER

FD15-072

INVESTIGATING FATIGUE FREQUENCY EFFECTS ON SINGLE PHASE DUCTILE MATERIALS

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This paper aims at a deeper understanding of frequency effects in the fatigue response. Commercially pure polycrystalline copper was investigated. Fatigue tests were conducted at 20 kHz using an ultrasonic technique and at 100 Hz using an electromagnetic fatigue device. The specimens were designed to get the same stress amplitude gradient along the specimen axis during both types of tests. Quasi-isothermal conditions were considered. The amount of slip markings at the specimen surface was estimated by the surface area covered by slip markings.

The number of cycles to failure was found much higher at 20 kHz than at 100 Hz while the amount of slip markings (for the same stress amplitude and number of cycles) was much lower. The slip markings amount increases with the number of cycles the specimen surface. This increase is much lower at high than low frequencies. The reasons for these differences are discussed.

This project was financially support by the Agence Nationale de la Recherche France ANR-09-BLAN-0025-01 - DISFAT project.

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Procedia Engineering (2015) 1877-7058

Procedia Engineering

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EXPERIMENTAL & NUMERICAL DESIGN METHODS S05-2
THURSDAY 19 NOVEMBER

FD15-103

CORRELATION CASE STUDIES ON FATIGUE TEST AND CALCULATION

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Calculations can be performed in Fatigue testing for the following reasons:

1. Preparation of a sample test,
2. The modification of an ongoing test,
3. The understanding of unexpected results.

Fatigue calculations could be (and should be) quite simple but requires a comprehensive knowledge of calculation theory and test engineering.

Material behaviour, fatigue analysis, fracture mechanics, signal processing are essential tools to deal with correlation calculations.

In a number of specific cases, an optimal correlation is obtained between experimental testing and calculations.

Authors have tried to illustrate this correlation approach between Testing and FEA (Finite Element Analysis) for the following examples:

1. Connecting rod modification of a test to obtain the right area of stress,
2. Simulation of Weld sample improvement by hammer peening,
3. Evaluation of test sample in “cascade”,
4. XFEM approach on samples.

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Procedia Engineering (2015) 1877-7058

Procedia Engineering

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EXPERIMENTAL & NUMERICAL DESIGN METHODS S05-3
THURSDAY 19 NOVEMBER

FD15-037

AN INTERACTIVE WEB-BASED TOOL FOR FATIGUE ANALYSIS AND LIFE PREDICTION

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This paper presents an interactive web-based tool for a modern fatigue analysis and life prediction methodology of smooth and notched components. Users around the globe may access it via Internet by means of multiple platforms such as desk- and laptop computers, tablets and/or smart-phones. In particular, the users with a limited fatigue background would benefit from “on-the-fly” fatigue learning experience. It makes a self-explanatory and frustration free web-based education software, which allows users to learn the fatigue fundamentals while expanding their knowledge on modern fatigue analysis methods. The tool is aimed to assist a designer in fatigue analysis and file predictions of parts subjected to constant amplitude, block loading, and variable loading histories. For variable amplitude loading a dedicated spectrum software package is provided, which is essential for a potential clean-up and/or desired modifications of a raw spectrum data.

Subsequently, a rainflow method is utilized and the corresponding hysteresis loops at the notch-root are determined and plotted. Then, the relevant interactive graphs, tables and obtained results are displayed. This web-based learning tool was created using PHP, Java and DB management.

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Procedia Engineering (2015) 1877-7058

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EXPERIMENTAL & NUMERICAL DESIGN METHODS S05-3
THURSDAY 19 NOVEMBER

FD15-012

FKM GUIDELINE : STRENGTHS, LIMITATIONS AND EXPERIMENTAL VALIDATION

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The FKM guideline for analytical strength assessment of mechanical components has gained an increasing interest for the last decade in the industry, because it describes a general procedure directly applicable in an industrial design office. It allows in particular a sound interpretation of finite element analysis, making an efficient bridge between stress results and a trustworthy safety margin.

The guideline unfortunately doesn't give any comparison to experimental results, requesting from the user a blind confidence in the procedure and in the included (indeed extensive) database.

A few experimental comparisons are presented in the following, in order to emphasize on one hand the power of the methodology, and on the other hand specific limitations which cannot be suspected at first sight.

- a cast iron sheave mounted on a tapered shaft shows the specificities of grey cast iron behaviour, which are clearly understated by the last release of EN-1561 (2011), and not completely included in the guideline. Experimental tests have shown a systematic failure at a different location from the prediction.

- mild steel laminate parts are of primary interest for an electrical machine manufacturer like Leroy Somer. Several fatigue tests have been conducted on laminate samples, as well as endurance tests on complete and representative assemblies (electric rotors subject to cyclic centrifugal loading). Whereas the detailed behavior is not well accounted for in the guideline for such a specific kind of material, especially regarding mean stress sensitivity and surface quality, the final result shows a rather good agreement with experimental results. It has been observed also that the experimental lifetimes fall approximately halfway between the prediction given by the traditional gradient method according to Stieler and the more recent material-mechanical method included in the last release (2012).

Based on these examples, a comparison with traditional multiaxial critera is eventually discussed, showing the efficiency of the FKM procedure in the product design stage.

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Procedia Engineering (2015) 1877-7058

Procedia Engineering

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EXPERIMENTAL & NUMERICAL DESIGN METHODS S05-3
THURSDAY 19 NOVEMBER

FD15-067

RESIDUAL STRESSES RELAXATION ON LOW CYCLE FATIGUE FOR NAVAL APPLICATION

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Sheet manufacturing processes can induce residual stresses in mechanical parts, especially in naval industry where welding and forming processes generate high residual stress levels which have to be considered in part design.

When parts present geometrical accidents, the stress concentration factors can generate local plasticity that can lead to a partial or complete relaxation of these residual stresses. On the other hand, residual stresses induce material hardening and modify the properties of the material which will influence the mechanisms of local plasticity. The interaction between residual stresses and local plasticity has to be studied in order to develop an accurate method for part design taking into account the effect of residual stresses on low cycle fatigue behaviour.

For this purpose, specimens were designed in order to obtain 3 configurations of initial residual stresses states: A first one without residual stresses to act as a reference specimen, a second one with tensile residual stresses and a third one with compression residual stresses.

The numerical simulations of the initial residual stress states have been realized and validated with X-Ray diffraction measurements. Each specimen has been loaded for one cycle under different loading conditions and new residual stresses measurements have been practiced showing the influence of the initial residual stress state.

S06 - Fatigue crack assessment

Chairmen:

FT. Ibanez Gutierrez, HP. Lieurade

D. Soria, I. Huther

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Procedia Engineering (2015) 1877-7058

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FATIGUE CRACK ASSESSMENT S06-1
WEDNESDAY 18 NOVEMBER

FD15-057

FATIGUE ASSESSMENT FOR IN-SERVICE COMPONENTS - A NEW PART FOR API 579-1/ASME FFS-1 2007 FITNESS-FOR-SERVICE

DAVID OSAGE

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The third edition of API 579-1/ASME FFS-1 Fitness-For-Service will include a new Part covering fatigue assessment procedures for in-service components. Fitness-For-Service (FFS) assessments are quantitative engineering evaluations that are performed to demonstrate the structural integrity of an in-service component that may contain a flaw or damage, or that may be operating under a specific condition that might cause a failure. The API 579-1/ASME FFS-1 Standard was specifically written to cover in-service pressurized equipment typically found in the refining and petrochemical industries as well as the fossil utility industry.

The new Part covering fatigue assessment will be written as a multi-tiered approach covering screening, current design code methods, and advanced methods that take into account the latest in technology. The screening and design code assessment methods will be based on an updated version of the procedures currently in the ASME B&PV Code, Section VIII, Division 2. The advanced methods will include next generation versions for the fatigue assessment of welded joints, the Master S-N Curve Method as described in WRC 523 and the Verity Fatigue Assessment Method developed by Battelle. The advanced methods will also include a new smooth-bar fatigue assessment method that incorporates a multi-axial fatigue criterion with a critical plane approach. Cycle counting methods for both welded joint and smooth-bar fatigue methods will be provided.

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Procedia Engineering (2015) 1877-7058

Procedia Engineering

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FATIGUE CRACK ASSESSMENT S06-1
WEDNESDAY 18 NOVEMBER

FD15-105

INFLUENCE OF T-STRESS ON FATIGUE CRACK GROWTH

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1. Introduction

Mechanical components of aircraft may suffer from shocks and scratches during their assembly. Under service, these structures are subjected to fatigue loading. This might lead to the initiation of micro-cracks, which will propagate, and in the worst cases, the fracture of the component might occur. Quantifying the total fatigue lifetime requires a good knowledge of mechanisms and kinetics of propagation throughout the evolution of the crack.

In the case of a crack, subjected to mode I, in the Fracture Mechanics framework, according to Irwin's plastic zone theory [1], the size of plastic zone at the crack tip will change with the presence of a not null T-stress. Especially a negative T-stress will increase this size. So, considering that crack propagation is governed by confined plasticity at the crack tip, as proposed by Laird [2] and Pelloux [3], it may affect fatigue crack growth rate. In the case of mechanically short cracks, this effect will be enhanced. Therefore, loading a long crack with a negative T-stress should mimic short fatigue crack conditions. The aim is to characterize the influence of T-stress on both long and short fatigue cracks growth and to propose a model accounting for this effect.

2. Experimental setups

Two kinds of INCO 718 DA specimens are subjected to fatigue loadings similar to the one undergone by a short fatigue crack tip. The loading is composed of periodic blocks of:

- 10 000 fatigue cycles at R = 0.1, on both axes in case of biaxial test ;
- followed by a static loading stage to take an image of the open crack ;
- marking stage by increasing the loading ratio to 0.55, exclusively on second axis if T≠0.

Crack length is determined during both tests via potential method, using a crack tracker. Forces are measured through the loading cells. Stress intensity factors are deduced from the measured crack length and reported into Paris diagrams.

Short fatigue crack: Tension-compression fatigue tests under displacement control are processed on a notched elliptic hole specimen (see figure 1a). Results are reported on figure 1b.

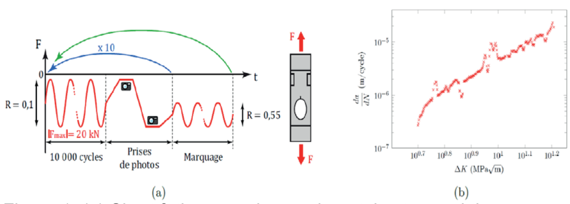

Figure 1: (a) Short fatigue crack experimental setup and the associated (b) Paris diagram

Long fatigue crack with T-stress: Biaxial fatigue displacement controlled tests are carried out on cross-shape specimen (see figure 2a), using four actuators of the triaxial tension-compression hydraulic machine ASTREE. Null T-stress and negative T-stress biaxial fatigue loadings are considered. The first corresponds to an equibiaxial mode. T-stresses can be generated by applying a compressive load in the first axis, parallel to the crack, whereas the loading applied on the second axis, perpendicular to the crack, is either tension or compression depending on the T-stress range. Two negative T-stress configurations are considered: T = □280MPa (respectively T = □180MPa) corresponding to a 100□m short crack (respectively 150□m).

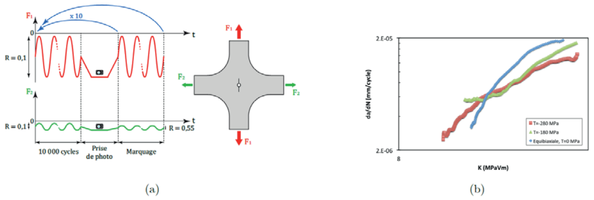

Figure 2: (a) Long fatigue crack experimental setup and the associated (b) Paris diagram, with various T-stress values (null and negatives).

3. Results and discussion

Once the results are reported in the Paris diagram (see figure 2b), it appears that in presence of a
T-stress, compared to null T-stress case, crack growth rate close to the propagation threshold is higher, whereas crack growth rate at higher stress intensity factor range becomes lower. The first result is in good agreement with the classical observations on short fatigue cracks, but the second remains unexpected. It might lead to the conclusion that the effect of T-stress on short fatigue cracks is temporary. A better analysis could be given by taking into account the ratio of stress intensity factor over the T-stress.

A model is also proposed through a modified Paris law, based on a non-propagation criterion taking account of T-stress. As the ratio between T-stress and Stress Intensity Factor increases, as it would be for a short crack, short fatigue crack regime is well simulated. However, there is no effect on the long crack regime which remains identical to Paris law.

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Procedia Engineering (2015) 1877-7058

6th Fatigue Design Conference, Fatigue Design 2015

FATIGUE CRACK ASSESSMENT S06-1
WEDNESDAY 18 NOVEMBER

FD15-114

3D CRACK PROPAGATION SIMULATIONS UNDER THERMO-ELASTO-PLASTIC FATIGUE LOADING

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The accurate prediction of crack propagation becomes increasingly necessary in a wide range of industrial applications (aeronautic, automotive industry, civil engineering, etc.). Mostly due to a better optimisation and a higher level of complexity, manufacturing requires ever more sophisticated design techniques and precise damage tolerance analysis in order to correctly evaluate lifetime assessment. On the one hand, in aircraft engines, critical parts, such as rotors, are actively investigated for cracks, using non-destructive means of detection. Such parts, if cracked, are usually replaced immediately for safety reason. However, crack detection technologies have limitations, and some very small initiated cracks might not be detected during inspections. It is thus necessary to find a way to correctly define when the next inspection should occur. On the other hand, in the automotive industry, environmental constrains lead to perform engine "downsizing" in order to increase efficiency, which produces higher temperature. Thus, cylinder head parts face severe thermo-mechanical fatigue involving generalized plasticity that can initiate cracks. If such a crack grows sufficiently to link the combustion chamber to the water circulation the performance of the engine will be highly impacted. To avoid such situation, crack initiation criteria are involved in the design process but are usually too conservative has small crack growth can eventually stop. For both such kind of situation, modelling how small cracks propagate due to fatigue loading is believed to be a solution.

Concerning the numerical process, during the last decades, many new approaches have been developed to efficiently deal with complex 3D crack growth simulations under fatigue loading. Two main families of methods have been highly investigated by the computational mechanical community: on the one hand, PUM based methods (like the famous X-FEM/Levelset method [1] with non-conform crack meshing), on the other hand method that describes the crack as evolving boundaries of the discrete domain (boundary elements based methods [2], etc.). The approach we have developed is based on an adaptive remeshing process [4], it gives us the opportunity to link our strategy to any commercial finite element solver (ie. ABAQUS or ANSYS, for now), as presented on figure 1. A few modules have been implemented, in order to deal with important stages of the process:

- a (re)meshing module which inserts or propagates crack in an existing mesh (connected to DISTENE meshing tools)
- a transfer module which re-adapt mesh depend data to the current mesh (displacements, stress, internal variables, temperature, etc. but also boundary conditions with flow, pressure, contact, etc.)

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Procedia Engineering (2015) 1877-7058

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- a finite element solver, Z-set, ANSYS or ABAQUS to compute the discrete solution of the problem over the required loading cycles
- the Z-mat module, which allows the use of a wide range of thermo-elasto-plastic models, during the FE solution (dealing for instance with the equilibrium stage after mesh transfer process)
- a post-processing module that compute stress intensity factors, energy release rate and branching criterion on the obtained discrete solution
- a module that takes into account the fatigue crack propagation law (simple Paris law or more complex user defined laws [4,5]), and computes the crack front extension.

Such an approach was successfully applied to simulate complex 3D crack path on industrial applications, like crack propagation in aircraft engine combustion chambers (see Figure 1).

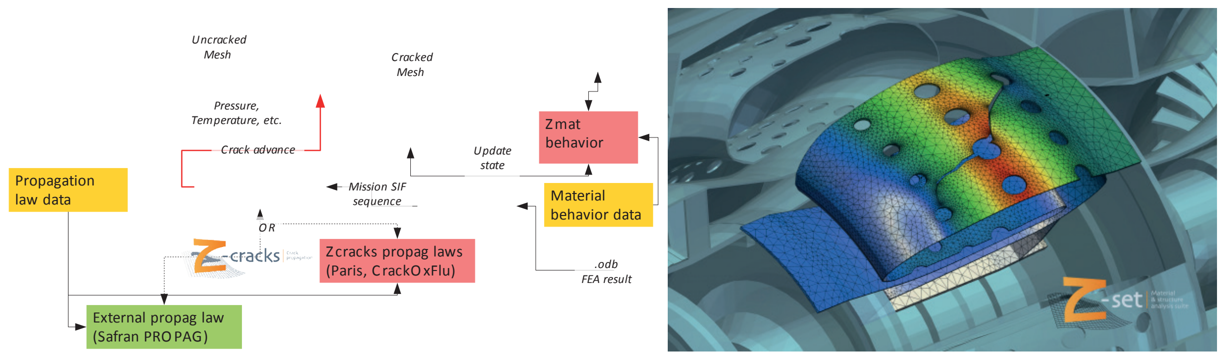

Fig.1. (a) on the left, thermo-elasto-plastic crack propagation flowchart coupled with ABAQUS and ; (b) on the right, numerical simulation of a cracked combustion chamber under thermo-mechanical fatigue loading (figure shows a studied deformed angular sector at high temperature).

Acknowledgements

Support for this work by Safran and Renault is gratefully acknowledged.

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FATIGUE CRACK ASSESSMENT S06-1
WEDNESDAY 18 NOVEMBER

FD15-033

FATIGUE CRACK GROWTH UNDER CONSTANT AND VARIABLE AMPLITUDE LOADING FOR MILD AND HIGH-STRENGTH STEEL APPLICATIONS

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An estimation of fatigue crack propagation in components and structures based on fracture mechanical approaches is fundamental to define periodic intervals for service inspections. In addition, light-weight design by application of high-strength materials is essential in order to fulfil nowadays strict demands to reduce fuel consumption and exhaust emissions.

Therefore, this paper focuses on the investigation of flat specimens made of mild steel S355 and high-strength steel S690. Experimental constant and variable amplitude fatigue tests show the influence of single overloads and effects of load sequences on crack propagation in order to obtain information about the remaining service life of components. Based on different load sequences, the crack propagation may be accelerated, delayed or in some cases stopped, which leads to striations within the area of fracture.

Therefore, fractographical analyses by the aid of light-optical, laser-confocal, and scanning electron microscopy of the tested specimens are carried out to determine different crack propagation stages. Additionally, the influence of position and shape of the starting notch on the fatigue crack growth is analysed experimentally.

Accompanying numerical fracture mechanical calculations based on two- and three-dimensional models are performed for constant and variable amplitude loads. Case studies involving a variation of the variable amplitude loading and crack configuration deliver additional insights to local effects at the crack tip during crack propagation.

A final comparison of the fractographical analyses and the numerical crack propagation calculations illustrate differences in the results and provide information to assess the fatigue crack growth and service inspection intervals of light-weight high-strength steel components under variable amplitude loading more precisely.

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FATIGUE CRACK ASSESSMENT S06-2
THURSDAY 19 NOVEMBER

FD15-111

INFLUENCE OF GASEOUS HYDROGEN ON FATIGUE BEHAVIOR OF FERRITIC STAINLESS STEEL – A FATIGUE-LIFE ESTIMATION

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The Bosch Group a leading global supplier of technology and services develops reliable and efficient fuel cell components for future mobility solutions. In the publicly funded research project “MatFuel” (FKZ: 03ET2051A) the fatigue life of high-alloy steels under gaseous hydrogen atmosphere is investigated.

This work studies the fatigue behavior of stainless ferritic steel optimized for electromagnetic properties under varying environmental conditions. Air-tested specimens are compared to specimens which are electrochemically precharged with hydrogen and tested in a gaseous atmosphere of 10 bar hydrogen pressure. The fracture surfaces of broken specimens are investigated by SEM in order to analyze the failure mechanisms in air and hydrogen.

Based on strain controlled fatigue tests using unnotched specimens, the influence of hydrogen on the cyclic material parameters are determined. Using these parameters a fatigue-life estimation on the basis of the local concept for stress controlled notched specimens is carried out. Experimental data and predicted strengths/fatigue-lifes are compared and different estimation approaches are evaluated.

A modified material model is derived to model the influence of hydrogen on cyclic behavior of stainless ferritic steel. Furthermore, the hydrogen contents of specimens before and after static and cyclic testing in gaseous hydrogen are measured. Finally hydrogen embrittlement mechanisms on cyclic loading are discussed and tested for its applicability.

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FATIGUE CRACK ASSESSMENT S06-2
THURSDAY 19 NOVEMBER

FD15-081

USE OF ACOUSTIC EMISSION METHOD FOR IDENTIFICATION OF FATIGUE MICRO-CRACKS CREATION

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This paper is a contribution to the discussion on the possibilities of identification of the time behaviour of various stages of fatigue lifetime directly during experiments using non-destructive testing methods (mainly acoustic emission method). We focus especially on detection and characterization of the transition from the stage of cycling damage cumulation to micro-cracks creation. In the past years, the laboratory of fatigue properties of FME received and published plenty of information about propagation of damage mainly in Al alloys. In this paper we present and compare the results of new experiments with steel used for nuclear reactors and Inconel alloy.

This work is focused on comparison of selected parameters of acoustic emission signal in pre-initiation and initiation stage of fatigue crack creation. Acoustic emission hits with higher stress were detected in the pre-initiation stage whereas the initiation stage hits exhibited low stress. Acoustic emission signal measurements are supplemented by fractographic and metallographic analysis.

Understanding to changes of AE signal and their connection to processes inside the material can significantly contribute to more reliable identification of the moment of fatigue crack initiation and to determination of the length of the stage of fatigue crack propagation until the final fracture. These studies are very important for higher safety of loaded constructions, mainly in energetics and transport systems.

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THURSDAY 19 NOVEMBER

FD15-107

INTEGRATED COMPUTATIONAL MODELING AND DESIGN STRATEGIES: SIMULATING AND PREDICTING FATIGUE CRACK GROWTH IN CAST ALUMINUM ALLOYS

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A computational toolset has been developed for microstructure-specific simulations and predictions of fatigue crack growth (FCG), with a focus on cast A356 (an Al-Si in-situ composite alloy) extensively used in the transportation sectors. Materials are represented by the superposition of matrix and secondary-phases behavior, with material property data generated using a novel micro-hardness indentation technique. Actual microstructural images are used as the basis for meso-scale simulations to make numerical evaluations of the dynamic loading response and optimize the materials for FCG resistance.

To validate this methodology, long and small FCG studies at various stress ratios have been conducted on different microstructures (altered through processing, chemistry, and heat treatment) in order to systematically investigate individual and combined effects of intrinsic microstructural characteristics on FCG. Mechanisms of FCG at the microstructural scale were identified at various stages, and loading-microstructure-damage mechanisms design maps were created.

Complementary to this work, a fracture mechanics methodology for data treatment and reduction has been developed for long-to-physically-small crack growth corrections, and an original model that further corrects for the microstructurally-small crack growth effect was created and validated. Examples of the application of these tools and techniques will be given as they relate to design for FCG resistance and life predictions.

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FATIGUE CRACK ASSESSMENT S06-2
THURSDAY 19 NOVEMBER

FD15-047

FATIGUE DESIGN WITH RESPECT TO COMPONENT RELATED CYCLIC MATERIAL BEHAVIOUR AND CONSIDERATIONS OF SIZE EFFECTS

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Local fatigue approaches, as for example the notch base approach, evaluate fatigue strength on the basis of strain controlled fatigue tests in conjunction with elastic plastic stress strain analyses of component structures, considering crack initiation as fatigue criterion. In case of constant amplitude loading, a cyclic stabilisation of the material behaviour is assumed, neglecting transient effects of cyclic straining at the start of the lifetime. Under variable amplitude loading, this simplification may not be valid, as the influences of load cycles of different magnitude on the material behaviour have to be carefully examined employing appropriate testing methods, such as incremental step tests, for the generation of cyclic material parameters.

Moreover, the fatigue life estimation under variable amplitude loading with local approaches may lead to large calculation times due to the necessity of non-linear finite element analyses for the damage evaluation of each load range within the rainflow counted load-time history.

A combination of the local approach with the nominal stress approach to a material based approach allows the use of the linear damage accumulation hypothesis according to Palmgren-Miner, thus substantially reducing the numerical effort for fatigue life estimation under variable amplitude loading. Although the local approach yields a reliable method for transferring material parameters from the specimen to the component geometry with the help of elastic plastic finite element analyses, the consideration of the effects of component size on fatigue life remains a complex objective, which requires a consistent differentiation of the size effects regarding their origin into mechanical, fracture mechanical and process related size effects.

The evaluation of mechanical size effects by means of the highly stressed area or volume approaches covers the geometrical as well as the gradient related statistical size effect. With increasing component size or increasing stress gradients, the crack propagation lifetime may increase or even crack arrest may occur. A decision about the expected lifetime to a massive failure of the component therefore requires a consideration of the fracture mechanical size effect. The presented work aims to convey a further development of the material based approach, including a thorough evaluation of mechanical size effects in the fatigue life estimation of components under variable amplitude loading.

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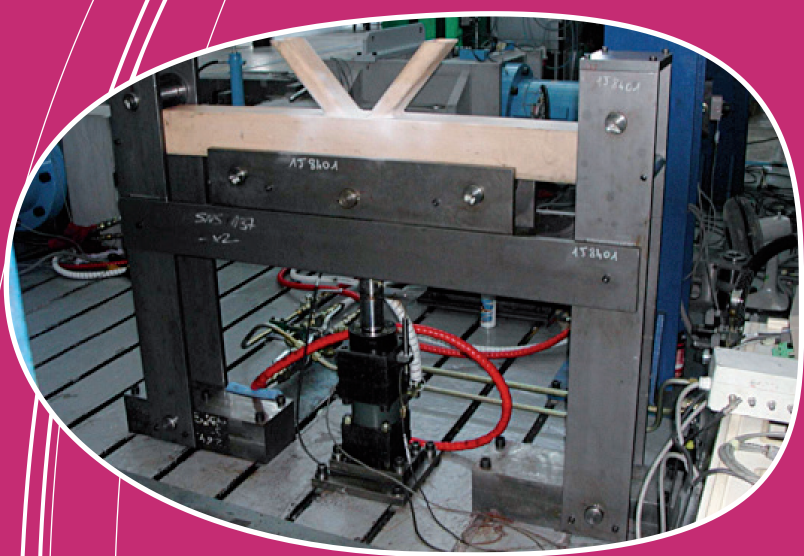

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WEDNESDAY 18 NOVEMBER

FD15-050

FATIGUE EVALUATION PROCEDURES FOR BI-AXIAL LOADED PLATE JOINT USING BATTELLE STRUCTURAL STRESS METHOD

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BATTELLE, COLUMBUS, OHIO, USA

Battelle has developed and investigated a series of multi-axial related weld fatigue behaviors. First one was flange-to-tube joint under torsional loading dominant. Second one was multi-axial stress state under uniaxial loading such as a tensile plate with fillet welded pipe or angled attachment. For multi-axial fatigue evaluation, an effective equivalent structural stress range (ΔEESS) parameter was formulated and employed. The fatigue behavior from these two cases shows differences clearly.

As an extension of these multi-axial fatigue evaluations, the Battelle structural stress method for fatigue life evaluation is examined for bi-axial loading in welded plate joints. The fatigue behavior resulted from biaxial loading is usually accepted as one of variation of multi-axial fatigue.

When the Battelle structural stress method was applied to the plate joints under bi-axial loading, the failure location can be predicted correctly and the fatigue life predictions using the master S-N curve approach are very accurate compared with fatigue test results from literature. Battelle structure stress method captures the bi-axial loading effects such as ratio of two directional loads, and the phase differences between two, and combination effects. As results of these effects, the effective stress range is varied and the failure locations also are changed.

In this article, it is found that the failure locations show the maximum normal structural stress (normal to weld line) but minimum in-plane shear structural stress (parallel to weld line) in this evaluation. It is also found that the cycles-to-failure data from the subject joint types are comparable with the master S-N curve for Mode I loading dominant behavior (inverse slope of 3.125). Therefore, the master S-N curve that was developed for Mode I failures can be equally applicable for fatigue life prediction for these joints under bi-axial loading.

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WEDNESDAY 18 NOVEMBER

FD15-021

COMPARATIVE STUDY OF FE-MODELS AND MATERIAL DATA FOR FATIGUE LIFE ASSESSMENTS OF WELDED THIN-WALLED CROSS-BEAM CONNECTIONS

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This paper investigates the effects of fatigue material data and finite element types on accuracy of residual life assessments under high cycle fatigue conditions. The bending of cross-beam connections is simulated in ANSYS Workbench for four different combinations of structural member shapes: RHS-RHS, RHS-angle, RHS-Channel and Channel-Channel. The weldments are made of the structural steel S355 according to the European standard EN 1FD15_0025:2004. The stress analysis of each weldment having specific profile size under specific cyclic loading is implemented using solid and shell elements using linear material and geometry consideration. The stress results are transferred to the embedded fatigue code nCode DesignLife for the residual life prediction. For both variants of FE-mesh, the nominal stress in the weld toes is extracted by splitting the total stress into membrane and bending components and filtering out non-linear component.

The membrane and bending stresses are combined with experimental pair of SN curves, which represent the fatigue strength of a weld under pure membrane (stiff) and bending (flexible) loading conditions. Considering the effects of bending, size and mean stress, failure locations and fatigue life are predicted using the Volvo method and rules from ASME Boiler and Pressure Vessel Code. Three different pairs of experimental SN curves are used including (1) conventional generic seam weld curves, (2) generic seam weld curves compliant with BS7608, and (3) curves for the Japanese steel JIS G3106-SM490B, which is equivalent to S355.

The numerical predictions are compared to the experimental results obtained and reported by Mashiri & Zhao (2006, 2008, 2010 & 2013). In addition to high computational costs, solid elements approach requires a Weld Definition File (WDF), which describes the geometry of weld toe together with a surface normal and another vector to define the orientation of the weld. The procedure for a semi-automatic generation of the WDF is implemented in SolidWorks. However, the predictions in terms of residual life with solid elements are not more than 10% different from predictions using shell elements, which do not require any extra efforts.

The predictions using the curves for SM490B steel demonstrate the best accuracy proving the fact that specific material data input is more effective than a generic.

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FD15-040

NEW SPOT WELD FATIGUE LIFE PREDICTION AND ROAD TRACK STRENGTH SIGNAL SIMPLIFICATION

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Spot welding is the main technique of joining sheet metal in the automotive industry. The fatigue failure of spot welds is critical for the safety of the vehicle structure and thus for the brand management of the car company. The number of both vehicle prototypes and design project time has decreased significantly during the last decade to reduce total project costs and time. Therefore, body-in-white numerical simulations and numerical life estimation of the spot weld must be accurate since designers require reliable information about the fatigue life of the structure early in the design phase. Some body-in-white numerical simulations are complex with material and contact nonlinearity for example. Thus, the full track road strength signal applied to the body-in-white cannot be used as boundary conditions for these numerical simulations. This signal must be simplified to obtain a strength signal with some few time steps.

An important database of spot weld fatigue tests is analyzed in order to test the correlation between the test results and the numerical results from spot weld fatigue life prediction criteria. Fracture mechanics approach for spot weld fatigue life is investigated. The fatigue life estimation error with this approach is decreased as compared to mechanical damage approach results. A new criterion, based on stress intensity factor, is developed through a nonlinear multiple regression optimization method. This criterion considerably improves the correlation between numerical and test results (correlation error divided by 3 at least). An application of this study is lead on a fatigue test of a full body-in-white with about 4000 spot welds.

To simplify the full track road strength signal, a new signal simplification method is developed, based on a spot weld life damage histories analysis. The objectives are to decrease the number of time steps and to obtain good correlation for sheet metal and spot weld life prediction between the non-simplified and simplified signal. An application of this study is lead on a full body-in-white simulation. A comparison of the numerical sheet metal and spot weld life prediction, obtained with a complex full track road strength signal (24 000 time discretization) and its simplified signal (88 time discretization) is made with a good correlation on damage.

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FD15-001

INFLUENCE OF MEASUREMENT AND MATERIAL UNCERTAINTIES ON THE PREDICTION OF RESIDUAL LIFE OF CRACKED STRUCTURES.

FABIEN LEFEBVRE[1], CATHERINE PEYRAC[1], CATHERINE VERDU[2], JEAN-YVES BUFFIÈRE[2], GUILLAUME ELBEL[3]

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The effect of hammer peening on the fatigue resistance of high strength welded steel S690 has been investigated. Cyclic four points bending tests have been performed on butt weld samples, manually and automatically hammered. Microstructural and mechanical modifications induced by both methods and their subsequent influences on fatigue life have been studied using several characterization techniques. A comparison of residual stress measurements using X-ray diffraction shows also differences between methods. On the other hand, hardness profile of the strain hardened region is very similar for both types of samples. The ultra-fine grain microstructure of the heat-affected zone (HAZ) induced by the hammer peening process has been studied by Field Emission Scanning Electron Microscopy and Electron Back Scattered Technique (EBSD).

In fatigue as expected, hammer peening increases the fatigue strength of weld structures in good agreement with the latest proposal of the International Institute of Welding (IIW). Compressive residual stresses play a key role. Microstructure does not seem to affect fatigue strength in spite of nanostructured layer. On the contrary to what is usually admitted, the local geometry of the weld toe is deteriorated because the process induces crack-like folds. In this paper, some recommendations are proposed for the hammer peening process in terms of sweeping strategy.

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Procedia Engineering (2015) 1877-7058

6th Fatigue Design Conference, Fatigue Design 2015

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WEDNESDAY 18 NOVEMBER

FD15-009

FATIGUE STRENGTH IMPROVEMENT OF ALUMINIUM AND HIGH STRENGTH STEEL WELDED STRUCTURES USING HIGH FREQUENCY MECHANICAL IMPACT TREATMENT

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Most of structures and components are fabricated using welded joints. A very high percentage of all fatigue failures locally occur at welded locations due to high tensile residual stresses and stress concentrations resulting from the weld process. High Frequency Mechanical Impact (HFMI) treatment has been increasingly used as an effective post-weld treatment technique to improve fatigue strength of welded structures.

Fatigue tests have been conducted for as-welded and HFMI treated 5083 grade aluminium and ASTM A514 steel welded specimens to investigate the effects of the HFMI treatment under constant amplitude R=0.1 and variable amplitude loadings. This paper presents fatigue test results including local metallurgical properties (metallography and microhardness) of cruciform welded specimens under the as-welded and the HFMI treatment conditions.

Fatigue test results showed that the HFMI treatment significantly improved fatigue life performance of the aluminium and steel welded specimens under both constant and variable amplitude load conditions. Therefore, the HFMI treatment is a quite promising post-weld treatment technique and its potential applications on the fatigue design of welded structures and components can lead to lighter structures and products, in which components and structures can be down-sized and optimized to reduce weights.

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Procedia Engineering (2015) 1877-7058

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WEDNESDAY 18 NOVEMBER

FD15-010

FATIGUE STRENGTH OF HFMI-TREATED AND STRESS-RELIEF ANNEALED HIGH-STRENGTH STEEL WELD JOINTS

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MONTANUNIVERSITÄT LEOBEN, CHAIR OF MECHANICAL ENGINEERING, LEOBEN, AUSTRIA

The fatigue strength of welded joints is generally independent from the base material yield strength due to notch effects at the weld toe or root, tensile residual stresses by the thermo-mechanical joining process and significant changes in local material properties within the heat-affected zone.

An effective way to increase the potential of light-weight design exhibits the application of post-weld treatments. Mechanical methods as the high-frequency mechanical impact treatment (HFMI) reduces the geometrical notch, introduces compressive residual stresses and increases the local hardness in the surface layer of the post-treated weld toe area. This increases the local fatigue strength of the welded joint in a major way. In addition, to overcome global distortions of welded structures or components, stress-relief annealing is a common and approved procedure in industrial applications.

In this paper the fatigue strength of HFMI-treated joints superimposed by stress-relief annealing is studied. Different steel grades ranging from common construction steel S355 to high-strength steel grades S690 and S960 are investigated in as-welded and HFMI-treated condition, both before and after stress-relief annealing. Characterization of the local properties by residual stress and distortion measurements show the influence of the considered post-treatment methods.

Fatigue tests at a tumescent stress ratio of R=0.1 show a significant increase of the fatigue strength due to the HFMI-treatment compared to the as-welded condition. In contrary, the superimposed stress-relief annealing lowers the fatigue strength of high-strength steel joints characteristically, but however, the final post-treated condition exhibits a higher fatigue strength compared to the initial as-welded state. Special focus is laid on the effect of welding distortion on the effective mean stress condition during the fatigue tests, whereat numerical simulations and experimental strain gauge measurements support the back tracing of the acting local mechanism.

Finally, a local fatigue assessment by the stress or strain based notch approach is presented to illustrate the influence of the investigated post-treatment methods on the local fatigue strength. A proposal to assess the fatigue strength of HFMI-treated and stress-relief annealed mild and high-strength steel joints concludes the work.

Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Engineering (2015) 1877-7058

6th Fatigue Design Conference, Fatigue Design 2015

FATIGUE OF ASSEMBLIES S07-2
WEDNESDAY 18 NOVEMBER

FD15-049

FATIGUE STRENGTH EVALUATION APPROACH OF WELDED JOINTS FOR MORE RELIABLE AND LIGHTER MILITARY GROUND VEHICLES

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Due to increasing land / amphibious mobility and performance requirements, fatigue assessment plays a vital role in the design of armoured amphibious military ground vehicles. Fatigue assessment study can be divided into two main branches, which are the determination of vehicle loading spectrum and the determination of vehicle fatigue strength. FNSS Defense Systems initiated a project in order to further vehicle fatigue strength evaluation capabilities on the way to design more reliable and lighter vehicles. The project is called “Design and manufacturing methods improving fatigue strength of welded joints”, which is financially supported by TUBITAK (The Scientific and Technological Research Council of Turkey).

In this paper, the work accomplished and the results obtained in the framework of the project are presented. In this scope, fatigue test samples are manufactured from 5XXX series aluminium armour plate with the selected welded joints configurations. Post-weld fatigue improvement methods; TIG dressing, hammer peening and shot peening, are applied to test samples. Residual stress measurements on selected configurations are accomplished per X-Ray Diffraction technique to evaluate the effect of post-weld treatments on residual stresses, which is a major factor affecting fatigue life. Welding process is simulated with finite element method to be able to compute welding induced residual stresses.

As input to simulations, temperature dependent thermo-mechanical and mechanical properties of utilized aluminium are determined on a forming dilatometer.

Then as a crucial step in weld process simulation, weld process experiment is designed and conducted to calibrate welding process heat source and to verify simulation model. Finally, constant amplitude fatigue tests are conducted on an in-house designed & built four point bending test machine. Test results are compared with the fatigue life calculated according to the IIW recommendations using various approaches and fatigue life computed on nCode DesignLife with different techniques.

As the outcomes of the project, FNSS weld class system is built highlighting the effect of post weld treatments, fatigue calculation procedures are enhanced and tuned accordingly, and substantial knowledge in weld process simulation is gained. Hence fatigue strength evaluation approach is evolved significantly.

Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Engineering (2015) 1877-7058

Procedia Engineering

6th Fatigue Design Conference, Fatigue Design 2015

FATIGUE OF ASSEMBLIES S07-3
THURSDAY 19 NOVEMBER

FD15-080

FATIGUE OF ALUMINIUM-GLASS FIBRE REINFORCED POLYMER COMPOSITE ASSEMBLY JOINED BY SELF-PIERCING RIVETING

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Lightweight structures are more and more widely used in the automotive industry due to the growing importance of environment regulations related to CO2 emissions. In this context of saving weight, a problematic becomes crucial: which process can be used to join efficiently composite and metallic parts?

Adhesive bonding requires a long processing time due to surface preparation and curing cycles. Another inconvenient is the retaining position of the structure during adhesive curing time. Mechanical fasteners like rivets or bolts involve pre-drilled hole which increases production cycle time and causes geometry issues.

An innovative way would be the application of self-piercing riveting to thermoplastic composite-metal structure. Since the self-piercing riveting does not require a pre-drilled hole, the time process is short. This process is well known, reliable, cost efficient and mature for the metal assemblies but it has been avoided for the composite-metal assemblies because of the damage generated in the composite by the rivet such as fiber cutting, stress concentration and delamination.

The aim of this work is to evaluate the fatigue strength of a PA6.6-GF (Glass Fiber reinforced Polyamide 6.6) /Aluminum assembly joined by self-piercing riveting. The fatigue strength tests were based on uniaxial shearing test. Joint manufacturing process parameters were investigated. Some fatigue tests were performed under severe environmental conditions like high temperature. The composite stresses ‘evolution was taken into account for the failure modes analyses.

Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Engineering (2015) 1877-7058

Procedia Engineering

6th Fatigue Design Conference, Fatigue Design 2015

FATIGUE OF ASSEMBLIES S07-3
WEDNESDAY 18 NOVEMBER

FD15-060

FATIGUE LIFE PREDICTIONS OF ADHESIVE JOINT OF SHEET STEELS

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Structural adhesive is widely employed in vehicle structures to enhance noise-vibration and crashworthiness performance. It is also known that structural durability is enhanced with application of structural adhesive. Many researchers reported the fatigue performance of adhesive joint but the test results showed noticeable scatter that made hard to develop a fatigue life prediction method. This study fabricated cross-tension specimens joined with adhesive only and adhesive with spot weld joint. Those specimens were subjected to 45 degree loading direction respect to adhesive joint plane.

The materials used for the specimens are various sheet steels including a mild steel, DP, and ultra-high strength steel. Fatigue tests were conducted for the specimens and constructed stress-life curve using a structural stress method. The test results were also correlated with a fracture mechanics approach. Both the approaches showed reasonable correlation with the test results.

Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Engineering (2015) 1877-7058

Procedia Engineering

6th Fatigue Design Conference, Fatigue Design 2015

FATIGUE OF ASSEMBLIES S07-3
WEDNESDAY 18 NOVEMBER

FD15-087

FATIGUE BEHAVIOUR OF ADHESIVE JOINTS

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The objective of weight reduction for lightweight structures is explained by the motivation of reducing energy consumption in many industrial sectors and particularly transportation. In this context, application of polymer-matrix composites as structural parts is expected to be one of the key-solutions. That explained their increasingly interest in partially substituting steel.

However, there are many technical issues which have to be solved for the implementation of these materials. If many solutions are linked to the choice of materials themselves, a single type material for a given structure is rarely realistic according to the principal stress and the different function of the structure.. In this context, economical and technical reasons lead to think that most engineering structures or products will be made of multi-components including several types of materials. Then the main important question is how to join dissimilar materials or structural parts made by them, how to characterize assembly zones and model them. The stability of the joint, its life-time and its durability become structurally sizing for designers.

This paper will treat of the complexity to mechanically characterize adhesives or (and) adhesive joints and to model the behaviour of the adhesive in an assembly. Different testing systems will be studied such as tensile tests on bulk specimens, Arcan-Mines tests in different loading-conditions, Thick-Adherend-Shear-Tests and single-lap-tensile-shear tests. Experimental results of different testing systems will be analysed and compared. Modelling of the behaviour of the joint will be proposed both in linear and non-linear field, either in static loading but also in fatigue. Results are presented on a structural single-part epoxy adhesive.

S08 - Fatigue under severe conditions environment

Chairmen:

B. Bignonnet, S. Calloch

Available online at www.sciencedirect.com

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Procedia Engineering (2015) 1877-7058

Procedia Engineering

6th Fatigue Design Conference, Fatigue Design 2015

FATIGUE UNDER SEVERE CONDITIONS ENVIRONMENT S08
THURSDAY 19 NOVEMBER

FD15-117

INFLUENCE OF COMPLEX LOADING SIGNALS ON THE LOW CYCLE FATIGUE RESISTANCE OF A 304L AUSTENITIC STAINLESS STEEL IN PRESSURIZED WATER REACTOR WATER ENVIRONMENT

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The fatigue design of Pressurized Water Reactor (PWR) components takes into account many parameters such as the surface finish, the scale effects, the material variability, etc. To optimise this design, it is necessary to understand the role of those parameters and to identify their possible interactions with PWR water environment.

This work is focused on the low cycle fatigue behaviour of a 304L austenitic stainless steel in three environments, namely vacuum, air and PWR water, through fatigue lifetimes and crack growth characterisations. In addition, the roles of both surface finish (polished or ground) and load signal form (triangular signals with different strain rates or complex signals representative of successive thermal shocks) were investigated.

The PWR water environment causes a fatigue life reduction and a crack propagation rate enhancement, regardless of surface finish or load signal shape. The signal shape effects on cyclic behaviour, damage kinetics and fatigue life are discussed. The influence of the position of the low strain rate parts within a complex cycle is analysed taking into account the time of crack exposure to the environment.

Keywords: Austenitic stainless steel, Low Cycle Fatigue, Load signal, PWR water environment

Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Engineering (2015) 1877-7058

Procedia Engineering

6th Fatigue Design Conference, Fatigue Design 2015

FATIGUE UNDER SEVERE CONDITIONS ENVIRONMENT S08
THURSDAY 19 NOVEMBER

FD15-074

EFFECT OF TEMPERATURE ON THE CORROSION FATIGUE BEHAVIOUR OF STAINLESS STEEL USED IN STEAM TURBINE

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The practical importance of fatigue failure in steam turbine materials has directed much experimental research towards assessing the physical reason for material sensitivity to corrosion fatigue and providing design rules for engineers. Metallic materials used in steam turbine are exposed to cyclic loading at high temperature and aggressive environment, during their service life. In this study, an original fatigue testing setup was developed to investigate the effect of aqueous solutions and temperature on the fatigue strength of steam turbine materials. High cycle fatigue (HCF) tests and low cycle fatigue (LCF) tests were carried out in corrosion media with in-situ electrochemical measurements to investigate the synergy effect between cyclic loading and corrosion activity.

Based on fractography analysis and in-situ electrochemical measurements during fatigue tests, fatigue failure mechanisms were investigated by comparing the electrochemical response of different stainless steels under in-situ corrosion fatigue test. It was possible to identify different scenarios for fatigue damage depending on the microstructure. Such different scenarios and their modelling will be discussed in this paper.

Keywords: steam turbine, corrosion fatigue strength, aqueous solutions, in-situ electrochemical measurements, fatigue failure mechanism.

Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Engineering (2015) 1877-7058

Procedia Engineering

6th Fatigue Design Conference, Fatigue Design 2015

FATIGUE UNDER SEVERE CONDITIONS ENVIRONMENT S08
THURSDAY 19 NOVEMBER

FD15-097

LONG TERM DURABILITY OF COMPOSITES IN MARINE ENVIRONMENT: COMPARATIVE STUDY OF FATIGUE BEHAVIOR.

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For marine applications, composite materials offer many advantages over metallic structures, with respect to ease of fabrication of complex profiles or light weight for installation and maintenance. Nevertheless, material selection is critical. In the case of a composite material, the choice of reinforcement is important if stress corrosion is to be avoided, while resin chemistry must be optimized to limit matrix damage. Fiber/matrix interface properties are also critical when composites are immersed for long periods.

The main objective of this study is to identify and quantify the influence of the specific environmental marine conditions on composite material behavior, especially in cyclic loading. In order to perform a comparative study of fatigue behavior, five composite materials have been tested and analyzed. Fatigue tests have been carried out in bending on composite materials at initial state and after sea water ageing. The fatigue life and the evolution of the damage have been compared for each material.

These experimental data allow us to identify and compare the fatigue behavior of several composite materials in a marine environment then to develop a numerical model to understand the coupling phenomena between the mechanical damage and the water absorption.

S09 - Manufacturing process effects in fatigue analysis

Chairmen:

V. Favier, N. Shamsaei

E. Pessard, G. Servanton

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Procedia Engineering (2015) 1877-7058

Procedia Engineering

6th Fatigue Design Conference, Fatigue Design 2015

MANUFACTURING PROCESS EFFECTS IN FATIGUE ANALYSIS S09-1
WEDNESDAY 18 NOVEMBER

FD15-027

LASER-PEENING TO IMPROVE FATIGUE STRENGTH AND LIFETIME OF CRITICAL COMPONENTS

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Laser Peening and Controlled Shot Peening technology are fully qualified production processes that are in routine and reliable use on diverse metal alloys. These technologies are capable of extending the fatigue and stress corrosion cracking life of components, and will enable designers to consider higher stress levels in certain life limited designs.

A broad range of materials and applications are in production or development, including but not limited to high/medium strength steel, case hardened steel, stainless steel, titanium and aluminium. Enhancement to the life of components with complex geometries and welds has also been demonstrated.

Controlled Shot Peening is in use for decades by a lot of industries to prevent premature failure and by some as a design tool to enable higher load carrying capacity.

Laser Peening as a further development of Controlled Shot Peening has been in production in the US, Europe and Asia. As only one example to date about 100.000 fan blades from new development or overhaul have been processed and the technique of Laser Peening established as a reliable, production proven process offering quality control of the end product, the residual compressive stress, to a level unknown previously. In aerospace this technology is or can be used on components of engine, undercarriage, airframe and wings. Today further applications especially in nuclear and non-nuclear power generation, medical or automotive components are established or under close investigation.

The processing capability is being extended with the introduction of a transportable Laser Peening system and a system with a moveable beam that can treat very large or heavy components.

Laser Peening and Controlled Shot Peening which are also used in combination offers all markets, substantial benefits in terms of metal fatigue both technically and commercially.

Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Engineering (2015) 1877-7058

Procedia Engineering

6th Fatigue Design Conference, Fatigue Design 2015

MANUFACTURING PROCESS EFFECTS IN FATIGUE ANALYSIS S09-1
WEDNESDAY 18 NOVEMBER

FD15-024

CHARACTERIZATION AND SIMULATION OF THE EFFECT OF PUNCHING ON THE HIGH CYCLE FATIGUE STRENGTH OF THIN ELECTRIC STEEL SHEETS

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Rotors of electrical machines are built from stacks of thin steel sheets. The fabrication process of these components usually involves punching operations that generate defects on the steel sheet edges. Since a degradation of the fatigue strength may result from these alterations, this study aims to elaborate a strategy for designing such punched parts against high cycle fatigue crack initiation. To reach this objective, high cycle fatigue tests are performed on different specimens with either punched or polished edges.

Results show a significant decrease of the fatigue strength for punched specimens. Investigations are carried out to understand the origin of fatigue failure in this case. SEM observations of the fracture surfaces reveal that crack initiation always occurs on the edge, especially on a punch defect. Additional investigations are combined to characterize how the edges are altered by punching operations.

Residual stresses on the punched edges are analyzed using X-Ray diffraction techniques. Results show that punching induces a high tensile residual stress level along the loading direction. In conjunction with the stress concentration associated with punching defects, tensile residual stresses promote crack initiation and fast crack propagation. For a better understanding of crack initiation, the edge geometries are scanned with 3D optical microscopy, allowing us to identify the real geometry of the most critical defect by comparing the edges before and after fatigue failure.

A finite element model, which accounts for both the influence of edge defects and the initial residual stress field on the fatigue strength of punched components, is then developed. The stress distribution around defects is determined from elastic-plastic finite element analyses (FEA) on both idealized and real defect geometries. A non-local high cycle fatigue criterion is finally used as post-processing of FEA to consider the effect of defects and the strong stress-strain gradients around them.

Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Engineering (2015) 1877-7058

6th Fatigue Design Conference, Fatigue Design 2015

MANUFACTURING PROCESS EFFECTS IN FATIGUE ANALYSIS S09-1
WEDNESDAY 18 NOVEMBER

FD15-035

EFFECTS OF MANUFACTURING PROCESS IN FATIGUE STRENGTH OF A PASSENGER VEHICLE REAR SUSPENSION: SIMULATION AND TEST CORRELATION

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The use of virtual simulations tools in the development process of automotive components is already widespread. But often, the effects of manufacturing processes of these components are not considered during the virtual development. The stamping process of sheet metal produces regions with severe work hardening, residual stresses and uneven thickness distribution, which can change its structural strength. The main objective of this paper was to evaluate the influence of the manufacturing process on the fatigue life of the cross member of a twist beam rear suspension. The twist beam rear suspension, is a semi independent suspension and its central beam is subject to high values of elastic deformation due to the asymmetrical vertical displacement between the wheels.

The structural design of this component is always a challenge due to the high stress amplitudes present during its operation. A rear suspension, currently used in a light vehicle, was selected for this study. Experimental torsional fatigue tests were carried out on the component, using higher loads compared to the component's workloads, in order to induce the fatigue failure. In possession of the experimental results, virtual analyses were performed considering the same boundary conditions of the experimental tests. In this step, we considered two scenarios, the first disregarding the effects of the manufacturing process. In the second scenario, a stamping process was simulated using the same stages of the physical process.

In this analysis, the work hardening, residual stresses and thickness variation along the beam profile were used as input data for the fatigue virtual simulation. When comparing the results of the virtual analyses with experimental results, the model that considered the influence of the stamping process in the component presented a better correlation than the first model, in terms of number of cycles and failure locations.

Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Engineering (2015) 1877-7058

Procedia Engineering

6th Fatigue Design Conference, Fatigue Design 2015

MANUFACTURING PROCESS EFFECTS IN FATIGUE ANALYSIS S09-1
WEDNESDAY 18 NOVEMBER

FD15-053

MICROSTRUCTURAL-BASED ANALYSIS AND MODELLING OF THE FATIGUE BEHAVIOR OF CAST AL-SI ALLOYS

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This article describes a microstructural-based fatigue strength modelling of cast Al-Si alloys used in automobile context. These materials are characterized by the presence of different microstructural heterogeneities at different scales: the aluminum matrix (DAS/SDAS and the precipitation hardening level), inclusions (Si particles, intermetallic) and casting defects (porosity). It is shown that the effects of these factors on the HCF damage mechanisms are important and can be different as a function of the loading mode. A multiaxial fatigue test campaign has been carried out using three cast aluminum alloys, fabricated by different casting processes (gravity die cast, lost foam cast) and associated with several heat treatment (T7, Hot Isostatique Pressing-HIP). The HIP treatment is used to close the shrinkage pores.

The first section is dedicated to experimental characterization of HCF damage mechanisms observed in the HIP treated material. It is seen that the formation of persistent slip bands (PSB) is the principal crack initiation mechanism, regardless of loading mode. The roles of the Si particles and the alpha matrix in PSB formation are decoupled using EBSD observations of fatigue specimens.

With regard to the effect of the casting defects, a study of natural fatigue crack growth and artificial long crack growth is presented and subsequently used to choose an appropriate fatigue strength criterion taking into account the defect effect for different loading modes (tension, torsion, combined tension-torsion). Finally, a flexible modelling framework, providing the possibility of combining any two suitable criteria, which leads to the construction of a multiaxial Kitagawa-Takahashi diagram, will be introduced.

Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Engineering (2015) 1877-7058

Procedia Engineering

6th Fatigue Design Conference, Fatigue Design 2015

MANUFACTURING PROCESS EFFECTS IN FATIGUE ANALYSIS S09-2
THURSDAY 19 NOVEMBER

FD15-043

FATIGUE BEHAVIOUR OF ADDITIVELY-MANUFACTURED TI-6AL-4V

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Fatigue behaviour of Ti-6Al-4V specimens additively-manufactured via Laser Engineered Net Shaping (LENS) is investigated. Additive manufacturing provides the opportunity to fabricate complex geometries layer by layer from 3D CAD files. As the mechanical behaviour of metallic materials depends on their microstructure which is affected by the time-temperature history, additive manufactured components are expected to have different properties from their wrought counterparts. A systematic approach is followed in this study to optimize the additive manufacturing process parameters in order to maximize the part density and minimize the manufacturing inherited voids. Using these process parameters, Ti-6Al-4V bars are fabricated and machined to ‘dogbone’ fatigue specimens with dimensions in conformance to ASTM standards. The thermal history, and molten pool temperature, of parts is monitored during fabrication using a Stratonics ThermaViz® combined infrared thermography/dual-wavelength pyrometer system. This spatio-temporal temperature data is related to the heterogeneities typically observed in material fabricated by additive manufacturing methods. Some bars are heat treated (i.e. annealed) before machining to investigate the effects of post manufacturing heat treatment on fatigue behaviour of this titanium alloy. Fully-reversed strain-controlled fatigue tests are performed on LENS produced Ti-6Al-4V specimens with and without heat treatment as well as wrought specimens and results are compared. Effect of surface quality is also investigated by comparing fatigue behaviour of LENS produced as-built specimens with the machined and polished ones. Fractography of the fractured surface is performed using Scanning Electron Microscopy (SEM) to determine the failure mechanism and realize the effects of impurities on fatigue resistance and data scatter of additively-manufactured Ti-6Al-4V.

Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Engineering (2015) 1877-7058

Procedia Engineering

6th Fatigue Design Conference, Fatigue Design 2015

MANUFACTURING PROCESS EFFECTS IN FATIGUE ANALYSIS S09-2
THURSDAY 19 NOVEMBER

FD15-051

RESIDUAL LIFETIME OF RAILWAY WHEEL'S WEB SUBJECTED TO PROCESS RESIDUAL STRESSES

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For security requirements, no fatigue failure of wheels is admitted in railway industry. Design process of wheels must ensure that there is no crack initiation during its life. Maintenance inspections are realized and guarantee that no critical propagation of fatigue cracks can occur.

A thermal treatment of the wheel is conducted after the forging process to improve the wear behaviour in the wheel/rail contact zone. This treatment induces residual stresses into the web part.

This present paper deals with the influence of the residual stresses induced by the thermal treatment on the web crack growth rate.

In a first part of the paper, the thermal treatment is modelled to evaluate the induced residual stresses, especially in the web part of the wheel.

Secondly, the mechanical loading is presented and its influence on crack propagation is studied using an XFEM based numerical strategy.

A relevant crack propagation law is proposed based on the NASGRO law according to experimental crack propagation tests conducted on specimens.

The last part of the paper is devoted to the presentation of numerical results of a propagation of an initial crack in the web. Different levels of residual stresses are considered and their influence on the crack growth rate is investigated.

Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Engineering (2015) 1877-7058

Procedia Engineering

6th Fatigue Design Conference, Fatigue Design 2015

MANUFACTURING PROCESS EFFECTS IN FATIGUE ANALYSIS S09-2
THURSDAY 19 NOVEMBER

FD15-029

FATIGUE PERFORMANCE OF THERMALLY CUT BOLT HOLES IN STRUCTURAL STEEL S460M

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Current fatigue codes only consider the fatigue performance of drilled and punched holes, limiting the use of thermal cutting processes to produce bolt holes. This paper analyses the fatigue performance of structural steel S460M containing thermally cut bolt holes. The research covers three thermal cutting methods: oxy-fuel, plasma and laser. The specimen geometry is defined by a rectangular cross section with a cut hole in the middle. All the specimens were conducted to failure by applying fatigue cycles, the stress ratio (R) being 0.1.

The corresponding S-N curve and fatigue limit were obtained for each cutting method. The results have been compared with previous research focused on the analysis of the fatigue performance of drilled and punched holes, and also with the S-N curves provided by current fatigue standards, equally focused on drilled and punched holes.

Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Engineering (2015) 1877-7058

Procedia Engineering

6th Fatigue Design Conference, Fatigue Design 2015

MANUFACTURING PROCESS EFFECTS IN FATIGUE ANALYSIS S09-2
THURSDAY 19 NOVEMBER

FD15-089

EFFECT OF COLD FORMING ON THE HIGH CYCLE FATIGUE BEHAVIOR OF A 27MNCR5 STEEL

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Cold extrusion is a process commonly used to manufacture drive train components in the automotive industry. Large plastic strains can be applied during this operation (up to 150%) and greatly changes the mechanical properties of the resulting material.

This study, part of the ANR project Defisurf focuses on the impact of cold-forging process parameters on the fatigue behavior of steel components. The goal is to decouple the various effects of cold-working by analyzing the material properties and performing fatigue tests. A specific tool has been developed, in collaboration with the Gevelot company, to get original fatigue specimen able to characterize the effect of the manufacturing process on the fatigue behavior. The specimens are extruded from two different initial diameters, giving two different reductions in cross-section of 18% and 75% respectively. These values represent the range of cross-section reduction found in cold-forging: a minimum reduction is always applied, and above 75% reduction the components can be damaged (e.g. tearing).

To understand the influence of cold-forging, the following analyses have been undertaken for each condition: monotonic tensile properties, microstructure, EBSD, residual stresses, hardness and surface roughness. Simulation of the forming process and microstructural observations of the two batches show that the plastic strain is homogeneous in the specimen section. For both reduction factors, the forming process has a positive effect on the components properties: induced residual stresses in compression and improve hardness and roughness (Ra decreasing).

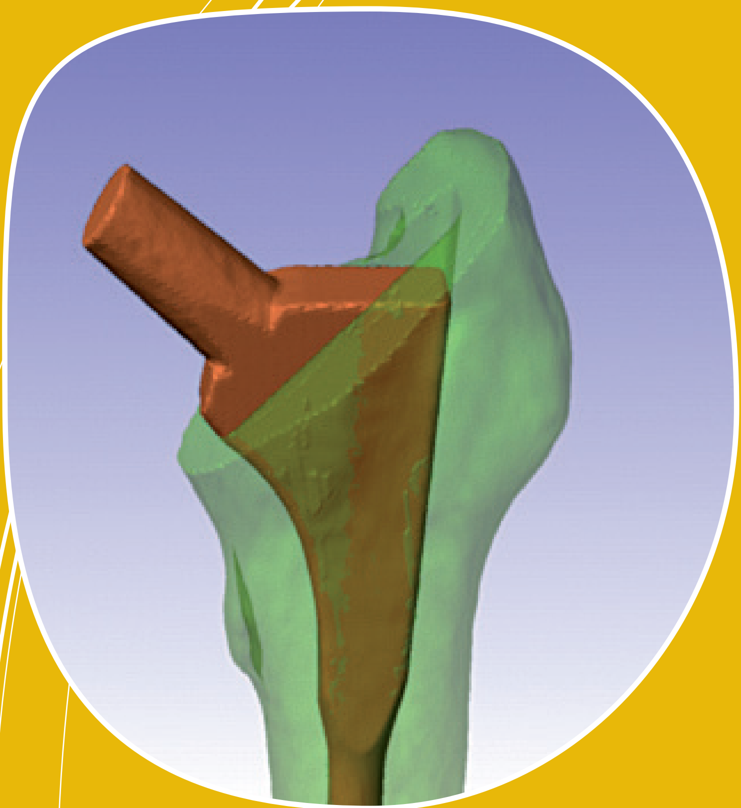
Push pull and plane bending fatigue tests show that the fatigue strength is about 30% higher for the high wrought batch. Residual stresses are not relaxed by the applied fatigue loads. SEM observations of the fatigue failure surfaces, for both extrusion conditions, show that there is no inclusion or surface defect at the initiation site.

All investigations show that strain hardening is the principal material parameter responsible for the increase in fatigue strength.

S10 - Reliability-based approaches and probabilistic methods

Chairmen:

YL. Lee, P. Bonnet



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Procedia Engineering (2015) 1877-7058

Procedia Engineering

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RELIABILITY-BASED APPROACHES AND PROBABILISTIC METHODS S10
WEDNESDAY 18 NOVEMBER

FD15-015

RESPONSE SPECTRA AND EXPECTED FATIGUE RELIABILITY: A LOOK AT HYDROELECTRIC TURBINES BEHAVIOR

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INSTITUT DE RECHERCHE D'HYDRO-QUEBEC (IREQ), VARENNES, QUEBEC, CANADA

The response of a turbine runner to both transient events and steady operating conditions has an impact on the runner remaining life. We observe, when looking at our current experimental data, that each turbine has some unique dynamic behavior. This renders difficult the standardization of turbines response spectra. However, even if it is impossible to generalize the behavior of turbine runners with one standard spectrum, we are able to distinguish some families of response spectra. Within each of these families, the importance of each event and operating condition can be defined in terms of their impact on the runner fatigue reliability. Given that the behavior of a runner belongs to one of these observed families of behavior, specific recommendations can be issued to maximize the runner life and reliability.

We define the reliability as the onset of high cycle fatigue (HCF). Specifically, the HCF onset is the contribution to crack propagation of small amplitude stress cycles which are different from the high amplitude cycles irrespective of their frequency. The high amplitude cycles are thus considered the low cycle fatigue (LCF) component of the spectra. For a large Francis turbine runner, this means that every steady operating condition should have a response spectrum below the HCF onset threshold at any given time. This statement has far reaching implications regarding the relation between the response spectra of the runner and its fatigue reliability. Using measured strain data from Hydro-Québec turbine runners as reference, we intend to propose families of response spectra from which we will study reliability and establish guidelines to maximize life expectancy. Our goal is to demonstrate that even if some response spectra are in accordance with current design specifications and practices, the behavior of some observed families of spectra might lead to counterintuitive results. This knowledge should help turbines operators and manufacturers to maximize the reliability of their equipment.

The paper will be structured as follows. First, we will present the typical type of response spectra expected, the reliability model and its relation to life expectancy. Next, we will propose families of response spectra based on the observed data from in situ measurements. Finally, specific guidelines and recommendations will be suggested.

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RELIABILITY-BASED APPROACHES AND PROBABILISTIC METHODS S10
WEDNESDAY 18 NOVEMBER

FD15-025

FAILURE PROBABILITY ASSESSMENT USING CO-KRIGING SURROGATE MODELS

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Key Words: eXtended Finite Element Method, co-Kriging, surrogate modeling, sub-modeling, failure risk.

Industries, among them the Aeronautics industry, have to justify the reliability of the structures they are designing. Static and modal analyses are the classical methods to validate a design. Nowadays, these are not sufficient anymore, and the damage tolerance approaches, characterizing the severity of a flaw occurring in the designed assembly, are thenceforth commonly used. Different methods such as simple finite element models or boundary element models can be applied. These methods introduce conservatism into the model that may be an issue with respect to some of the design constraints (light-weighting, final cost...). Moreover, they are often computationally expensive.

This paper proposes a methodology for the computation of the probability of sudden failure applied to landing gear assemblies at a reasonable computational cost while keeping a similar level of accuracy considering the computed probabilities. To that purpose, different strategies are coupled. First, a sub-modeling strategy is setting up. It allows to reduce the restitution time by considering separately the different critical zones. The critical areas are identified through a dedicated methodology based on the assessment of maximal principal stress. For each of them, a surrogate model is built based on a limited number of numerical simulations. Even though this solution allows non negligible gain on the restitution time, a co-Kriging multi-fidelity approach is applied. The surrogate model is built thanks to the combination of two sampling databases that are computed using XFEM simulations with different levels of refinement. Thanks to this methodology, a response with an equivalent level of accuracy is built-up. The failure probability is finally determined by running a large Monte-Carlo analysis based on the previously built surrogate models. The gains, limitations and perspectives to improve the current methodology are discussed.

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RELIABILITY-BASED APPROACHES AND PROBABILISTIC METHODS S10
WEDNESDAY 18 NOVEMBER

FD15-031

AN APPLICATION OF STOCHASTIC SIMULATION TO THE STUDY OF THE VARIABILITY OF ROAD INDUCED FATIGUE LOADS.

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Reliable designs can only be achieved if car manufacturers possess a suitable methodology to quantify the large variety of road induced fatigue loads that vehicles' components undergo during their life. The load data acquisition process is generally based on long and costly measurement campaigns.

The latter necessarily involve a strongly selective sampling of the set of all possible loads. Furthermore, they deliver load information which is closely tied to the vehicle used for the measurement. Consequently, when car manufacturers seek to adapt their different products for various markets, and their validation procedures accordingly, the necessity to gather load information becomes a cost-and-time-consuming issue if it implies the use of measurement campaigns.

To overcome such difficulties, an alternative load characterization methodology is proposed here. It is based on stochastic modelling and simulation rather than purely on a collection of load measurements. The underlying concept at the core of this approach is to focus the effort towards an understanding of the variability of the factors influencing the loads, instead of trying to asses directly the variability of loads themselves. Stochastic models, in the form of random processes, are proposed for vehicle-independent influential factors, namely road roughness and vehicle's speed. Random realizations are generated and used as inputs for multi-body simulation of any vehicle. An arbitrarily large set of fatigue loads can be obtained inexpensively, for any given elementary life situation, and subsequently, for the total life of the vehicle, using customer usage information.

A study of the influence of a change in market region is performed as an illustration of the methodology. It makes use of data provided by a measurement campaign. A stochastic road model is chosen from literature. Then, an efficient input estimation method is proposed as a mean to identify the parameters of the road model from measured dynamic responses of a vehicle. Several simulation campaigns are generated and processed in order to gain insight into the effect of a change in market region on the fatigue loads experienced by a vehicle.

S11 - Shape memory alloys

Chairmen:

A. Galtier, H. Rognon

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Procedia Engineering

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SHAPE MEMORY ALLOYS S11
THURSDAY 19 NOVEMBER

FD15-069

UNDERSTANDING THE RELATIONS BETWEEN SELF-HEATING EFFECTS AND FATIGUE PROPERTIES OF NITI WIRES UNDER TENSILE CYCLIC LOADING: EXPERIMENT AND MODELING

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This work deals with the development of a novel method capable of prediction fatigue of NiTi based on the experimental detection of selfheating.The method, when fully developed, can be potentially applied to any thermomechanical cyclic loading but since we are not that far yet, we will discuss only superelasticity of NiTi wires under uniaxial loading in this paper. NiTi wires, having three different microstructures due to different annealing treatments were tested.

A high-frequency infrared camera with high resolution was used to precisely follow the temperature evolution of the material during the tensile tests. In order to localize the start of the phase transformation in one single spot and facilitate thus the temperature measurements, specimens having nonconventional shape of varying cross section were used.

Comparisons between force-controlled and displacement-controlled responses are discussed. In the interest of complement the physical interpretation of the results, a modeling effort is presented in the second part. The model proposes the interaction of several hypothetical thermomechanical couplings to reproduce the observed phenomena.

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SHAPE MEMORY ALLOYS S11
THURSDAY 19 NOVEMBER

FD15-045

MEAN STRAIN/STRESS EFFECTS ON THE FATIGUE BEHAVIOUR OF SUPERELASTIC NITINOL ALLOYS

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Nitinol alloys are used in many applications such as aerospace and bioengineering at which these alloys may be subjected to cyclic loading with mean strains/stresses. For traditional metals, presence of tensile mean strain/stress can significantly reduce fatigue lives. For superelastic Nitinol alloys, however, a more complex behaviour is observed under tensile mean strains and ironically some beneficial effects of tensile mean strains are reported in the literature. This paper aims to study the effects of tensile mean strains/stresses on the fatigue resistance of superelastic Nitinol alloys. Due to the sensitivity of the mechanical behaviour of Nitinol alloys to operational temperature, the tests are conducted in multiple temperature levels to investigate such effects on the fatigue behaviour. Strain-controlled uniaxial fatigue tests with and without tensile mean strains are conducted.

Consequently, both strain-based and stress-based approaches are employed for fatigue analysis as this material is known to exhibit different behaviour depending on the fatigue approach. Phase transformation phenomenon and its contribution to the non-zero mean strain fatigue behaviour is also investigated.

Finally, capabilities of some well-known fatigue models to capture mean strain/stress effects are evaluated for superelastic Nitinol alloys.

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SHAPE MEMORY ALLOYS S11
THURSDAY 19 NOVEMBER

FD15-039

EFFECTS OF LOCALIZED PHASE TRANSITION ON FATIGUE FAILURE OF NITI SHAPE MEMORY ALLOY

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Based on shape memory effect and superelasticity with martensitic phase transition, NiTi Shape Memory Alloy (SMA) has many applications from human artificial joints and stents, to small-scale sensors and actuators. The fatigue performance of this material is mainly governed by the interaction between the crack initiation/growth and the cyclic phase transition.

There is a special feature of the phase transition in NiTi SMA polycrystals: Luders bands (the zones with large phase-transition strain) would appear. In recent study, we observed the pattern evolution of the localized phase transition under cyclic tensile loadings of various frequencies (changing frequency leads to different patterns and different fatigue life). It was found that there were strong interactions between the crack initiation/growth and the pattern formation: Luders bands preferred to nucleate around defects or micro-cracks; on the other hand, the dominant crack leading to fatigue failure would nucleate in the Luders bands.

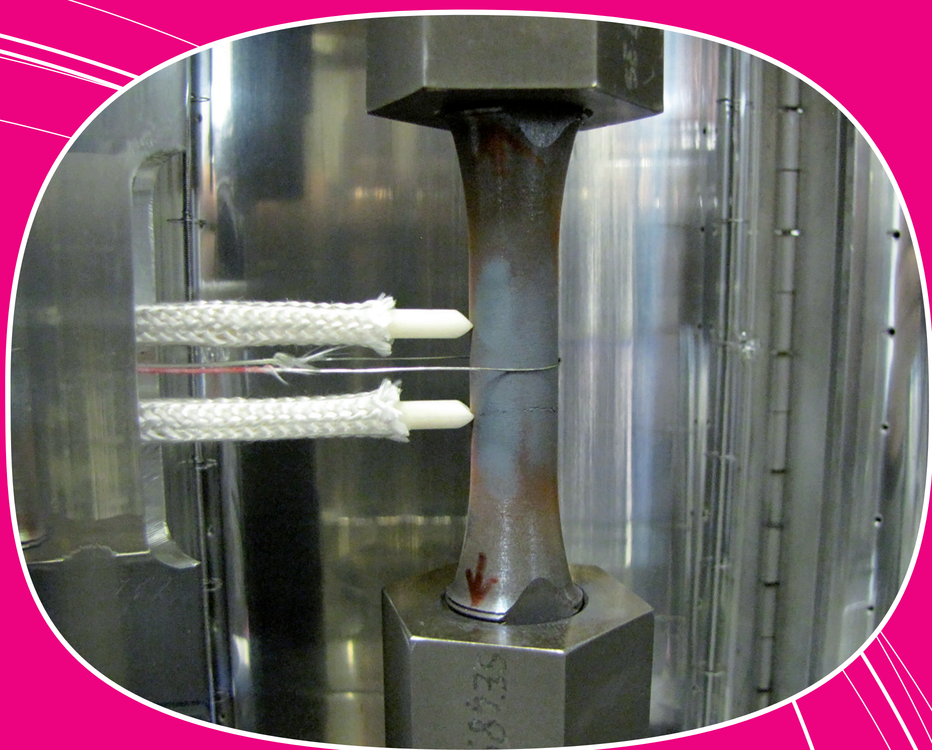
The systematic experiments on the relation between the localized phase transition and the fatigue failure are important in understanding the fatigue mechanisms and providing fatigue predictions (fatigue criteria).

S12 - Thermal and thermo-mechanical fatigue

Chairmen:

L. Remy, Y. Suchier

F. Szmytka, ML. Nguyen-Tajan



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THERMAL & THERMO-MECHANICAL FATIGUE S12-1
WEDNESDAY 18 NOVEMBER

FD15-013

EFFECT OF CONSTITUTIVE MODEL ON THERMO-MECHANICAL FATIGUE LIFE PREDICTION

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In this paper, thermo-mechanical fatigue life (TMF) prediction is performed on an automotive exhaust manifold using in-house postprocessor code (HOTLIFE) with four different constitutive models: elastoplastic with kinematic hardening, rate-dependent viscoplastic, and two unified elasto-viscoplastic models based on the equations proposed by Sehitoglu and Chaboche, respectively.

Commercial FEA software ABAQUS has been used for the analysis. The first two models are already implemented into ABAQUS; the Chaboche and Sehitoglu models were implemented using a user material subroutine (UMAT, available in ABAQUS). The stress, strain and temperature history calculated by these four models are output to HOTLIFE for post-processing. The results from the prediction are then compared to the experimental TMF life obtained from a component thermal fatigue bench test.

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THERMAL & THERMO-MECHANICAL FATIGUE S12-1
WEDNESDAY 18 NOVEMBER

FD15-034

THE EFFECT OF METAL-CARBIDE MORPHOLOGY ON THE THERMO-MECHANICAL FATIGUE (TMF) BEHAVIOR OF AUSTENITIC CAST ALLOYS FOR EXHAUST MANIFOLDS

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Out-of-phase thermo-mechanical fatigue (TMF) tests between 600℃ and 950℃ have been conducted for three cast alloys with the different metal-carbide (MC) morphologies: dense skeleton-like, sparse skeleton-like and blocky, respectively. The alloy with dense skeleton-like MC exhibit longer TMF life than the other two, even though their chemical composition and casting process are very similar. This could be understood based on the dissipated inelastic strain energy (evaluated from hysteresis loops at half-life). The fracture surface and longitudinal section were characterized and analyzed in detail. These results provide the basis for bridging microstructure and TMF behavior, which can be used for tailoring the properties of the alloys.

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THERMAL & THERMO-MECHANICAL FATIGUE S12-1
WEDNESDAY 18 NOVEMBER

FD15-046

EFFECT OF A THERMOCHEMICAL TREATMENT OF SURFACE LAYER ON FATIGUE PROPERTIES OF STEEL BY SELF-HEATING MEASUREMENT UNDER CYCLIC LOAD

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To improve life time of components subject to rolling contact fatigue, the increasing of the surface hardness is recommended in industry. The thermo-chemical treatment of carburizing is one way to obtain this hardness layer with good wear resistance. However, the quantitative prediction of fatigue life of components with carburized layer is still a difficult task. In the case of rolling contact fatigue, different levels of difficulty exist. Firstly, material properties are heterogeneous, at the minimum two layers can be identified: the original material and the surface layer with an enrichment of carbon. Secondly rolling contact fatigue leads to cyclic multiaxial non proportional loadings in the component.

This study will focus on material heterogeneity and these quantitative consequences on fatigue life. Three steels grade are studied and three treatments are applied: quenching, carburizing and carburizing with annealing. In order to identify the carburizing contribution, tubular specimens composed only of a treated layer, are designed.

The objective is to have a homogeneous specimen. The last difficulty concerns the time and cost of classical fatigue tests. To remedy this difficulty, fatigue properties are determined by self-heating measurement under cyclic loadings. Lastly, differences between fatigue properties identified by self-heating measurements are linked with material properties.

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THERMAL & THERMO-MECHANICAL FATIGUE S12-2
THURSDAY 19 NOVEMBER

FD15-075

FATIGUE CRACK PROPAGATION IN LARGE SCALE YIELDING CONDITIONS

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In Industry, some components are subjected to fatigue thermal loadings due to thermal fluctuations coming from the meet of a cold and a hot fluid. A large scale yielding conditions zone can be created: plasticity is not only located at the crack tip, but extends to a larger area of the component.

Fatigue crack propagation in an elastic material is well known and usually estimated thanks to Paris type laws. These laws give a good estimation of the crack propagation fatigue life for a component. On the contrary, fatigue crack propagation in large scale yielding conditions is not well known. Thus, traditional hypothesis of elasticity cannot be used. Nevertheless, crack propagation needs to be estimated with adapted numerical models.

One of the ways for this objective to be achieved is to use experiments where a specimen is loaded in order to propagate cracks in a large scale yielding conditions area. In this paper, the device of tests is firstly presented with the particular geometry of the specimen. During the thermal fatigue tests, temperatures, strains and surface crack lengths are measured and registered. In a second phase, finite element calculations are performed in order to correlate experiments and calculations. The influence of a large scale yielding conditions area on the fatigue crack growth under thermal loadings can be extracted. Finally, after the tests, the specimen is cut. Microscopic analyses, such as MEB and EBSD measurements, are performed in order to observe the influence of the microstructure on the fatigue crack path.

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THERMAL & THERMO-MECHANICAL FATIGUE S12-2
THURSDAY 19 NOVEMBER

FD15-048

THERMO-MECHANICAL FINITE ELEMENT SIMULATION AND FATIGUE LIFE ASSESSMENT OF A COPPER MOULD FOR CONTINUOUS CASTING OF STEEL

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During the process of continuous steel casting, a copper mould is used for cooling and shaping the molten steel. The high temperature of the molten steel causes thermal fluxes and steep temperature gradients in the mould. As a result, considerable stresses and plastic strains are induced in the mould, which leads to deformations and thermal cracks at the inner surface.

In order to estimate the service life of the copper mould, a simulation model was developed. Hence, a suited material and life time model were selected and parameterized.

Low-cycle fatigue tests on specimens were performed to obtain the material cyclic response and the strain-life data. Based on the test results, the parameters for the material model were determined using routines created in MATLAB. Simulations with the obtained material model parameters match the test data precisely.

The data from the LCF test was also used to determine the parameters for the life time model. Using the life time model parameters and the simulated stress-strain distribution in the mould model, the local, weakly coupled damage of the mould was calculated. The estimated damage is proportional to the local fatigue life. The comparison between calculated and tested fatigue life of the specimens shows a satisfying correspondence.

Finally, the positions of the most critical regions of the mould were confirmed by the simulation.

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THERMAL & THERMO-MECHANICAL FATIGUE S12-2
THURSDAY 19 NOVEMBER

FD15-099

THERMAL FATIGUE BEHAVIOUR OF A COPPER-BASED ARCHITECTURED MATERIAL FOR POWER ELECTRONICS

HIBA FEKIRI, VLADIMIR ESIN, ALAIN KOSTER, VINCENT MAUREL, MATTHIEU RAMBAUDON, STEVE DUVINAGE, YVES BIENVENU

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Materials for power electronic modules are subjected to a number of thermal cycles during the exploitation. It leads to an internal stress generation due to the use of materials with different coefficients of thermal expansion leading thus to a fast material degradation. The architectured materials represent therefore new opportunities to obtain a compromise between different properties and to increase material lifetime. The architectured Cu/Invar colaminates for power electronic modules are an attractive option: a combination of copper and Invar leads to a good thermal conductivity and acceptable coefficient of thermal expansion for power electronic application.

The aim of this work was to study thermal fatigue behaviour of Cu/Invar colaminates and describe damage mode.

Different thermal cycles were carried out on the colaminate with conditions close to those applied in avionic and automotive applications. Structure observation in light optical and scanning electron microscopes (SEM) coupled with thermal conductivity measurements allowed to identify a critical number of thermal cycles, when a delamination of the colaminate structure takes place. Moreover, crack initiation at Cu/Invar interface was observed and influence of thermal cycling on crack dimensions was analysed. The measurements of the thermal conductivity complete and confirm structure observation.

A Finite-Element method has been used to interpret experimental results and to propose thus an optimization in architectured structure and to increase material lifetime.

Acknowledgements. David Guinet (GRISET) is gratefully acknowledged for the samples providing. The work is carried out in the frame of MeGaN project.

S13 - Vibration fatigue behavior

Chairmen:

B. Colin, Y. Goth

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VIBRATION FATIGUE BEHAVIOR S13
WEDNESDAY 18 NOVEMBER

FD15-056

FATIGUE LIFE FROM KURTOSIS CONTROLLED EXCITATIONS

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Typically electronic and mechanical components for ground and flight vehicles are subjected to random vibration excitations. To qualify such components a common approach is to expose them to a random Gaussian excitation, defined by the power spectral density (PSD) of the vibration under consideration.

In real life, however, it is common to experience non-Gaussian acceleration inputs such as road irregularities in the automotive world or turbulent pressure fluctuations for the aerospace sector. Traditional Gaussian random test signals do not accurately represent the bursts and peaks seen in service use. The consequence of not using the right type of test signal during vibration testing of the product leads to higher in the field failure rates and added warranty costs.

Modern controllers can generate non-Gaussian excitation signals with a given PSD and kurtosis. A simulation with kurtosis control makes the vibration test more realistic and therefore closer to real-world excitations. This paper addresses the question of linking fatigue damage with the prescribed input kurtosis. Direct applications of these results include improved fatigue life estimations and a method to accelerate shaker tests by generating high kurtosis, non-Gaussian drive signals.

The algorithm is validated using numerical simulations and a case study illustrates the application of the method.

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VIBRATION FATIGUE BEHAVIOR S13
WEDNESDAY 18 NOVEMBER

FD15-008

INTEREST OF THE TRANSIENT ACCELERATED TESTING APPROACH ON THE QUALIFICATION OF RAILWAY EQUIPMENT

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Railway equipment is highly subjected to fatigue failure. Fatigue occurring through long term exposure to time varying loads associated to dynamic effects may create microscopic cracks that would eventually lead to failure. Railway equipment must fulfill the IEC 61373 (Railway international standard) durability certification tests prior to production.

Real service loads have been registered on many different railway equipments mounted on the bogie or axle. Both transient and random vibration methods are used to generate acceleration Power Spectral Densities (PSD) from these test signals which lead to an equivalent fatigue damage content as that seen by the equipment over its whole life. The transient approach is based on the French military standard GAM EG-13 using the Fatigue Damage Spectrum (FDS).

Firstly, to understand these approaches, some theoretical aspects are given and Shock Response Spectrum (SRS), Extreme Response Spectrum (ERS), and FDS are detailed. A special attention is paid to how each of these quantities is used to describe the fatigue damage and the extreme response during the lifetime, as well as to qualify the generated acceleration PSDs.

Random vibration analyses are performed in the frequency domain and are relatively simple. At the contrary, transient analyses are performed in the time domain and are more accurate. The paper compares both methods in term of damage on real service railway loads to help identifying the most appropriate and efficient test method. Railway real service loads are usually no Gaussian signals, indeed the transient methods is the most representative in term of damage. According to several Wohler slope curves, this paper presents an estimation of discrepancy damage related to each method.

The paper concludes with a critical analysis of the IEC 61373. The IEC 61373 test specification is compared to the acceleration PSDs generated from real railway loads, originating from transient approach. Fatigue damage contents and frequency range of interest are compared for bogie and axle mounted equipments.

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VIBRATION FATIGUE BEHAVIOR S13
WEDNESDAY 18 NOVEMBER

FD15-006

CHALLENGES IN THE FATIGUE ASSESSMENT OF LARGE COMPONENTS FROM FORGED OR CAST IRON,

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IABG MBH, OTTOBRUNN, GERMANY

Hydroelectric, thermal or wind power plants contain large power transmitting components which are often produced from forged or cast iron. These components set high requirements to efficient and reliable methods for design, validation and quality assurance. Due to their large dimensions and the high forces and moments acting during operation, full scale fatigue tests with the actual components are usually not possible with the number of specimen required for a reliable verification of safety against failure. Hence, usually a theoretical fatigue assessment based on the results of finite element calculations and material parameters is performed. The great uncertainties about material parameters are covered by safety factors that reduce the allowable stresses. Since this reduction is normally applied for the whole component, the material tends to be over specified for regions that are not highly stressed. In this paper, important aspects will be shown that have to be taken into account when dealing with large cast or forged power transmitting components. A method for obtaining a set of valuable and reliable local material parameters for a safe fatigue assessment is presented that facilitates a better material utilization and also takes into account the need for precise criteria for quality assurance in series production. A special focus is set on the importance of metallographic investigations along the process of specimen testing and quality control.

Keywords: fatigue, strength, casting, forging, quality assurance

Poster Session

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POSTER SESSION

FD15-011

KINETO-STATIC THEORY AND INTEGRATED STRUCTURAL MODELS OF FATIGUE

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At the present time the mechanics of fracture is the theoretical basis for forecasting of a resource in the condition of damage accumulation and of cracks propagation. This section of mechanics of materials and structures is under intensive development. The major direction of this development is mechanics structures with cracks. Although the first classical works on mechanics of cracks were performed at the beginning of the last century, interest in a problem arose only in the last decades. Mostly it was caused by development of CAE methods of fatigue and durability analysis. Although, the semi-empirical models of damage accumulations still are popular because of the simplicity, in general, development of structural models of damage and destruction is one of the most actual directions of mechanics of materials. These models undoubtedly possess the future.

The paper presents the structural models of scattered fatigue damage accumulation and cracks propagation. Also the paper introduces the integrated structural model of fatigue damage accumulation (ISMF), based on the novel Kineto-Static Theory of Fatigue (KSTF). ISMF allows describing all forms of fatigue damage accumulation by single mathematic dependence. The presented structural models can be used as more accurate and reliable theoretical platform for CAE/FEA Fatigue and Durability Analysis, methodology of structural health assessment and individual life time prediction.

Key words: Kineto-Static Theory of Fatigue, Integrated Structural Model of Fatigue.

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Procedia Engineering (2015) 1877-7058

Procedia Engineering

6th Fatigue Design Conference, Fatigue Design 2015

POSTER SESSION

FD15-016

FATIGUE DAMAGE LIFE PREDICTION IN ALUMINIUM AND STEEL SPECIMENS UNDER BENDING-ROTATION TESTS

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Fatigue material properties are obtained from standard S-N or ε-N curves. However, during service life, damage can be produced and the direct use of these properties is no longer possible. It becomes important to a designer to have available damage theory that permits estimations of fatigue property changes during fatigue life.

Although fatigue damage models have already taken more than 50 years, it does not seem to have reached a satisfactory conclusion, and new criteria are still being proposed every year. In this paper, fatigue life prediction of aluminium and steel specimens under bending-rotation tests is presented. Damage will be calculated using the nonlinear fatigue damage cumulative model proposed by Shang and Yao in 1999. This theory considers fatigue limit, alternating and mean stresses, and loading sequence effects.

Electrical resistance changes, strain gage and Eddy current measurements were performed over specimen length during cycle numbers previously determined. Thus, the tests were interrupted and the specimens were removed from the testing machine to measure damage parameters. Besides, fracture prediction was also performed by using four different methodologies. Among these, two methodologies have been performed using data of broken specimens. For another two methodologies it was utilized data of unbroken specimens. Experimental and theoretical values were compared and discussed.

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Procedia Engineering (2015) 1877-7058

6th Fatigue Design Conference, Fatigue Design 2015

POSTER SESSION

FD15-023

FRETTING FATIGUE LIFE PREDICTION OF A MONO CONTACT STEEL/ALUMINUM AT VARIABLE AMPLITUDE

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The fretting fatigue behavior of 6082-T6 under variable amplitude loadings was investigated. This involved two and four blocks loadings at a frequency of 20 Hz. The measured fretting-fatigue lives were compared with the predicted lives obtained from the Palmgren–Miner linear damage rule and Damage Stress Model (DSM) nonlinear damage rule. The multiaxial fatigue parameters, based on critical plane approach, were coupled with DSM damage law. The estimates we have obtained seem very promising.

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Procedia Engineering (2015) 1877-7058

Procedia Engineering

6th Fatigue Design Conference, Fatigue Design 2015

POSTER SESSION

FD15-038

A DEVIATORIC INTERPRETATION OF NEUBER'S RULE

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Neuber's rule has been used for more than fifty years to estimate elastic-plastic stresses and strains at notches. Usually, for notches under plane stress conditions Neuber's rule gives reasonable conservative estimations.

On the other hand, it has been shown that Neuber's rule gives very poor results for circumferential grooves in shafts under axial tension, where relatively high hydrostatic state of stress exists. Therefore, so called linear rule is often used to estimate the local notch root strain, εnotch, as $k_{t\varepsilon nom}$ or $k_{f\varepsilon nom}$, where k_t and k_f are the theoretical stress concentration and the fatigue notch factor, respectively. Another method to lower estimated strains at notches in comparison to Neuber's rule has been proposed by Molski and Glinka called the equivalent strain energy density (ESED) method.

Poor results of Neuber's rule seem to be a consequence of the fact that his rule is used for loading cases that may significantly differ from a pure shear. It should be noted that Neuber derived his rule specifically for sharp notches in prismatic bodies subjected to two-dimensional shear, which represents deviatoric state of stress.

Therefore, a deviatoric representation of Neuber's rule is proposed and discussed. An application of the deviatoric Neuber's rule doesn't involve any additional constants of fitting parameters. It is shown that the deviatoric representation of Neuber's rule results in inelastic stresses and strains that are between estimations obtained from the conventional Neuber's rule and the ESED method.

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Procedia Engineering (2015) 1877-7058

Procedia Engineering

6th Fatigue Design Conference, Fatigue Design 2015

POSTER SESSION

FD15-046

EFFECT OF A THERMOCHEMICAL TREATMENT OF SURFACE LAYER ON FATIGUE PROPERTIES OF STEEL BY SELF-HEATING MEASUREMENT UNDER CYCLIC LOAD

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To improve life time of components subject to rolling contact fatigue, the increasing of the surface hardness is recommended in industry. The thermo-chemical treatment of carburizing is one way to obtain this hardness layer with good wear resistance. However, the quantitative prediction of fatigue life of components with carburized layer is still a difficult task. In the case of rolling contact fatigue, different levels of difficulty exist. Firstly, material properties are heterogeneous, at the minimum two layers can be identified: the original material and the surface layer with an enrichment of carbon. Secondly rolling contact fatigue leads to cyclic multiaxial non proportional loadings in the component.

This study will focus on material heterogeneity and these quantitative consequences on fatigue life. Three steels grade are studied and three treatments are applied: quenching, carburizing and carburizing with annealing. In order to identify the carburizing contribution, tubular specimens composed only of a treated layer, are designed.

The objective is to have a homogeneous specimen. The last difficulty concerns the time and cost of classical fatigue tests. To remedy this difficulty, fatigue properties are determined by self-heating measurement under cyclic loadings. Lastly, differences between fatigue properties identified by self-heating measurements are linked with material properties.

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Procedia Engineering (2015) 1877-7058

Procedia Engineering

6th Fatigue Design Conference, Fatigue Design 2015

POSTER SESSION

FD15-058

FAST DETERMINATION OF WELDED COMPONENTS FATIGUE PROPERTIES WITH THE SELF-HEATING METHOD: APPLICATION TO A CAR WISHBONE

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The determination of welded assemblies' high cycle fatigue properties is of prior concern for the automotive industry. Many high cycle fatigue tests have to be performed in order to feed numerical model and validate pieces before the mass production and insure customer's safety. These tests are long and expensive, several days of testing and specimens are required to get reliable data on fatigue properties.

The self-heating method offers the possibility to decrease the number of specimens and the testing time for the determination of fatigue properties. It consists in measuring the mean temperature evolution of the specimen under cyclic loading caused by intrinsic dissipation and micro-plasticity responsible of high cycle fatigue. Thus, this intrinsic dissipation is identified and linked to fatigue properties. Only one specimen and few hours are required. Results have already been proved efficient to determine simple steel sheet fatigue properties.

This method is now extended to a welded structure: a car wishbone. An experimental protocol is proposed to measure the temperature of a car wishbone during cyclic loading and extract the mean temperature evolution caused by self-heating. Then, a model is proposed to identify the thermal source field caused by intrinsic dissipation, taking into account the welded joint, and the concentration of dissipative phenomena associated to it.

Finally, the evolution of this identified heat source with the loading amplitude applied leads to the determination of the wishbone fatigue properties.

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Procedia Engineering (2015) 1877-7058

6th Fatigue Design Conference, Fatigue Design 2015

POSTER SESSION

FD15-059

FATIGUE EVALUATION OF AN AUTOMOTIVE COMPONENT USING LATERAL LOAD EXTRACTION THROUGH VIRTUAL DRIVING ON A KNOWN CIRCUIT

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The first step in a virtual development of any component is to define the type of loads which this component will be subjected. In an automotive environment, the load history is complex, both to acquire but also to analyze.

This study aims to evaluate the fatigue strength of a front suspension lower control arm using the virtual driving methodology to acquire the load time history. From a real-time multibody correlated model guided by a virtual driver in a known circuit, it is possible to predict loads on a specific component. Using this load data, the fatigue analysis can be performed through two different methods.

The first one is considering the complete time history. This method has its drawbacks, such as the length of the input data, the duration of the analysis and the size of results file that requires larger cpu resources. The simplest way is using the Inertia Relief technique. The second method is to compress the load data using a cycle counting method, in this case the Level Crossing. The fatigue analysis of the lower control arm were done using these two methodologies and the results were compared and discussed.

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Procedia Engineering (2015) 1877-7058

Procedia Engineering

6th Fatigue Design Conference, Fatigue Design 2015

POSTER SESSION

FD15-061

THE STRESS-STRENGTH INTERFERENCE METHOD APPLIED TO FATIGUE DESIGN OF STRUCTURES AND COMPONENTS: THE INDEPENDENCE OF THE RANDOM VARIABLES

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The use of the probabilistic analysis called Stress-Strength Interference Method (SSIM) is being analysed through the scope of a common criterion for the assessment of fatigue failure: uniaxial design below the conventional fatigue limit. In most studies, mean stress effect is included to modify this fatigue limit. Plus, through the use of K factors, the fatigue limit is usually modified to account for the influence of loading mode, temperature, component size, corrosion, roughness...

However, a necessary assumption of the SSIM is that random variables, i.e. stress, fatigue strength and K factors, are independent. In this study, the independence of stress, fatigue strength and K factors is discussed from a physical viewpoint. It appears that in some approaches of the literature, many of the variables may be in fact dependent. In particular, the independence between strength and stress is untrue because of the mean stress correction. This error might lead to unconservative reliability predictions.

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Procedia Engineering (2015) 1877-7058

6th Fatigue Design Conference, Fatigue Design 2015

POSTER SESSION

FD15-063

THE DURABILITY ESTIMATION OF CARBONE/EPOXY COMPOSITE MATERIALS USING ADAPTIVE NEURO FUZZY INFERENCE SYSTEM (ANFIS)

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The problem of fatigue failure prediction for fiber-reinforced composites is of importance in design and inspection of composite structures used in the aircraft industry. In the absence of a defined failure criterion that can be used to predict fatigue life, extensive tests must be carried out for different fiber orientation angles and loading conditions. For this raison, the designers rely on different fatigue life prediction methodology in order to avoid costly and time consuming fatigue tests.

In the present work, an attempt has been made to predict the fatigue life of Carbone /Epoxy composite material by adopting one of the artificial intelligence concepts that have proved to be useful for various engineering applications.

For this purpose, an adaptive network based fuzzy inference system (ANFIS) was implemented by using MATLAB Toolbox to predict the fatigue crack growth life in case of interspersed mixed-mode (I and II) overload of Carbone/Epoxy composite material up to fracture. Further, the prediction results have been compared with the available references experimental data.

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Procedia Engineering (2015) 1877-7058

Procedia Engineering

6th Fatigue Design Conference, Fatigue Design 2015

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FD15-068

FATIGUE OF SUPERELASTIC NITI SHAPE MEMORY ALLOY ENDODONTIC FILES

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With their superelasticity, shape memory alloys wires are used as the base of endodontic files. These files are used in the dental field to prepare root canals of teeth. During their use, file separation by fatigue can occur and complicates the realized operation. Unfortunately, the fatigue property of shape memory alloys remains an unexplored area and their fatigue is not taking into account in dimensioning of the endodontic files. In this study, we focus on the fatigue of superelastic NiTi and on the self-heating phenomena. This study begins by using this fast method based on self-heating to determine fatigue properties. Self-heating measurements under cyclic loading have been set up on dog-bone samples. Using a modeling based on dissipation and thermo-mechanical coupling, self-heating results have been reproduced and in addition with a fatigue model we can predict fatigue properties of our samples. These results have been validated by fatigue tests at low and high number of cycles. With this fast method, process parameters effects as electropolishing or heat treatment on fatigue properties have been studied. Finally, the model which has been identified on dog-bone samples has been used to predict fatigue life of endondontic files. These results have been validated by realizing rotating bending fatigue tests on the existing files.

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Procedia Engineering (2015) 1877-7058

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POSTER SESSION

FD15-070

INCREASING THE FATIGUE LIFE OF CIVIL ENGINEERING CABLES, BY USING A SHAPE MEMORY ALLOYS-BASED DAMPER.

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Shape memory alloys (SMA) have many interesting properties due to solid-solid phase transformations (usually between austenite and martensite), such as super-elasticity. More particularly, Nickel-Titanium (NiTi) based SMA are currently used in many industrial fields for their oxydation resistance and their fatigue resistance. Furthermore, their dissipation capacities make them particularly suitable for using as dampers dedicated to Civil Engineering issues. Indeed, several phenomena (road traffic, earthquakes, wind, rain...) which are the main causes of structure vibrations, affect the High Cycle Fatigue life of bridge cables.

Current solutions enabling to mitigate vibration amplitudes, consisting in setting-up hydraulic dampers, are not satisfactory out of their working range in terms of amplitude and frequency. Thus, a new device based on NiTi wires is presented in this study.

Two objectives had been set. First, a damping device is tested on a full-scale bridge cable, using Ifsttar's facilities (Nantes, France). Secondly, a numerical tool is developed to predict the NiTi wires based damper influence on the dynamical response of the cable. The purpose of this tool is to get a better understanding on the contribution of several phenomena for SMA, which affect wires dissipation properties and so their damping capacities: the martensitic and "intermediate" R-phase transformations, the strain rate effects and the phase interfaces propagation.

Thus, cable vibration tests are presented. The purposed device shows a real damping power effectiveness. Then, a finite elements model is briefly presented. A transient dynamic analysis is conducted using a beam elements made-cable. The damper is modelled as a truss elements-made wire. Its behaviour is based on a non-local formulation regarding the internal variables from the assigned superelastic thermomechanical behaviour. Eventually, an iteration process based on the numerical model and dedicated to optimizing the global system is described.

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Procedia Engineering (2015) 1877-7058

Procedia Engineering

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FD15-085

INFLUENCE OF MEASUREMENT AND MATERIAL UNCERTAINTIES ON THE PREDICTION OF RESIDUAL LIFE OF CRACKED STRUCTURES.

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Composite materials are used extensively in aerospace and more recently in automotive applications. Their high mechanical performances and good fatigue durability offer definite advantages compared to more traditional materials. However, in comparison with metal, damage mechanisms are complex and avoiding manufacturing defects is difficult. To be able to design composite parts, understanding the micro-mechanisms of damage is essential.

The aim of this study is to understand the difficulties in fatigue testing on thermoplastic composites, understand the damage mechanisms that occur during static loading and fatigue and to identify and characterize by Acoustic Emission the damage mechanisms in fatigue. The first results show the EA signal signatures may be identify for cracks in matrix or fiber failure in a thermoplastic composite. New developments are still in progress to increase the test frequency in dealing with the noise seen by EA sensors.

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Procedia Engineering (2015) 1877-7058

Procedia Engineering

6th Fatigue Design Conference, Fatigue Design 2015

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FD15-092

LEFM BASED FATIGUE DESIGN FOR WELDED CONNECTIONS IN ORTHOTROPIC STEEL BRIDGE DECKS

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Although fatigue in steel constructions is the most important form of fracture, it is the least understood. This remains especially true for orthotropic steel bridge decks. These decks are used in long span steel bridges since they are efficient for carrying heavy traffic loads when compared with the required amount of steel. However, many complex welding details exist due to the reinforcement with closed stiffeners intersecting crossbeams.

Therefore, these decks are sensitive to fatigue. Even recently built decks suffer fatigue problems, indicating the lack of knowledge on the fatigue behaviour. Improvements are made through increased weld quality reducing the lack of weld penetration. However, a trend of increasing the dimensions, which reduces the advantage of small structural weight, exists because of fear of fatigue cracks.

To increase the understanding of the fatigue behaviour of these welded details an improved analysing tool using Linear Elastic Fracture Mechanics (LEFM) is proposed in this paper. Apart from the fatigue life of the weld detail, the crack propagation and crack growth direction are evaluated with an eXtended FEM (XFEM) model, also including residual stresses. Residual stresses can have a profound influence on the material strength and the fatigue life.

Nevertheless they are often neglected during practical fatigue design. Because of their influence, these stresses are included in the XFEM model. In addition, thickness effects are evaluated for both longitudinal stiffener and deck plate. These calculations result in a better understanding of the increased fatigue properties. With the developed calculation method, a better understanding of fatigue in orthotropic steel decks is achieved, indicating that traditional calculation methods should be updated because of modern construction technologies.

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Procedia Engineering (2015) 1877-7058

Procedia Engineering

6th Fatigue Design Conference, Fatigue Design 2015

POSTER SESSION

FD15-095

FATIGUE BEHAVIOUR OF A THERMOPLASTIC COMPOSITE REINFORCED WITH WOVEN GLASS FIBRES FOR AUTOMOTIVE APPLICATION

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This work is the result of the cooperation between the DPMM laboratory (PPrime Institute) and the vehicles manufacturer Renault. This project aims to develop lightening solutions for cars using composite materials. Thus, the purpose of this study is to characterise the behaviour of a woven glass-fibre-reinforced composite with a thermoplastic matrix during a low-cycle fatigue test.

Optimization of the coupons geometry has been done in order to obtain a valid failure during fatigue tests. Thus, three different geometries have been investigated: rectangular (ASTM D3479), dumbbell and dogbone (as proposed by De Baere et al. [Pol. Test. 2011]). It is worth mentioning that for the three geometries, the gauge section is the same (equal to 20mm). The use of IR camera has allowed following the evolution of temperature cartography during fatigue tests and so, the location of stress concentration leading to the specimen failure. For rectangular specimen, the stress concentration is systematically located near the grip.

For dumbbell specimen, it is located in the fillets whereas the failure occurs in the center of the specimen for dogbone coupons. So, dogbone specimen has been chosen as the optimised geometry. Once the appropriate specimen geometry has been chosen, instrumented fatigue tests have been carried out at room temperature on 0° coupons (warp bundle in the same orientation as the loading direction). During these tests, damage mechanisms have been analysed.

Damage identification has been carried out using several methods such as acoustic emission, thermography and microscopic observations (optical microscopy, SEM, X-Ray microtomography). Acoustic emission associated to microscopic observations allowed identifying different types of damage occurring in fatigue within the material: fibre-matrix interface debonding, longitudinal fibre failures and meta-delamination. The next step of this project is to analyze the influence of fibre orientation and moisture on fatigue life. Three different orientations (0°, 90° and 45°) and three conditioning types (RH0, RH50 and RH100) will be studied.

In parallel, these tests were used for the evaluation of two different fatigue life models: a hybrid model based on the power and the exponential models proposed by Sarfaraz et al. [Comp. A. 2012], and the Epaarachchi et al. model [Comp. A. 2003] already validated in other studies [De Vasconcellos et al., Comp. B. 2014]. These models have shown good fitting to experimental data. Work is in progress to evaluate the ability of these models to predict fatigue life for this type of composites under different conditions.

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Procedia Engineering (2015) 1877-7058

6th Fatigue Design Conference, Fatigue Design 2015

POSTER SESSION

FD15-103

CORRELATION CASE STUDIES ON FATIGUE TEST AND CALCULATION

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Calculations can be performed in Fatigue testing for the following reasons:

4. preparation of a sample test,
5. the modification of an ongoing test,
6. the understanding of unexpected results.

Fatigue calculations could be (and should be) quite simple but requires a comprehensive knowledge of calculation theory and test engineering.

Material behaviour, fatigue analysis, fracture mechanics, signal processing are essential tools to deal with correlation calculations.

In a number of specific cases, an optimal correlation is obtained between experimental testing and calculations.

Authors have tried to illustrate this correlation approach between Testing and FEA (Finite Element Analysis) for the following examples:

5. Connecting rod modification of a test to obtain the right area of stress,
6. Simulation of Weld sample improvement by hammer peening,
7. Evaluation of test sample in “cascade”,
8. XFEM approach on samples.

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Procedia Engineering (2015) 1877-7058

Procedia Engineering

6th Fatigue Design Conference, Fatigue Design 2015

POSTER SESSION

FD15-106

DESIGN, FABRICATION AND FIRST USE OF A PNEUMATIC ROTATING BENDING SETUP FOR CONSTANT AND VARIABLE AMPLITUDE FATIGUE TESTING

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This work covers the design, fabrication and first use of a modular four point rotating bending test rig for fatigue analysis of cylindrical samples at controlled room temperature. The test rig consists of commercially available components and contains an in-house developed pneumatic actuator with closed loop force control. Cylindrical samples of various diameters (2-26mm) and lengths (100-300mm) can be tested at repeated bending loads at test frequencies up to 100Hz.

The sinusoidal stress amplitude can be constant or variable, allowing for a broad range of real-life loading conditions. The paper gives a detailed overview of the mechanical design and calculation of all subsystems including the alignment- and calibration procedure, study of dynamical behavior, sensor and control strategy, and development of the pneumatic actuator. Also the results of first tests on aluminum 7075 T6 and Ti6Al4V specimens are discussed.

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Procedia Engineering (2015) 1877-7058

Procedia Engineering

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POSTER SESSION

FD15-111

INFLUENCE OF GASEOUS HYDROGEN ON FATIGUE BEHAVIOR OF FERRITIC STAINLESS STEEL – A FATIGUE-LIFE ESTIMATION

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The Bosch Group a leading global supplier of technology and services develops reliable and efficient fuel cell components for future mobility solutions. In the publicly funded research project “MatFuel” (FKZ: 03ET2051A) the fatigue life of high-alloy steels under gaseous hydrogen atmosphere is investigated.

This work studies the fatigue behavior of stainless ferritic steel optimized for electromagnetic properties under varying environmental conditions. Air-tested specimens are compared to specimens which are electrochemically precharged with hydrogen and tested in a gaseous atmosphere of 10 bar hydrogen pressure. The fracture surfaces of broken specimens are investigated by SEM in order to analyze the failure mechanisms in air and hydrogen.

Based on strain controlled fatigue tests using unnotched specimens, the influence of hydrogen on the cyclic material parameters are determined. Using these parameters a fatigue-life estimation on the basis of the local concept for stress controlled notched specimens is carried out. Experimental data and predicted strengths/fatigue-lifes are compared and different estimation approaches are evaluated.

A modified material model is derived to model the influence of hydrogen on cyclic behavior of stainless ferritic steel. Furthermore, the hydrogen contents of specimens before and after static and cyclic testing in gaseous hydrogen are measured. Finally hydrogen embrittlement mechanisms on cyclic loading are discussed and tested for its applicability.

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Procedia Engineering (2015) 1877-7058

Procedia Engineering

6th Fatigue Design Conference, Fatigue Design 2015

POSTER SESSION

FD15-112

EDGE EFFECTS AND FATIGUE DELAMINATION OF COMPOSITE LAMINATES AND BONDED ASSEMBLIES

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Scale up wind turbine blades to catch more energy is a challenge of the offshore wind turbine market, and lengthening blades is permitted by lightening them using more efficient materials or improving the design. For these reasons, composite materials are widely used in wind turbine blades because of their density and capacity to sustain fatigue. However, the use of composite regarding fatigue, which mainly drives blade design, raises the question of the accuracy of the laws used to compute fatigue life.

Today, these laws are based on Goodman and Miner formulation on the laminate which leads to the following limitations: lack of precision corrected by high safety factors, long testing campaigns, no physical description of the damage state in composite and no taking into account the loading history.

Regarding these limitations, working at the ply scale with a fatigue damage model seams promising. However, we wonder if such models are accurate enough to predict fatigue life of the blade. Indeed, unidirectional plies are used in wind turbine blades. Their on-axis behaviour is well known but they are very sensitive to multiaxial loading which leads to early damage propagation.

To answer this question of law accuracy to compute fatigue life in composite wind turbine blade, multiaxial stress state has been calculated in fatigue in an existing blade by finite element analysis, damage has been observed under critical multiaxial stress states and predictions of existing ply-to-laminate fatigue damage models have been compared under this realistic stress state.

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Procedia Engineering (2015) 1877-7058

Procedia Engineering

6th Fatigue Design Conference, Fatigue Design 2015

POSTER SESSION

FD15-113

ASSESSMENT OF FATIGUE BEHAVIOUR OF ORTHOTROPIC STEEL BRIDGE DECKS USING MONITORING SYSTEM

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During the last decades orthotropic steel decks have become a widely used component of steel bridges, however high numbers of fatigue cracks have been recently detected in these structure types. It is well known, that the orthotropic decks are sensitive to fatigue damage, therefore safe fatigue design is important for the safety assessment of bridge structures. The fatigue damage assessment and life prediction of steel bridges can be carried out by using online structural health monitoring systems (SHM). By using the SHM system, it is possible to detect deterioration, determine anomalies and assess the safety level which will allow optimum maintenance strategies. On-structure long-term monitoring systems have been already successfully implemented on bridges all around the world in order to detect cracks just like on the orthotropic steel deck structure of M0 Háros Danube highway Bridge in Hungary. The purpose of the current research program is the investigation and analysis of the fatigue behaviour of this orthotropic steel bridge deck and the evaluation process improvement of the data rows collected by the monitoring system. Additional laboratory tests are carried out at 6 large scale test specimens at the Budapest University of Technology and Economics, Department of Structural Engineering to determine the fatigue resistance of closed section longitudinal stiffeners. In parallel finite element model is developed to simulate the fatigue behaviour of the analyzed components and to investigate its fatigue behaviour by numerical analysis. The aim of the current study is to analyze and verify the structural behaviour of the orthotropic steel deck on the basis of the executed test results, numerical simulations and the strain-time history data from the online structural health monitoring system implemented on the studied bridge.

Keywords: Orthotropic steel deck; Structural health monitoring system; Fatigue behaviour

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FATIGUE DESIGN 2017

29 and 30 November 2017

Senlis, France

Publisher of the Fatigue Design 2013 proceedings

1511-004

Fatigue Design 2015 - Abstracts Book