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# ABSTRACTS BOOK

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## POSTERS

# Fatigue assessment of welded joints : Notch Stress concepts - Background and applications

*Cetin Morris Sonsino (LBF Darmstadt), Germany*

Among modern fatigue design concepts for welded structures, the linear elastic notch stress concept gains increasing industrial acceptance. There are two variants of this concept, one for thick walled ($t \geq 5$ mm) welded joints with the reference radius $r_{ref} = 1.00$ mm, which is already included in the fatigue design recommendations of the IIW and applied for the assessment of big welded structures, and one for thin walled ($t < 5$ mm) welded joints with the reference radius $r_{ref} = 0.05$ mm, which more and more used in the automotive industry.

The concept with $r_{ref} = 1.00$ mm is based on the micro-support theory of Neuber with the fictitious radius $r_{ref} = 1.00$ mm, derived by Radaj. The background of the concept with $r_{ref} = 0.05$ mm is the relationship between the stress-intensity factor and the notch stress according to Creager and Paris as well as Irvin's theory of crack blunting. Besides these two theories, the definition of both of these radii has also an experimental background; they are observed in many welded joints.

In the proposed paper, first the background and then different applications of both concept variants will be presented: The application of the reference radius of $r_{ref} = 1.00$ mm for MAG-welded offshore K-nodes ($t = 30$ mm), and the application of $r_{ref} = 0.05$ mm for spot welded automotive doors ($t = 1$ mm) and MAG-welded automotive trailing links ($t = 3$ to 4 mm). Calculations and experimental results are compared and the reliability of the notch stress concept variants underlined. Additionally, recommendations for a further development of design lines distinguishing between thin and thick dimensions are given.

# Design and analysis methods and tools

*Wilfried Eichleseder (Institute of mechanical engineering), Austria*

The calculation of the fatigue life of geometrically complex structures requires the knowledge of the local fatigue behaviour of the material. Generally the investigation of the local fatigue behaviour by component test is not possible, as the study of parameters influencing the components fatigue behaviour takes too much time. Therefore a method is required to compute the fatigue life under local influences.

The local fatigue strength is influenced by notches, type of loading, temperature, load level and sequence etc.. The manufacturing process has a considerable influence. This paper is concerned with the manufacturing processes and their influences on the microstructure and fatigue strength. Especially the effects of casting-, forming-, welding- and surface treatment-processes are investigated. The different processes were simulated to get local effects such as solidification time, strain rates or residual stresses. Specimens with defined process parameters were produced and their fatigue life determined by tests. These test results are the base for the models created to compute local S/N-curves by simulation. The models allow the fatigue life prediction of geometrically complex components based on finite element results, taking into account local stresses, stress gradients and the manufacturing process.

The simulation of the manufacturing process and the understanding of the influence of the local condition on the fatigue life enable to close the simulation chain from manufacturing process to fatigue life prediction.

# Plastic work in fatigue design : a theoretical background

*Eric Charkaluk (LML-Ecole Centrale de Lille), France*
*Co-author : A. Constantinescu (LMS-Ecole Polytechnique), France*

Computer-aided fatigue design supposes many ingredients among which a damage indicator. During the past ten years, many proposals have been presented and they have kept our critical attention: among many, we mention those of Charkaluk, Park and Nelson, Koh, Haddar, Amiable, Riedel and Thalmair. However, as energy can be split in several parts which conduct to the definition of elastic, plastic, dissipated or stored energies, a discussion on the role of each of them is necessary. This is the objective of this paper in order to synthesize the different propositions which have been made during the last decades. A particular attention will be devoted to the link with shakedown concepts and to the thermodynamical justification of these different approaches.

# The effect on calculated fatigue life of phase changes at resonance

*John Draper (SAFE Technology), England*

Some components exhibit resonances in response to the loading. Resonant frequencies may imply both a change in gain and a change in phase. The phase change may occur over a narrow band of frequencies close to the resonant frequency. Conventional methods of calculating fatigue lives from PSD's of stress may ignore this phase change, because phase information is not present in the PSD.

This paper examines the effect on calculated fatigue life of phase changes at resonance. Data is taken from a finite element of a real industrial component, and the analysis uses load histories measured in service.

# Environmental Accelerated Testing
# Use of virtual test to extend physical approach

*Andrew Halfpennya (HBM – nCode Durability Products – Sheffield) England*
*Frédéric Kihm (HBM – nCode Durability Products – Roissy), France*

Vibrating components are highly susceptible to fatigue failure. Most components must fulfil some form of durability certification test prior to production. Tests are conducted on real prototype components or use a CAE based simulation of the component. The drive signals are often in the form of PSD obtained using the FDS and SRS/ERS test tailoring approach. The sign-off test can be accelerated using reduction factors applied on the PSD in order to optimise costs and development duration. Numerical Simulation may help by verifying the loading is realistic and representative and by showing a contour plot of the component damage calculated using real materials fatigue data. This paper presents this mixed Test/CAE approach and its application in a case study.

# Development of simple plate bending fatigue testing machine and fatigue tests

*Kentaro Yamada (Nagoya University), Japan*
*Co-Authors : K. Yamada, T. Ishikawa, T. Ojio, B. Biehn, Y. Samol, S. Yamada*

Fatigue testing machine for plate bending type of loading was developed using commercially available vibrator, a motor with built-in eccentric mass. The machine enables us to carry out plate bending fatigue tests in a relatively easy, fast and economical way. We carried out fatigue tests on fillet welded specimens to observe fatigue crack propagation behaviors in the last four years. The test data were compared with the same type of specimens in tension. Deck plate and a part of trough rib, and fillet welds between deck plate and trough ribs of orthotropic steel decks were also fatigue tested. The data are used to evaluate fatigue durability of existing orthotropic steel decks in Japan by FEM analysis and by stress measurement.

# Recent developments in the fatigue design and assessment of welded structures

*Gary Marquis (Helsinki University of Technology), Finland*

Materials and fabrication technologies for welded structures are continually evolving and developing. End users are also continuing to push the application limits of structures used in transportation, lifting and hoisting, offshore, energy production and many other fields. The drives to reduce weight and cost, increase energy efficiency, improve performance and reduce the environmental footprint of welded structures continue to provide challenges for designers in fatigue design of welded structures. This presentation attempts to provide a brief overview of current research topics and recent technological developments related to fatigue assessment for welded structures. Much of the work has been performed and reported within the scope of the International Institute of Welding (IIW), but other groups and individuals have also made important contributions [1]. The IIW has recently published new fatigue design recommendations for welded structures [2] which replace the widely used 1996 recommendations. These recommendations given most attention to the nominal stress method for analysis, but other methods are also described. A document devoted to the structural hot spot stress approach is available [3] and detailed recommendations for implementing the effective notch stress approach are being published [4]. These later methods give good accuracy even for complex structures, but the amount of effort required both to develop the FE model and perform the analysis increases rapidly in moving from the nominal stress to the fracture mechanics analyses. This is partially reflected in the element density required in the critical regions of the structure. As seen in Fig. 1, required element density may increase by 6-7 orders of magnitude between methods.

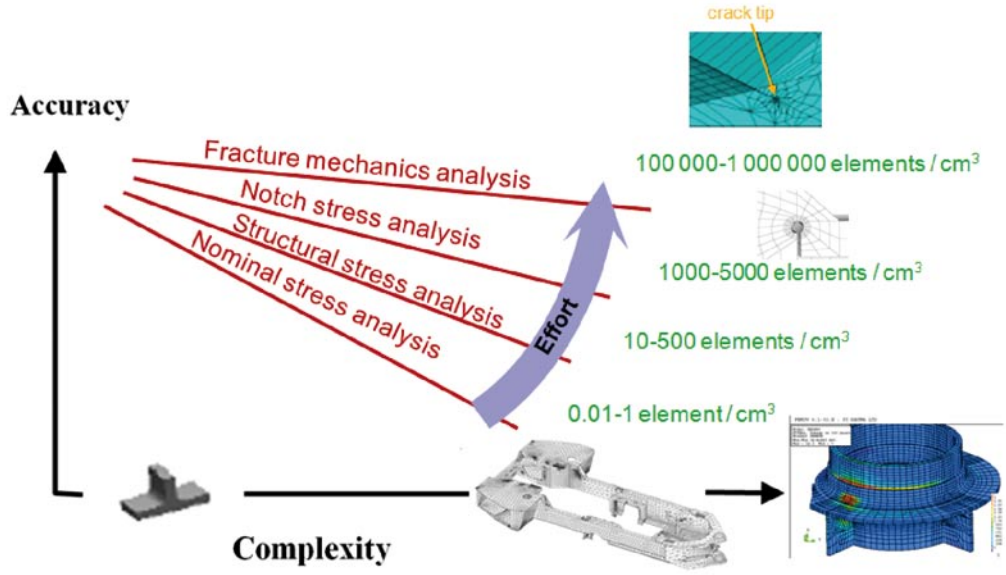


*Figure 1. Qualitative view of accuracy and effort for several fatigue assessment methods for welded structures*

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# Fatigue assessment and structural analysis of arc welded components in vehicle constructions–estimation and applicability

*Martin Vogt (TU Braunschweig), Germany,*
*Co-authors : E.Hanssen, K. Dilger*

For thin-walled steel structures welded joints often turn out to be the weak spots under cyclic loading with constant or variable amplitudes. For the dimensioning of welded safety components in vehicle construction well-defined and in terms of their prediction accuracy reviewed strength concepts are necessary.
Within the scope of the research results presented here, the applicability of the nominal, structural and notch stress approach is under examination on the basis of different arc welded and cyclic loaded steel structures, taken from the automotive and railway sector. In detail these are a transverse control arm and a crossbeam connection from the underframe of a railcar body. Different sheet thicknesses in the range of 3 mm, 4 mm and 7 mm leads in combination with a misalignment to an increase of load in the region of the weld seams. Several different Components and specimens with critical regions of failure are tested under cyclic loading with constant amplitude. With the help of strain gauges, the technical crack initiation is determined. A short outlook of the possibility to get information about the crack initiation by the ultrasonic-burst-phase-thermography is also given.
The specimens are the basis for application and evaluation of the different concepts for the assessment of fatigue life. The numerical determination of the nominal, structural and notch stresses is performed with finite-element models. For a local approach, according to the notch stress analysis, a submodelling technique is used. The FE models are compared with the experiment by means of optical 3D deformation analysis and strain measurements with strain gauges. Existing weld seam and specimen tolerances are included by the usage of parametric models. Finally the experimental and computational results allow the derivation of structural and notch Woehler-lines (S-N-curves) for the crack initiation and the rupture of the specimen.

# Crane runways - fatigue evaluation of crane rail weld using local concepts

*Mathias Euler (Stuttgart University), Germany, Co-author : Ulrike Kuhlmann*

The introduction of the wheel loads into a crane runway with hot rolled I-section and block rail fixed by longitudinal fillet welds forms a multiaxial fatigue problem. At the point of wheel load application the top region of the runway beam is subjected to a stress field comprising local stress components induced by the concentrated load, i. e. local transverse pressure $\sigma_z$ and local shear stress $\sigma_{xz}$ , in addition to the global stress components $\sigma_x$ und $\sigma_{xz}$ due to global bending. The superposition of all forementioned stress components (and stress ranges, resp.) during each single crane pass results in a so-called non-proportional cyclic stressing of the rail welds with alternating principal stress direction.

Due to the variation of principal stress direction in case of a non-proportional stressing the fati-gue evaluation of IIW and Eurocode is based for these design situations on a damage accumulation by *Palmgren-Miner* rather than on equivalent stresses. Interestingly, test data show that the damage accu-mulation is not conservative [1]. Moreover, a reduction of the allowable damage sum *D* below unity (for ex. IIW only allows for $D = 0.5$) seems not to be sufficient. Thus, it can be stated that the today's evaluation procedures do not adress the reasons of multiaxial fatigue in a realistic and conservative way. Local concepts appear to be more appropriate to describe the multiaxial fatigue phenomenon.

This paper presents the usage of local concepts for the fatigue evaluation of the wheel load application. The critical plane approach proposed by *Findley* and the effective equivalent stress hypothesis developed by *Sonsino* are used. The paper compares the results of both methods with test data of own girder tests [2] and those from literature.

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# Fatigue design of welded joints based on European fitness-for-service procedure FITNET

*Shahroukh Daneshpour (GKSS-Research Center Geesthacht), Germany*
*Co-authors : M.Koçak, W.Vaidya, S.Riekehr*

This study describes the fatigue performance of laser beam spot welds on automotive grade steel sheets in overlap and butt-joint Al-alloy welds subjected to constant amplitude loading. Laser spot weld geometries, consist of open and closed weld ring, were welded by Nd:YAG laser welding on DC04 (deep drawing) sheet steels with 2.0 mm thickness and then tested to find the optimum weld configuration from fatigue performance point of view. Here, new laser spot weld geometry was developed, where both the start and end points were protected from external forces by a layer of continuous welded material, since the start and end points of the welds are often prone to failure due to low penetration, weld defects and impurities. This weld geometry showed high fatigue life with failure occurring outside of the start and end points and can also be used to reduce the edge size of profiles used in automobile body-in-white, and lead to weight saving. Fatigue tests of laser welded butt joints of Al alloys sheets of 3.0 to 5.0 mm thicknesses were also performed. Fatigue lives analyses of those joints have been performed based on "structural stress and notch stress approaches" of the Fatigue "Route 2" of newly developed European FITNET fitness for service (FFS) assessment procedure. The structural stress makes use of the stress adjacent to the weld that includes the stress concentration effect of the welded joint, but excludes the local notch effect of the weld itself which is accounted in the notch stress approach. Here, the structural stress and notch stress have been used as fatigue damage parameters to correlate the fatigue test data of different joint configurations. Results reveal that the Fatigue "Route 2" of the FITNET FFS procedure can qualitatively and quantitatively describe fatigue performance of those joints.

# Fatigue design for laser welded structures

*Thi Thuy Trang Lê (LMS-Ecole Polytechnique), France, Co-authors : H.Maitournam, L. Augustini*

The welded areas are the weakness parts of the structures. They require more care about design,fabrication and control. However, the fatigue life prediction of the welded structure is complicated because of change of micro-structure, material mechanical properties at thermically affected zones and residual stresses. The aim of this work is to propose a simple methodology for fatigue design of laser welded structures for automotive application.
This methodology is a structural approach which couples the finite element calculation and the fatigue experimental results. It consists in defining a structural stress, determined by averaging the stress on an elementary volume of special size at the most critical point of the structure (at the weld root or weld toe). Based on the Dang Van fatigue multi-scale criterion, the proposed definition of structural stress is function of equivalent shear stress amplitude and maximal hydrostatic stress. It takes into account of different slip systems and enables the fatigue life prediction of weld structures under uniaxial, in-phase or out-of-phase multiaxial loading. This structural stress, determined on different elementary volumes, is used to derive Woehler diagrams. The volume which gives the smallest scattering of the Woehler curve is the optimal one.
The proposed methodology is practically applied by using a special finite element model initiated by Fayard. This method consists to simulate the weld by the rigid beams and model the sheets by quadrilateral shell elements which have, at the weld toe, the same size as the elementary volume.

# Life prediction of welded steel joints, accuracy and shape of the S-N curves under constant and variable amplitude loading

*Tom Lassen (University of Agder), Norway,*
*Co-authors : N. Recho (ERMESS, LAMI-Université Blaise Pascal), France*

Experimental life data for welded joints are usually modelled by an S-N curve that is used for fatigue life predictions. It has, up until now, been consensus on the facts that these curves have an inverse slope of $m_1$=3 and that there exists a fatigue limit at N=$10^7$ cycles under Constant Amplitude (CA) loading. However, in the last proposal made by the International Institute of Welding (IIW-2005) the existence of a fatigue limit was questioned and it was suggested that the curve should continue to fall with a shallow slope even beyond N=$10^7$ cycles. The present paper pursues this hypothesis further. The traditional linear regression analysis of fatigue life data is replaced by a Random Fatigue Limit Model (RFLM). Furthermore, as a complementary approach, the physical damage process itself is modelled by both fracture mechanics and a Two Phase Model (TPM) that takes fatigue crack initiation phases into account. The statistical modelling by the RFLM and the physical modelling by the TPM gives consistent results. The obtained S-N curves are non-linear for a log-log scale and they do not predict any fatigue limit. The curves change slope gradually and the stress range continue to decrease with increasing number of cycles. The long fatigue lives at low stress ranges are explained by a significant crack initiation period. The curves fit collected life data far better than the conventional bi-linear curves found in rules and regulations. The curves predict considerably longer fatigue lives at low stresses than the conventional curves do, despite the non-existence of a fatigue limit under CA loading.

This proposed model will also have an impact on life predictions made under Variable Amplitude (VA) loading which is the most common case for structures in service. At present the S-N curves, given in rules and regulation, changes slope from $m_1$= 3 to $m_2$= 5 at N=$10^7$ cycles under VA loading in air. There are very few data that actually corroborates this change in slope. The lower curve with $m_2$=5 is based on a work carried out by Haibach (IIW 1970). The model explains the fatigue limit by pure fracture mechanics, applying the notion of a threshold value for the Stress Intensity Factor Range (SIFR) in conjunction with the Miner's summation rule. Load cycles with stress ranges that for the current crack size does not result in a SIFR that exceeds the threshold value of the SIFR will not contribute to the fatigue damage. The analysis resulted in an equivalent slope of $m_2=2m_1-1$ for the S-N curve. The present work questions the validity of the assumptions on which the slope of m=5 was obtained. As recent works have indicated, it is doubtful if the fatigue limit exists. Furthermore, small initial cracks are not likely to obey the threshold value for the SIFR. This threshold value is proven for longer cracks only. Hence, the paper tries to shed some light on these topics and makes an attempt to reconsider the slope of the lower part of the S-N curve for VA loading.

# Fatigue assessment of tubular welded connections with the structural stress approach

*Fabien Conti (Bureau Veritas)*
*Co-authors: Laurent Verney (Bureau Veritas), France, André Bignonnet (AB Consulting)*

The fatigue behavior of tubular joints for offshore industry was analyzed within the framework of a European programme in the 70s and 80s.
The objective of this paper is to summarize the application of DANG VAN Fatigue criterion with the structural stress approach for several tests of the database.
Then some issues are briefly discussed, like meshing strategy, stress concentration factor, fatigue curve, the weld toe influence, and a comparison with the hot spot stress methodology currently used for the design of offshore structure

# Brifag-Bridge Fatigue Guidance:a European Research Project

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*Co-author : Timothy Righiniotis (The Univ. of Surrey, Guildford), UK, Ladislav Frýba (Inst. Of Theorical and Applied Mechanics, Prague), Czech Republic*

Bridges are a vital part of the infrastructure in any modern society. Their service lives – when steel and composite bridges are concerned – are invariably governed by fatigue, making thus the adequate fatigue performance essential for their competitiveness. Unfortunately, actual fatigue verification rules are becoming outdated for the design, both in terms of the coverage of design details and applicability to modern structural analysis methods; furthermore they have never been adapted to address maintenance issues such as inspection and repair. The aim of the three-year RFCS research project described in this paper is to cover as reasonably many gaps identified in current standards and recommendations as possible that a practicing engineer may face when carrying out fatigue design or assessment using those documents. The achievement of that aim is expected in five work-packages on which nine partners have been working since July 2008. The end of the project is scheduled for June 2011, followed by the publication of its findings. That should provide a comprehensive guidance for the fatigue design of new and maintenance of old steel bridges.

# Fatigue Classification of welded joints in Orthotropic steel bridge decks

*Henk Kolstein (Delft University of Technology), Netherlands*

The objective of the study in this paper is to provide the code writers of the Eurocode on Steel Structures with additional information on the fatigue classification of welded details in orthotropic steel bridge decks. The current Eurocode 3 – Design of steel structures – Part 1.9: Fatigue (EN 1993-1-9, 2005), still needs some modification with respect to the design Äó-N curves and there is a strong need for considering the mean Äó-N curves for the fatigue evaluation of the existing orthotropic bridge decks. A review of all available data on orthotropic decks and related fatigue test results (762 tests) is included. The statistical analysis procedure used to derive the weld classes for Eurocode 3 is used to place all of the main joints in the appropriate class, and rank different designs of each joint.
For a risk-based maintenance it is necessary to guarantee the safety of the structure with a required safety level described as the reliability index â. Target values for the reliability index â are given in the Eurocode: Basis of structural design (EN 1990, 2002). Depending on degree of possible inspection, repair and damage tolerance, the target reliability index â for fatigue varies from 1.5 to 3.8. In the fatigue lifetime calculations different safety factors are used considering the detail classification, the number of stress cycles or the stress ranges. These safety factors all have to be used in combination with the mean value of the fatigue strength and not with the characteristic value of these curves. In this paper also the mean values at two million cycles of the different data sets are given

# Fatigue behaviour of plate material, beams and welded joints made out of hollow sections regarding size effects and repair techniques

*Ömer Bucak (Muenchen University), I.Mangerig (Univ. der Bundeswehr), Germany*
*Co-author : J. Lorenz, N. Romen*

Regulations for the consideration of bigger wall thickness are given in the European codes. The wall thickness correction factor is given by EC 3. Part 1.9 for plates thickness > 25 mm:
SR = SR,D x (to / t) 0,25
In CIDECT- Design Guide Nr. 8, a reference wall thickness of 16 mm and two different values for the exponents are given. Different standarts and different research in many countries show different results. New tests an X-Joints performed in Germany for a bridge project show a better fatique life for specimen with wall thickness of 30 mm and more. In the CIDECT / AIF- Project we will check following items:

- with new tests on specimen made of CHS and RHS it will be checked, how far the wall thickness correction factor can be modified.
- the dimensions of the specimen are elected as well, to extend the area of validity of the CIDICT- Design Guide
- the extension of the fatique life through a subsequent treatment method (PITec and/or HiFIT) will be checked
- after the fatique crack, the joint will be repaired by gauging and rewelding; thus the fatique life after repairing / rewelding will be tested
- repaired joints will also be tested with subsequent treatment methods (UIT and/or HiFIT) for testing the extension of fatique life of rewelded joints.

# Fatigue life extension of new and ageing offshore structure techniques and life assessment

*Per J. Haagensen (Norwegian University of Technology), Norway*

Generally, fatigue failures in welded structures can be avoided by good design practice, i.e. avoiding details with sharp notches, choice of suitable welding techniques, by using materials with high resistance to crack initiation and low propagation rates, or by post weld treatments. For existing structures in which fatigue damage has developed, the options for repair and life extension are normally more limited. The methodologies for assessment of remaining service life are however, similar in the two situations as they may be based on either fracture mechanics crack growth analyses or, by assuming a crack initiation phase, on strain-life models.

Recent developments in steel and filler materials with enhanced fatigue properties are discussed and examples of gains in fatigue life are reported. Impacts on the use of higher strength steels in light weight structures are discussed. Developments in industry approaches to life enhancement and numerical modeling of the total fatigue life comprising crack initiation and crack growth are reviewed.
Examples of applications of life improvement techniques in repair and life extension of structures are given. Future developments to ensure improved fatigue performance of welded structures are identified.

# Approval by Classification Societies of LETS Global ® life extension procedure for Offshore Installations.

*Luis Lopez Martinez*
*LETS Global ®. Postbus 50531 JA Rotterdam, The Netherlands*

LETS Global ® has during five years developed its own ultrasonic peening equipment and procedures for fatigue life extension of offshore structures.

Independent fatigue testing has been carried out at NTNU in Trondheim, Norway, with LETS Global ® equipment and procedures and in close co-operation with Classification Societies. That is to ensure the fatigue test results of the improved welds are consistent with current standards and regulations.

The fatigue life extension achieved of improved specimens is four times calculated on the base of fatigue design curves when compared to endurance in as-welded condition for a given welded detail. The degree of improvement is up to ten times when high cycle fatigue regime is considered. For specimens which have already consumed half of their fatigue life the treatment resets the clock to zero, as a minimum value.

The fatigue test specimens have been subjected to static load before fatigue testing to achieve almost complete relaxation of compressive residual stresses induced during ultrasonic peening treatment. This demonstrated that the degree of life extension could be retained even if the more severe load conditions would appear for a structure during its remaining service life and after ultrasonic peening treatment was applied.

The paper explains the trajectory before and during the approval and presents some of the works carried out on the offshore installations by LETS Global ® during these years.

# Life extension of offshore structures, what can be learned from decommissioned installations ?

*Kenneth Macdonald (University of Stavanger), Norway*
*Co-author : P. Haagensen (Norwegian University of Technology), Norway*

This paper presents a study of life extension on the Norwegian continental shelf where fatigue of weldments remains a central theme for structural integrity. As an increasingly large number of offshore installations are ageing, regulatory interest in ageing and life extension of offshore structures in Norway is supporting a number of diverse studies aiming to establish a better understanding of the pertinent issues. This present study deals with the question of what should be tested given that decommissioned structures on the Norwegian shelf can be made available for study. The background to this initiative lies in the increasing number of applications received for lifetime extension for installations where there exists only limited knowledge of the behaviour of structures and materials beyond their original design lives. As more and more structures are being removed, the regulations (from early 2008) now propose that testing of these removed structures be used to fill gaps in our knowledge of ageing processes and degradation mechanisms.

The challenges facing operators working with lifetime extension and the capabilities of R&D organizations to generate knowledge about relevant degradation mechanisms in ageing structures were reviwed and collated at a national workshop. Subsequently, a group of projects was funded to determine the state-of-the-art in relation to lifetime extension and propose what could reasonably be expected from testing performed on aged structures removed from service. The present group of studies aims to identify the important ageing and degradation mechanisms and to establish a framework of materials tests that could be performed on sections of decommissioned structures in order to extend our current knowledge. Of equal importance is to identify those aspects of aging that cannot be resolved by materials testing. An overview of the life extension project as a whole is also given.

# ECCS guides on good design practice and design according to EN 1993-1-9

*Alain Nussbaumer (ICOM-EPFL), Switzerland*
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The European Convention for Constructional Steelwork (ECCS/EKS/CECM) publishes various technical documents : guidelines, design examples, manuals, to ease in engineering offices the use of steel in structures. Guideline n° 105, first published in 2000, is dedicated to the manufacture of structures subjected to fatigue loads induced by frequently changing actions, traffic actions, wind induced oscillations or comparable actions. It contains a review of the current knowledge in fatigue design and in fabrication of fatigue resistant structures. This guideline also contains information about design in conformity with Eurocode 3 standards, which deals with the design of steel structures. Furthermore, it contains information about fabrication aspects not fully covered in the Eurocodes.
Currently, new ECCS design manuals are being drafted to cover all subjects in the different parts of Eurocode 3. One of these manual deals with EN1993-1-9 and all parts in Eurocode 3 where fatigue is a limiting design state.
This paper will present an overview of these two documents, which are closely related, in order to give the principal rules and specifities of good fatigue design. Both these ECCS publications should be viewed as a source of advice to be consulted before designing, fabricating, or repairing a structure subjected to fatigue.

# Fatigue failures at stiffener connections in highway composite bridges

*Andres Taras (Graz University of Technology) Austria*
*Co-author : Richard Greiner*

Many large highway bridges on the route through the Alps of Austria are designed as open-section composite plate girder bridges with two main girders and a thin pre-stressed concrete slab that protrudes to both sides. A number of these show numerous fatigue cracks of the welds connecting the vertical web-stiffeners with the upper flanges. One reason for these failures is the fact that the carriageway width has been increased leading to enlarged cantilever lengths of the concrete slab of up to 4 m. A second reason is that the outmost traffic lane is used as heavy truck lane, which increases the cantilever bending moment significantly. A third reason results from the high increase of the traffic, both in number and weight of the trucks.

A research project was carried out by the Austrian Highway Authority ASFINAG to clarify the background of the failures and to investigate proper solutions for refurbishment. Numerical simulations using non-linear FEM techniques, measurements of strains and deflections on site and experimental fatigue testing on large-scale specimens have been performed. These investigations made clear that the lifetime of the weld connection is influenced by numerous structural effects, as the bending stiffness of the concrete slab, the stiffness of the shear studs, the thickness of the upper flange and the bracing system of the cross-section. Different types of weld connection and weld improvement methods have been tested and evaluated.

This paper gives a summary of the most significant findings of this research project and presents the chosen refurbishment solutions.

# Fatigue testing and analysis of an orthotropic bridge welded detail using structural hot spot stress method

*Mohamed Al-Emrani (Chalmers University of Technology), Sweden*
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At present, more powerful tools for numerical modeling and structural analysis are available to fatigue design and assessment of complex structures. Taking advantage of these tools, hot spot stress approach (HSS) gives more accurate results than the nominal stress method. It incorporates the effect of structural geometry into the local stress ranges at the welds and predicts the fatigue life based on these local stress ranges. Eurocode 3 has recently accepted the hot spot method for fatigue design of welded steel structures.

In this study, fatigue tests are conducted on part of the orthotropic bridge decks. Strains at the points close to the weld toe are measured by means of strain gauges. Different finite element models are made and different methods for calculation of the hot spot stress (or structural
stress) range are examined to evaluate the fatigue life of specimens based on both EC3 and IIW codes. the theoretical results are then compared to the results from the experiments to determine which method(s) can better predict the real behavior. This research also provides valuable information on how finite element models could be made for use in the HSS approach to predict the fatigue life with acceptable accuracy.

# Classification of various butt welds with regard to steel grade and post weld treatment

*Stefan Herion (University of Karlsruhe), Germany*
*Co-author : J. Hrabowski*

At the Research Centre for Steel, Timber and Masonry at the University of Karlsruhe extensive fatigue tests on butt welded plates were carried out in the last years. Butt welded plates with different weld executions, in various dimensions and made of different steel grades, and also specimens treated with high frequency hammer peening have been investigated.

To reduce the weight of a structure without loosing load-capacity, high-strength steels are more and more applied. Thereby both, material and energy costs and weld volume can be reduced. Since for structures made of high-strength steels the fatigue design mostly is the decisive factor, different variants of butt welded plates are investigated regarding their fatigue strength. Therefore steels with yield strengths from 355N/mm² up to 1100 N/mm² are used. The butt welded plates are welded with and without backing strip, with sealing run and with sealing run and grinded root. Also butt welds with wall thicknesses up to 30 mm are investigated. Some test series have also been investigated treated with high frequency peening methods, which have an very positive effect on the fatigue strength and can extend the lifetime of a structure by a multiple.

The results of the fatigue tests will be summarized and evaluated regarding different welds, wall thicknesses and the use of high strength steels. In addition the possible benefits of the high frequency hammer peening methods will be presented. The results are discussed referring to the classification into the detail categories of Eurocode 3 [2] as well as with the new IIW guideline [3].

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# Geometrical aspects of the fatigue behaviour of laser hybrid fillet welds

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*Co-authors : Z.Barsmoum (Royal Institut of Technology) Sweden, P.Jonsén, H.A Häggblad, A.F.H. Kaplan (Lulea University of Technology), Sweden*

Cracking of laser hybrid welding of eccentric fillet joints has been studied for stainless steel. Laser hybrid welding enables narrow deep welds with freedom for shaping the upper weld geometry. The significance of geometrical aspects like weld toe radius, weld surface topography and lack of fusion on fatigue cracking is discussed. Constant amplitude four point bending tests, S/N-curve, topography measurement, microscopic analysis, FE-simulation and other methods were carried out. Cracking is initiated inside the weld, thus not in the HAZ. The influence of both global and local weld geometry, like the toe radii, on the stress concentration factor was studied by FE-analysis. The FEA revealed that surface roughness profiles can generate high stress peaks. In particular, it was found that the typical fishbone-like resolidification pattern at the top surface determines the crack propagation direction at the surface. Thus not necessarily the toe radius but rather the surface topography determined the crack initiation. Correlations between toe radii, the corresponding stress maxima and FAT values of each specimen were studied. Moreover, it could be explained why even significant lack of fusion does not affect stress raisers during the initial cracking phase, as long as the lack of fusion interface experiences compressive stresses only.

# Influence of several weld bead finishings and post-weld improvements on the fatigue resistance of welded attachments

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Attachments of machines such as loaders, hydraulic shovels, cranes or tractors are submitted to high mechanical stresses during loading and unloading of heavy weights, leading to fatigue damage in the welded joints between the attachment and the beam (figure 1). Today, many different types of welded joints and post-weld improvements are being used by manufacturers. However, to the knowledge of the authors, few studies have tried to evaluate and classify the fatigue resistance of those welded joints and post-weld treatments under a realistic mechanical stress state induced by traction loading of the attachment. Indeed, most studies have considered the fatigue life of such welded joints using standard T-joint fillet weld specimens, which do not reproduce the real stress state in the attachment and in the welded joint. In this context, the Commission Interprofessionnelle du Soudage (CIS) of the Fédération des Industries Mécaniques (FIM) and the Centre Technique des Industries Mécaniques (CETIM) are leading a research project carried out by the Institut de Soudure (IS), which aims to evaluate and compare the fatigue life of different types of welded joints as well as the influence of different post-weld treatments under traction loading of the real structure. In a first step, the optimal geometry of attachment has been identified using finite element analysis. In a second step, fatigue tests combined with finite element analysis, performed on the optimal geometry extracted from the first step, have been carried out to evaluate and compare the fatigue resistance of different welded joints and post-weld improvements. In a third step, a reinforcement seeking to increase the fatigue life of the welded joint has being designed using finite element analysis and validated by fatigue tests.

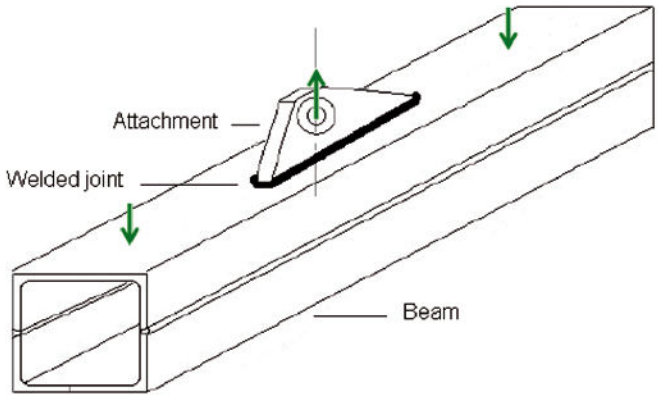


*Figure 1. Geometry of the component considered in this study.*

# Extending fatigue life by closing crack opening ICR treatment

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Numerous fatigue cracks have been found in Japanese highway bridges since 1990s. It was mainly due to heavy truck traffics associated with economic growth and modal shift from cargo trains to trucks and unfavorable weld details being used in the old bridges built after the World War II. It is therefore urgent to develop efficient repair and retrofit methods for such fatigue cracks in order to maintain such highway bridges. One technique we developed was to use air tool to peen plate near and to produce plastic deformation of the steel surface in order to close crack opening. Theoretically it reduces crack length, and hence reduces stress intensity factor of the crack. The technique is now called ICR treatment, abbreviated from the full name of Impact Crack Closure Retrofit treatment.

First fatigue crack was developed in notched flat plate, and then it was closed by peen both sides of crack and right on the crack. Plate bending fatigue tests showed significant improvement of fatigue lives for the cracked and ICR-treated specimens. Then, we carried out plate bending fatigue tests of out-of-plane gusset specimens. Fatigue cracks at turn-around welds and those which propagated 10mm were ICR-treated. Both showed again significant improvement of the remaining fatigue life.

# Determination of the parameters responsible for the run off district heating steel pipes

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Dalkia's district heating networks are made of steel pipes carrying hot or overheated water (from 110°C to 180°C). Those pipes are often isolated and buried in a concrete channel. Their maintenance is mainly curative because of their lack of accessibility. Due to economic and security reasons, Dalkia would like to anticipate the renewal of its pipes.

The pipes are subjected to complex thermo-mechanical loading. The in service boundary conditions depend on parameters of various kinds: the conception parameters (isolation, embedding), the exploitation parameters (fatigue, water hammer) and the environmental parameters (corrosion, collapse of concrete channel culvert). Numerical modelling with the help of finite element (FE) analysis was attempted. The thermo-elastic mechanical properties were obtained thanks to experimental tests, whereas the Wöhler curve was issued from the literature. FE modelling was purposed to analyse which of the abovementioned parameters are the more detrimental for the pipes.

The results seem to show that the fatigue due to the exploitation of the district heating and the localized defect due to corrosion (environmental parameter) are the more critical for the pipes.

# Shielding effects in multiple fatigue cracks: an experimental simulation of thermal fatigue effects, in stainless steel 304.

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Thermal fatigue often gives rise to 2 dimensional networks of cracks in components. This is especially the case in mixing zones of the cooling systems in nuclear power plants. A major concern is to assess if such complex networks yield to crack arrest or if a crack may become critical due to uncertain boundary loading conditions. An array of parallel notches at constant spacing was therefore used with a central deeper crack. Tests were carried out on austenitic stainless steel 304, at room temperature, using a load shedding programme prescribed as a function of dominant crack depth: this loading was deduced from a numerical fracture mechanics analysis of thermal fatigue cracks in components made by EDF. The behaviour of the dominant crack, in the array of parallel cracks, was compared with that of a single crack for the same loading programme. The difference in notch depth between the dominant crack and secondary cracks was varied to identify conditions giving rise to crack arrest. Both infrared thermo-graphic measurements and finite element computation of stress-strain field were used to rationalize fatigue crack growth results.

# High cycle fatigue modelling of casting of nickel superalloy for hot part elements of gas turbine at compressor stations

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In the present work we studied the relation between the high-cycle fatigue strength and melting and casting regimes of high-temperature nickel alloy ZMI-3 (KhN64WMCYuTL), which is used for example instead of IN738 for hot part elements of gas turbine GTN 25 I at compressor stations (Pipeline Russia-EU). Alloys for the study were obtained by induction melting in VIAM-24, UPPF-1, UPPF-2M furnaces at a pressure of 5,3 - 1,4Pa. The melted alloys were cast under vacuum into heated ceramic molds. We used the method of experimental design for the choice of temperature regimes of casting. The independent variables were the temperature of overheating (1550 - 1590°C), the temperature of metal bath under casting into heated ceramic molds (1510 - 1550°C) and the temperature of molds (700 - 900°C). The optimization parameters were: high-cycle fatigue strength at N= 2.107 cycles, the elongation at 900oC, and the size of macro grains. Analyzing the results of the study we obtained adequate regression equations describing the influence of the temperature regimes of casting on the optimization parameters (in the ranges of the study). The high-cycle fatigue strength decreases at the temperature rise of overheating and metal bath under casting (in the range of study). We also established that as the temperature of overheating was increased from 1550 to 1590°C (the temperature of molds 900°C) the macro grains in homogeneous in size decreased. At the temperature rise of molds from 700 to 900°C, the high-cycle fatigue strength and an elongation grows. The obtained models are used to predict the relation between the high-cycle fatigue strength and melting and casting regimes of high-temperature nickel alloy ZMI-3 (KhN64WMCYuTL), which is used for example for hot part elements of gas turbine GTN 25 I at compressor stations (Pipeline Russia-EU).

# High cycle thermal fatigue prediction in piping mixing zones nuclear power plants

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Nuclear power plant piping may be submitted to time temperature fluctuations coupled with space fluctuations in mixing zones. This High Cycle Thermal Fatigue (HCTF) phenomenon occurs in pipes where flows at different temperature and different flow rate ratio mix in a turbulent manner. Local or global temperature fields resulting from this turbulent mixing lead to stresses that may cause fatigue damages.
Starting from the Civaux reactor incident in 1998 linked to this phenomenom, FATHER is a test campaign devoted to the understanding of thermal fatigue. It constitutes the centre of the CEA/EDF/AREVA collaboration on this frame since then. This facility is exceptional and unique in the world since it allows reproducing, in laboratory conditions, a 6" mixing tee area in representative dimensions and loading conditions (temperature difference and pressure) (cf. Figure 1).
However, even in such experimental devices, HCTF analyses are complex and involve expertises in thermal hydraulics for thermal loading, mechanics for structure response calculation and materials for fatigue resistance. In this paper, we will focus on the second point, mechanics, to explore the capability to predict crack initiation by current fatigue criteria.
For the moment, nuclear industrial partners have at their disposal simplified methods only relevant as screening techniques. The latter enable to compare several configurations to judge their efficiency to reduce HCTF consequences but they are not able to give reliable quantitative elements for damage analyses.
Therefore, developing new methodologies for evaluating crack initiation is needed. The challenges that one has to face are the AISI 304L HCF viscoplastic behavior and the modelling of aggravating effects like surface finishes, mean stress, plastic preloading or multiaxial loading.
Within the framework of the CEA/EDF/AREVA collaboration, benchmark tests on several fatigue criteria have been performed. The distribution of unsteady temperatures in the wall of the 6" FATHER mixing tee mock-up was the start point of the calculation. The results seem realistic even if they are not still very accurate. The major issue was to test stress, strain and energy based criteria. This paper proposes to have a closer look at the results.

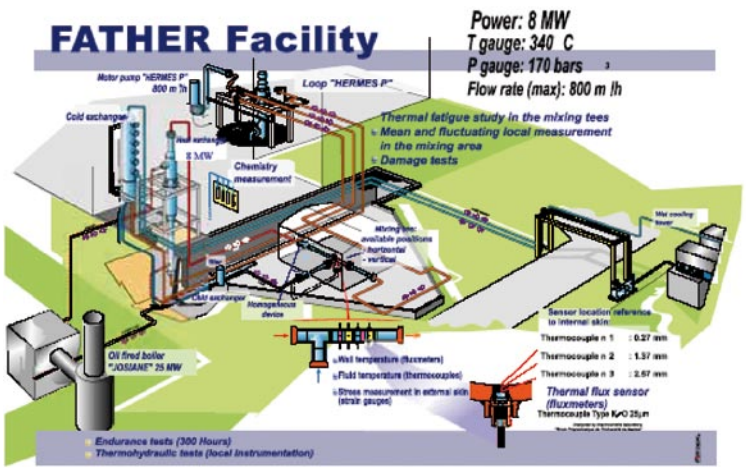


Figure 1: Description of the FATHER facility

# Assessment of thermomechanical fatigue and sealing of cast iron and steel sheet exhaust manifolds

*Bertrand Leturcq (PSA Peugeot Citröen)*
*Co-author : F. Szmytka*

The thermomechanical fatigue issues in the automotive industry are more than ever of great concern for the definition of a new engine, especially in these times of hard cost hunting and guarantee extensions policies. It is particularly true for the exhaust manifold itself, which has to be durable and leakage free, but also for the engineering and long run testing activities primary for components approval. In the same time the level of requirement for the manifold rises slowly but endlessly due to the increases of gas flow and temperatures, the extension of thermal and acoustic shields and, most of all, the shrinking of the allowed space due to the crash line and catalytic systems. In these industrial conditions, the aim of this study is to improve the existing fatigue and sealing assessment method for cast iron manifolds and also to develop a new one for the sheet metal technology now often used on Diesel engines. The fatigue lifetime and sealing predictions must be as accurate as possible in order to make the best compromises at the first project stage without multiplying the design / testing loops. This compromise should be best determined considering the vehicles specifications in which the engine will be used and the customers use in the common and uncommon situations as well as the goal for the failure rate. The main difficulty is that the system responds to any small evolution in the boundary conditions by a great variation in life span and dimensional stability. So it was decided to analyze and rework almost all the individual operations or boundary conditions with the best possible respect to physics in order to correlate well with the standard testing.

Accuracy of the constitutive law use to describe the anisothermal complex behavior of cast irons or stainless steel is also a main issue in the simulation process. Two flow rules and the corresponding constitutive elasto-viscoplastic models, combined with new experimental strategy are introduced in order to correctly represent cast-iron and ferritic steel behavior on a wide range of strain, strain rate and temperature. These two macroscopic models are able to cope with the various load conditions tested - progressive straining and cyclic hardening tests- and to correctly describe anisothermal evolution. A very good correlation, for example, is obtained in the description of dwell phases. Energy-based criteria are used in order to predict the lifetime of the manifold for thermomechanical fatigue. Criteria parameters are identified thanks to dedicated experimental database and corresponding constitutive laws. FEM simulations are then performed on Abaqus for different engine exhaust manifold and confirm the good results obtained from the experimental basis. We obtain more accurate results than those given by more traditional laws and less physical boundary condition estimation. A very good correlation is observed between the simulations and engine bench tests.

# Creep damage calculation for thermomechanical fatigue

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Endurance of automotive components and other products that operate at high temperatures is determined by thermo mechanical fatigue. Damage mechanisms that arise at such conditions are mainly due to mechanical fatigue and creep. Model that calculates damage due to mechanical fatigue is based on Prandtl operators and has already been presented while creep damage calculation has been neglected up to the present. The paper represents further development of the model which also takes creep damage into account. From the standard creep – rupture tests at distinct temperatures and stress levels, experimental data are gained. For the experimental data set master curves are determined using linear or parabolic regression which resembles master curve determination using Larson – Miller compensation parameter. Master curves for unmeasured temperatures are interpolated using different interpolation methods. The damage calculation itself is based on the Robinson's temperature dependent rule and runs online while processing stress – temperature load history. For evaluating the presented creep damage model, calculation is done on a real set of experimental data. First, master curve determination is performed. Different interpolation methods for the unknown temperatures are performed and compared. Finally, damage calculation for a simple stress history is performed using only fatigue damage into account and using fatigue and creep damage into account. Results are compared and discussed.

# Mechanism of subsurface fatigue cracking of compacted superalloy EP417 at environment temperature 650 °C

*A.A. Shanyavskiy (State Center for Civil Aviation Safety Flight), Russia*
*Co-authors : T.P. Zaharova, A.Y. Potapenko*

The phenomenon of in-service fatigue cracking of structural elements is well-known for aircraft engines. Temperature influence on the superalloys stress- state under cyclic loads can be very complicated because of Low-, High- and Ultra (Very) High-Cycle Fatigue (VHCF) regime. The phenomenon of VHCF can be discussed in two ways based on mechanical or physical sense. For the physical sense the VHCF is not regime, for instance it can be very high frequency of cyclic loads (25-35 kHz), but it is area of material behaviour where crack has origination subsurface. In this case specific mechanism, may be not one, for different metals (alloys) can be seen.

The paper discussed mechanism of subsurface crack initiation and propagation for compacted superalloy EP417 which has tested in the range of durability $8x10^4$ – $5x10^7$ cycles with frequency 36Hz at the environment temperature $650^0$C. It was performed special technology for manufactured specimens to introduce in them inclusions. This manner of material performance was to analyze role inclusions in crack initiation mechanism and to estimate durability alloy with inclusions.

Based on fractographic analyses of fatigued specimens it was shown two stages of the crack subsurface propagation: fist, under modes II+III and, then, because of drastically change to mode I crack opening.

The paper discussed the mechanism of the crack propagation on the fist stage based on the twisting manner of the damages accumulation and free (fracture) surface creation.

# Fatigue life assessment of preloaded API line pipe threaded connections

*Jeroen Van Wittenberghe (Laboratory Soete- Ghent University), Belgium*
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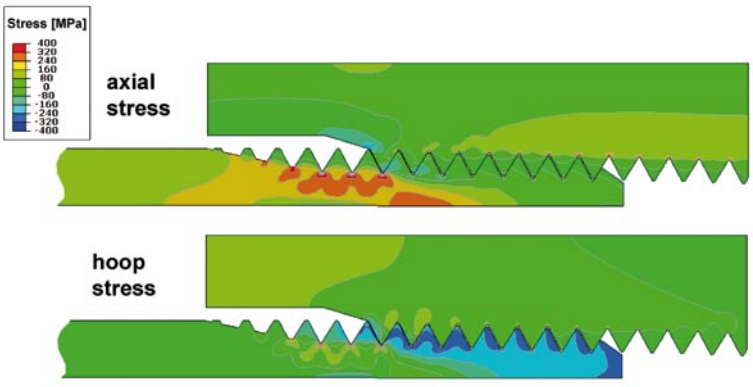
Threaded pipe connections used in on-shore and off-shore applications are often subjected to cyclic loads. They generally have a conical shape which enables them to be preloaded as a result of make-up torque. This ensures that a sealed and secure connection between the different pipes is maintained. The combination of the preload and the additional external loads, together with the thread geometry results in a complex multi-axial stress distribution over the connection. The highest concentration of axial tensile stresses typically appears at the last engaged thread of the male part of the connection. Consequently, this region will be highly susceptible for fatigue crack initiation. The stress distribution over the connection depends on the connection's geometry, interface and material properties, but the exact influence of those parameters on the fatigue life of the connections is not well documented.

In the present study, the influence of geometry changes of the female part of an API Line Pipe connection on the fatigue life of the total connection is investigated. This is done by performing a parametric finite element study, using 2D axisymmetric models. The preload is modelled by giving an initial overlap to the male and female part of the connection, corresponding to the number of make-up turns specified by the API 5B standard. This results in a compressive hoop stress in the male part of the connection. Afterwards an additional axial tensile load is applied. The final aim of this numerical study is to reduce the acting axial tensile stress concentrations as much as possible.

To validate the finite element results, four-point bending fatigue tests were carried out on threaded pipe samples with a nominal size of 1" (load controlled, R = 0.1). Cracks emanated from the last engaged thread of the male part of the connection, as could be expected from the models. Through thickness cracks were detected by pressurizing the tube-samples. When a crack grows through the wall thickness of a pipe, pressure drops and the test is stopped. The number of elapsed load cycles defines the fatigue life of the connection. This way an S-N curve was obtained for the standard API Line Pipe connection and compared to the results of connections with changed geometries.



# Integrated approach to design an offshore floating unit

*Mathieu Bargues (Bureau Veritas), France*
*Co-authors : F. X. Sireta, G. Gourdet*

The Offshore industry is moving more and more to deeper and deeper waters limiting the possibility to use fixed conventional oil platform (jacket). That's why offshore floating facilities have been created. The increasing demand of these floating process storage offloading (F(P)SO) had been made possible by the conversion of existing trading vessel.
F(P)SO conversions are considered as the quickest track to the first oil. Those tankers thought for conversion had minor issues or any at all during their sailing time. In a logical way of thinking "If in the past, it didn't have problems: it won't have problem in the future considering a controlled corrosion".
However F(P)SO and trading vessels have very different design constraints. Tankers are build considering that it will be from time to time in harbor safety, frequent dry docking and the captain always has the possibility to act on speed and heading to avoid extreme weather. The latter is build expecting it to remain anchored on site for several years with minimum maintenance. For this reason, one of the major issues for the F(P)SO is the fatigue behavior of the structure.

The Bureau Veritas computer based methodologies, for the fatigue assessment, with hydrodynamic and structural analysis are described in this paper.
The main challenges tackled are:

- Dynamic coupling of sea keeping and sloshing
- Consistent transfer of hydrodynamics loads on hull and tanks to FE model
- Combination of stresses with on site weather data (meteocean) to compute long term distribution

Two types of procedure will be shown: "complete ship computation" and "three tanks computation".

Throughout the development of the presentation, feedback from existing oil and gas units will be used to illustrate the speech, for converted and new built units in mild and severe environments.

# Calculation and load measurement of an open 60 sailing yacht canting keel

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Since 2007, DCNS group has trusted in a three years new project named « Les Filières du Talent » with the aim to associate the apprenticeship of young workers and technicians in ship building with the apprenticeship of a young skipper. In parallel, DCNS group had asked to Finot-Conq group to design an Open 60 sailing yacht in order to race. She names *DCNS 1000*.

With this sailing yacht, we want to present several technical specificities which are usually integrated in warships designed by DCNS. Then, the canting keel of *DCNS 1000* is designed with an high yield strength steel usually used by DCNS for submarine hulls. This canting keel has been fitted with a data acquisition system, strain gauges and accelerometers, with the aim to know the actual loads viewed by canting keel of Open 60 sailing yachts. The benefits of such measurements are first the verification of design hypothesis, such as dynamic behaviour of the canting keel, and second the improving the knowledge of realistic loads in order to design these canting keels.

The *DCNS 1000* sailing yacht canting keel, designed by Finot-Conq then calculated and manufactured by DCNS, has mainly the same weight than a carbon epoxy composite one for an improved slenderness. Furthermore, the fact that it is designed with a high strength yield steel gives it an improved mechanical resistance. Because DCNS controls the fatigue resistance and welding capabilities of this submarine hull steel, we can perform, with the knowledge of the keel loadings when the sailing yacht is at sea, the identification of the keel length of life left over.

The communication presents the calculations that we have performed in order to check the mechanical behaviour of the canting keel, its resistance under exceptional loadings and the fatigue loadings taking into account its expected performances. This communication analyses also measurement results and their comparison with calculations results.

# A continuum damage model for composite materials under static and fatigue loadings

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Thick Composite laminate structures, which can support significant efforts, are increasingly being used in engineering systems. To make an effective use of those structures it is necessary to consider the ability of a laminate to resist damage, as well as degradation of mechanical properties (stiffness principally) caused by the apparition of damage. Thus, it requires the development of helpful tools to forecast the evolution of damage and the influence on mechanical properties.

Damage mechanism, up to failure, in composite laminates is complex. Indeed, there are several damage phenomena (matrix cracking, delamination, fibres breaking, fibre/matrix debonding…). However, this study is focused on intra-laminar matrix cracking which is one of the main damage. Without being really detrimental for the integrity of the structure this damage directly affects the mechanical properties of the material over a long period of its life-time and accelerates other types of damage which are more detrimental to the structure.

Numerous quasi-static and fatigue tests have been performed in the aim of understanding matrix cracking mechanism, to point out the characteristics, the evolution of cracks and their influence on the mechanical properties. Different stacking sequences have been tested ((0°3/90°n)s, (0°3/±45°3)s and (0°3/±55°3)s ) in order to study different modes of apparition of the damage.

Experimental results show that matrix cracking is a diffuse damage so we choose to develop a damage model within the framework of the Damage Mechanic. The model is written at the scale of the ply and describes the multiplication of cracks and loss of rigidity caused by damage. The ply cracking is described by two internal variables: the first one, scalar characterizes the damage state of the materials and the second one is a vector which describes the direction of the damage. Moreover the damage evolution law is written with locale variables that allows to use it for calculate any complex structure. Finally, the damage model has been implemented in a finite element code and applied to an open holed structure in order to be validated by comparison with experimental results on this kind of structure.

# Measurements and modelling of the fatigue damage initiation in oil and gas steel pipes

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Steel structures used in installations of the oil and gas industry, such as drill pipes, risers and pipelines, undergo the action of cyclic loadings which can cause their failure by fatigue. These structures are made of high strength steels, such as API 5L of different grades, X-60, X-70, X-80 and X-100. The fatigue failure of these structures can not only cause considerable financial loss, but also generate catastrophic environmental damage. A consistent evaluation of the fatigue behavior of these structures should identify and take into account the micromechanisms of the fatigue damage initiation. This will allow an accurate prediction of the residual life of structures submitted to previous fatigue damage. The aim of the study is to quantify the evolutions of microdeformations as well as residual stresses associated to the fatigue damage initiation, in order to increase the reliability of oil and gas steel pipes under cyclic loadings. One of the goals of the study is to develop and propose a microstructural criterion for the fatigue damage initiation. Fatigue tests are carried out to identify and quantify the microstructural mechanisms associated to the fatigue damage initiation from real-time measurements of microdeformations and residual stresses with the aid of the X-ray diffraction technique. Samples cut off from API 5L X-60 grade steel pipes are submitted to fatigue tests performed with the aid of a fatigue testing machine capable to apply bending loadings with fully reverse stress. The quantification of the microstructural evolutions and the residual stresses associated to the mechanisms of fatigue damage initiation will be taken into account to define a fatigue damage microstructural criterion for the API 5L X-60 steel. This criterion will allow an evaluation of the residual life of steel pipes previously submitted to fatigue loadings. A model for cumulative fatigue damage according to this criterion will be proposed and then implemented and validated in a finite element model to simulate the microstructural evolutions and the fatigue damage initiation micromechanisms in oil and gas steel pipes.

# Anisotropic multiaxial fatigue criterion for short-fiber-reinforced thermoplastics based on micromechanics

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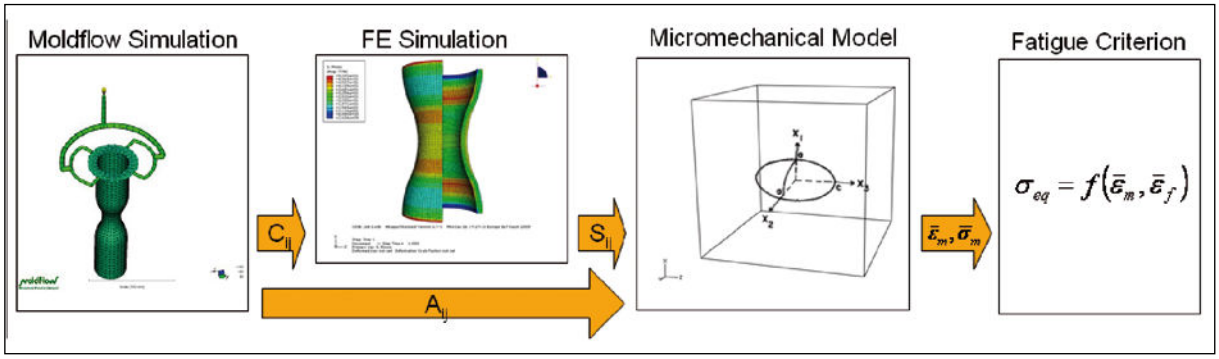
One of the concerns in the design of automotive components is the reduction of weight to increase dynamic vehicle behavior and to reduce CO2 emissions. But also high production rates and low costs are wished. Short-fiber-reinforced thermoplastics can meet these specifications and furthermore they can be molded into complex forms. However, the fatigue behavior must be taken into account to design oscillating stressed parts.

The material is a PBT-PET GF30 which is a mixture of polybutylene terephtalate and polyethylene terephtalate charged by 30 % short glass fibers in mass with an aspect ratio of approximately 15. All specimens are processed by the injection molding process.

To dimension parts, it is essential to identify the fatigue behavior for different loadings (e.g. uniaxial traction, pure shear), for different load ratios and as the material is anisotropic for different fiber orientations. Therefore, test results are obtained for the load ratios R = 0.1 and R = -1 for tension, torsion, tension / torsion and pure shear Iosipescu experiments. Furthermore, the fiber direction has been varied for these experiments. Linear elastic orthotropic finite element calculations have been carried out to take into account the stress states in these experiments.

In a previous study the damage mechanisms has been studied. The results lead us to the conclusion that strains and stresses should be modeled on the microscale to correctly predict the SN curves for different fiber orientations. We have implemented a micromechanical model which is based on the Eshelby inclusion problem and the Mori Tanaka approach.

To evaluate the lifetime of our test specimens and in a more general context of an application, the following procedure is employed: A Moldflow simulation calculates the local orientation tensors and stiffness tensors. Then a finite element simulation takes into account the so calculated stiffness tensors and determines in conjunction with the applied boundary conditions the local stress tensors. Finally, the micromechanical model has to take into account the orientation tensors of the Moldflow simulation and the stress tensors of the FE simulation to evaluate the lifetime by means of the appropriate fatigue criterion.



# Fatigue crack propagation behaviour of laser welded skin-clip joints for aluminium alloy air craft structures

*Funda Bayraktar (GKSS research Center), Germany*
*Co-authors : M. Koçak, M. Horstmann, S. Riekehr*

Currently, the laser beam welding (LBW) is successfully applied to the fabrication of stiffened panels to join skin-stringer (T-joint) parts for integral airframe structures made of 6xxx series of weldable Al-alloys for weight and cost savings purposes. This technological development provides basis to use of LBW process in joining of further components such as "skin-clip", "clip-frame" or "frame-skin" applications to achieve further weight and cost savings as well as part-count reductions in future metallic airframes.
A 3.3 kW Nd:YAG laser source was used to weld a 2 mm thick AA 6013 T6 sheet (as a clip) to base plate (as a skin), which would serve as a 400 mm wide center cracked (M(T) 400) fatigue specimen to resemble clip-skin joints of an airframe. As a base plate 4.5 mm thick AA 6156 T6 was selected and one side welding of 120 mm length was performed using 12% Si containing wire.
The damage tolerance behaviour of the welded components needs to be well-understood. Hence, the fatigue crack propagation (FCP) tests were performed (R=0.1) for several short distance welded T-joints of aluminium alloys. Furthermore, to investigate the evolution of the residual stresses and their effects on the FCP behaviour of the skin-clip joints, systematic study was undertaken in this work. Strain measurements were performed using neutron diffraction methods. Moreover, panels containing two skin-stringer joints (longitudinal to the loading axis) and one central skin-clip joint (perpendicular to the loading axis) were also tested.
This paper aims to report the results of these investigations to describe the FCP behaviours of the welded clips for future airframe applications. The differences between da/dN vs. a curves as well as crack path behaviours were discussed and role of residual stresses and microstructural gradient as well as roles of stringers on the damage tolerance performance were presented. Stringer and clip welded panels demonstrated higher FCP rates compared to the stringer welded panels, which need to be developed futher with a new clip (and stringer joint area) design and knowledge of residual stresses of stringer and clip welded panels.

# Fatigue crack growth studies on carbon steel and stainless steel pipes

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This paper deals with studies related to fatigue crack growth behaviour of carbon steel and stainless steel pipes with circumferential surface notch. Straight pipes, Tees and elbows form the primary heat transport system of nuclear power plants. Leak-Before-Break design philosophy is used in the design of nuclear power plants. In Leak-Before-Break analyses, a postulated flaw is assumed to exist. Leak-Before-Break analyses assume that the flaw becomes a through-wall crack, and that the through-wall crack can be detected by leakage at normal operating loads in advance of a catastrophic failure. It is also necessary in Leak-Before-Break analysis to show that the flaw will remain stable under various events causing dynamic loading such as a Safe Shutdown Earthquake (SSE) condition. Hence, a systematic study was undertaken to study the fatigue crack growth behaviour of straight pipes used in primary heat transport systems of nuclear power plants.

Fatigue crack growth tests were conducted on carbon steel and stainless steel straight pipes with various outer diameters ranging from 169 mm to 406 mm having circumferential surface notch on the outer surface. The fatigue crack growth tests were conducted using computer controlled servo-hydraulic actuators. The cyclic load was applied as four-point bending load so that the mid section of the pipe is subjected to pure bending. The fatigue tests were conducted at stress ratios (R) of 0.1, 0.5 and -1 under load or displacement control. Fatigue crack detection and sizing were carried out using Alternating Current Potential Difference and Ultrasonic Techniques. Crack initiation and growth were closely monitored at regular intervals of loading. Fatigue crack growth rate and crack profile development curves were generated based on experimental data. Paris crack growth constants, C and m, were also generated for various pipes. In order to validate the fatigue crack growth measurements obtained from ACPD technique, crack growth studies were carried out on carbon steel and stainless pipes using beach mark loading technique. A two step block loading program was used for producing beach marks on crack surface of straight pipes. Fatigue crack growth measurement using ACPD technique is found to have an average error of approximately 12% for pipes when compared with beach mark measurements on the failure surface. Fatigue analysis was carried out on carbon steel and stainless steel pipes having part-through circumferential crack on the outer surface under bending. The analysis was carried out using linear elastic fracture mechanics and finite element method. The stress intensity factors were obtained for different crack depths in increment of 0.5 mm using FEM based ABAQUS software package. Paris equation was used for obtaining number of cycles using the crack growth constants obtained from standard specimens (CT, TPB) machined from actual pipes. The predicted values of fatigue life were found to be in good agreement with experimental values.

# Statistical models to analyze failure, wear, fatigue and degradation data in dynamic environnements

*Mikhail Nikulin (l'IMB, l'U.F.R. «Sciences et Modelisation», Université Victor Segalen, Bordeaux, France*

Failures of highly reliable units are rare. One way of obtaining a complementary reliability information is to do accelerated life testing (ALT), i.e. to use higher level of experimental factors, hence to obtain failures quickly. Another way of obtaining complementary reliability information is to measure some parameters which characterize the aging or wear of the product in time.
Statistical inference from ALT is possible if failure time regression models relating failure time distribution with external explanatory variables (covariates, stresses) in°uencing the reliability are well chosen. Statistical inference from failure time-degradation data with covariates needs even more complicated models relating failure time distribution not only with external but also with internal explanatory variables (degradation, fatigue, wear) which explain the state of units before the failures. In the last case models for degradation process distribution are needed, too. In this talk we discuss the most used failure time dynamic regression models used for analysis of failure time and failure time-degradation data with time depending covariates, which determine the design of statistical trials.

Key Words: accelerated life models, covariates, design, degradation models, failure time regression; fatigue, reliability, wear.

# Investigation on cumulative fatigue life : multilevel controlled strain on a type 304-L stainless steel used for pressure water reactor

*Antoine Fissolo (CEA Saclay), France*
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In order to estimate the crack initiation damage, and also the water leakage conditions on pipes, uniaxial fatigue curves are often used. They were built from strain or stress load control tests, performed with constant amplitude. However, important thermo-mechanical loading fluctuations are observed in operating conditions. For example, incomplete mixing of different temperature flows on pipes may generate very variable cyclical temperature gradients in thickness combined with the stiffness induced by colder or massive parts. The purpose of the present work is to start investigation on the fatigue life with a variable loading, in order to examine cumulative damage and transient overloading effects in fatigue. In this frame, multilevel strain controlled fatigue tests have been performed on a Type 304-L. stainless steel (elaborated in accordance with the RCC-M specifications).

The experimental results show that linear Miner's rule is not verified in our conditions. When the strains are applied in a decreasing order (High-Low strain sequence), the summation of cycle ratios is smaller than unity, whatever the number of applied levels, whereas this summation is higher than one for an increasing order (Low-High strain sequence) (Fig. 1).

An accurate estimation of the fatigue life could be probably obtained taking into account the loading history and to modify damage rule itself. Improvement of the damage evaluation as a function of the fatigue life requires probably to consider two separated stages in the fatigue process: a first stage corresponding to crack initiation, a second stage corresponding to crack propagation. In this frame, different procedures for the evaluation of the remaining fatigue life have been experienced on the present programme. A "Double Damage Curve Approach" seems to give accurate estimation (Fig. 2).

Key words: 304-L stainless steel, thermal fatigue, cumulative fatigue life, multilevel fatigue tests

# A new technique for the fatigue life prediction in notched components

*Thibault Herbland (CETIM-Centre des Matériaux Mines Paritech), France*
*Co-authors : G.Cailletaud, S.Quilici (Centre des Matériaux Mines Paritech), France*

After pointing out the limitations of the classical Neuber type methods, we propose a new procedure for calculating fatigue life of notched components.

It includes a new approach for accelerated evaluation of stress and strain histories at the notch tip.

A methodology coming from the study of uniform fields models is used to describe the evolution of the residual stresses at the notch tip. A tensorial variable allows us to take into account the stress redistribution around the notch tip. The model is calibrated by two short FEM computations of the component representing a monotonic preload of the structure, first with the elastic behaviour, then with the real elasto-plastic behaviour. These computation results are used to determine the parameters of the transition rule, which allows to simulate the whole loading history.

The local stress histories are then treated through a new multiaxial rainflow cycle counting algorithm. Contrary to classical rainflow algorithms that count an equivalent variable, it takes into account the whole stress tensor. First, a new algorithm is used to determine the minimum circle circumscribed to the deviatoric load path. The cycles are extracted following the “active surfaces” concept used in some plasticity models. Then, the multiaxial Chaboche model is applied to compute the elementary damage generated by each extracted cycle.

Finally, a non-linear cumulation rule is used to achieve the total damage generated by a load sequence, and the fatigue life of the component.
The full method was successfully applied to several notch geometries of components subjected to different proportional loadings, under cyclic or random signals.

# Optimal control approach in non linear mechanics

*Claude Stolz (LMS-Ecole Polytechnique), France*

The purpose of this paper is to present some applications of optimal control theory for the resolution of particular non-linear problem. We present an original contribution to determination of cyclic asymptotic behaviour of structures under cyclic loading,. The stabilized response is obtained as a minimum of a functional which takes into account of initial conditions. Applications in fatigue and in contact are discussed

# A multi-scale fatigue life model for variable amplitude loadings

*Cécile Krebs (Cetim- LMS Ecole Polytechnique), France*
*Co-authors : H. Maitournam (LMS Ecole Polytechnique), France, A. Galtier (Cetim), France*

The paper deals with the estimation of the lifetime of structure in high-cycle fatigue. The methodology adopted is a multiscale approach initiated by M. Jabbado and M. Habibou (2008) based on the following points :

1- at the macroscopic scale, the material has an elastic or an elastic shakedown behaviour,

2- at the mesoscopic scale the material presents an elastic shakedown behaviour (infinite life domain) or a plastic shakedown behaviour or ratchetting (finite life domain),

3- at the mesoscopic scale, the material has a pressure dependent elastoplastic behaviour related to the damage processes and the fatigue crack nucleation,

4- the damage is governed at the mesoscopic scale by the accumulated plastic deformation per stabilized cycle.

A robust identification procedure is established. The models are validated by comparing the simulated fatigue lives to experimental tests from the literature. A simplified version of the model is proposed ; its implementation is easier and leads to acceptable results.

# Crack propagation with XFEM

*Eric Wyart (CENAERO), Belgium*
*Co-authors : M.Duflot, H.Minnebo, F.Lani*

This contribution summarizes the developments made at Cenaero in the field of Damage Tolerant Approaches using advanced three-dimensional simulations of crack propagation with the eXtended Finite Element Method such as implemented in the in-house FE software Morfeo and in the proprietary XFEM plug-in of Morfeo developed for Samcef.

In particular, this contribution presents a procedure for the analysis of 3D cracks with the XFEM, ensuring accuracy, quality and robustness of the solution both for static and propagating cracks. This procedure can be considered as a 'state-of-the-art' modeling practice.

Several applications are briefly shown, including aerostructures, aircraft and spacecraft equipments and engine components, with:
- multi-body assemblies
- complex boundary conditions (fixations, loads, pressure, temperature, accelerations, peridiocity, multi-point constraints,...)
- contacts inside and outside cracked zones
- large number of degrees of freedom (over 3 MDOFs) and parallel computing
- residual stresses due to assembly (welding) and forming processes
- mesh refinement and adaptivity
- coupled problems (thermal-mechanical)
- error estimation
- multi-site crack problems
- 3D crack propagation.

Besides, validation cases are provided, including comparisons with analytical, FEM and BEM solutions mainly in terms of stress intensity factors, but also confrontations with experiments in terms of crack length Vs number of cycles, crack paths, crack stability analyses,...

Finally an application is presented which illustrates the ability of Morfeo to simulate in a row the welding of two plates (mixed v,p formulation) and the propagation of a fatigue crack in the weld line (displacement formulation), with the following results:
- the residual stress field due to the welding and its subsequent evolution after crack insertion and propagation,
- the stress intensity factors in the presence of a residual stress field
- the crack path under cyclic loading.

# Study on crack propagation in tubular joints under compressive fatigue loadings

*Claire Acevedo (ICOM-EPFL), Switzerland*
*Co-author : A.Nussbaumer*

Large.scale tubular truss beams, approx. 9m long and 2 m high, were tested under constant amplitude fatigue loading. The beams were made out of circular hollow sections of steel S355, welded to form an uniplanar truss with K-joints, in a shape common to bridge construction. The main goal of these tests was to focus on the fatigue behavior of the joints loaded in compression, that is with chord in compression, one diagonal in compression and the remaining diagonal in tension.
The study showed, as in other studies, that fatigue cracks develop in compressive stress field zones from applied loads due to the presence of large welding tensile residual stresses. An alternate current potential drop system was used to follow during the tests the crack development from the weld toes. This paper contains the results, presented in terms of number of cycles vs crack depth and crack growth rate, from the cracks that developped. In order to evaluate the level of residual stresses near the weld toes, both measurements by hole drilling and neutron diffraction were carried out. This paper includes the first results of the residual stress field, more measurements being in progress.
Among the interesting results, it was observed that crack initiation and growth occurred first from hot spot 1c (weld toe in-between the braces, compression brace side) until the crack reached about 2 mm deep. Than, the crack growth decreased and, simultaneously, a crack started to develop from hot spot 1 (tension brace side). Both crack continued to grow, the failure being triggered by a fatigue crack in a joint on the tension chord. Characteristics of the different cracks (shapes, angles of propagation, etc.) are given in the paper. The S-N results are compared with previously obtained results on beams with different tube dimensions.

# Study of crack arrest under thermo-mechanical variable amplitude loading for 3D plane cracks by remeshing and XFEM

*Said Taheri (EDF R&D AMA, UMR CNRS-EDF 2832), France*
*Co-authors : S.Sbitti (EDF R&D AMA), E.Galenne (UMR CNRS-EDF 2832),*

Thermal crazing is observed through the presence of a dense, shallow, uniaxial or multiaxial crack network in high cycle thermal fatigue due to thermal fluctuation in residual heat removal (RHR) system of some nuclear power plants. It is explained by crack arrest in the depth due to a decreasing stress intensity factor reaching a threshold value. This is related to high frequencies of thermal loading. The aim is to study crack propagation and arrest conditions under variable loading for plane cracks; semi-elliptical or free, by remeshing methodology or XFEM methodology and codification methodology.

A parametric study has shown that for the crack arrest study for RHR there is a need for crack propagation over millions of cycles. So FE 3D crcak propagation under variable amplitude loading in performed in Code_Aster for that porpose.

Performance of automatic remeshing and XFEM under variable amplitude loading are compared figure 1. It is shown that an small difference on SIF at the beginning will be amplified through the propagation. For XFEM simulation semi-elliptical crack propagation but also free geometrical crack propagation are also compared.

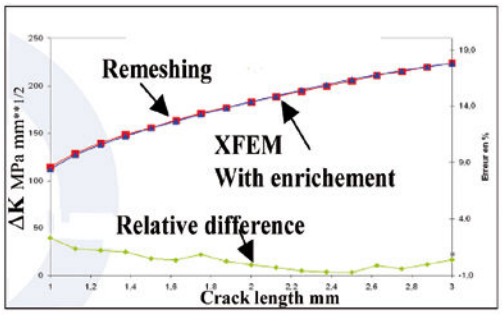


Fig. 1a $\Delta K_I$ at depth versus number of cycles for a semi-elliptical crack

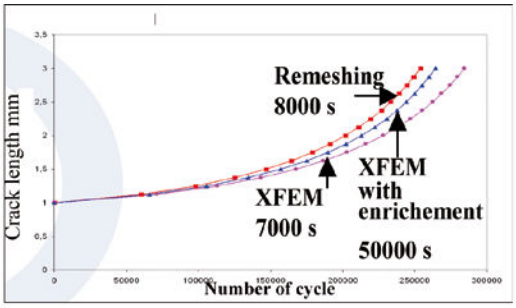


Fig. 1b Crack depth versus number of cycle for a semi-elliptical crack

## PROPAGATION UNDER VARIABLE AMPLITUDE LAODING

A thermo hydraulic experiment called FATHER has been conducted at French Atomic Resarch Center (CEA) in collaboration with AREVA and the French electricity company EDF, in order to reproduce conditions as close as possible from the in-service ones just after a mixing tee between cold and hot fluids. From this thermohydraulic experiment, temperature records in the fluid can be obtained. The measurements are recorded with a sampling frequency of 50 Hz during 1 hour. CPU time necessary to do a 3D propagation simulation for 1 hours is huge. We begin the study with sequence of 10 seconds of the signal that seems to be very small duration compared to one hour recorded. However for instance it is comparable to the time on which thermohydraulic solutions are feasible. The aim is here to evaluate the error margin on propagation, if 10 seconds is taken as representative of the signal. To evaluate the representivity of a sequence of 10 seconds, propagation is studied (figure 2a and 2b) for bloc loadings between following instances : 0-to-30, 100-to-130, and 500-to-530 seconds.

Figure 3a shows the part of signal between 0 and 30 seconds, and figure 3b between 100 and 130 seconds. These results show that 10 seconds at beginning may not be representative but it may be considered as representative at 100 seconds. Later crack study arrest has been performed with the signal between 100 and 110 seconds and compared with the mock-up results.

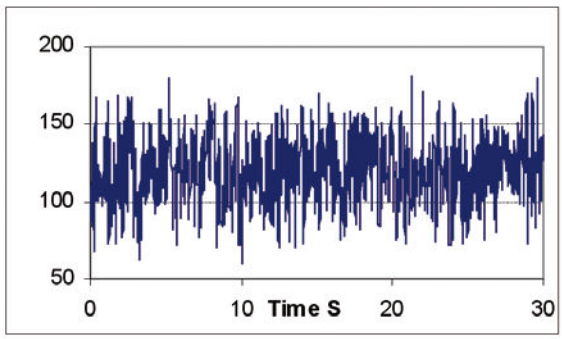


Fig. 2a temperature signal, Father mock-up

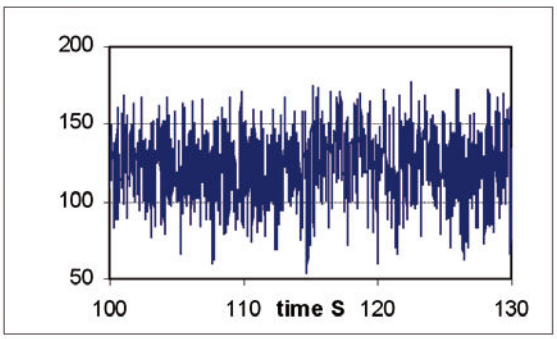


Fig. 2b temperature signal, Father mock-up

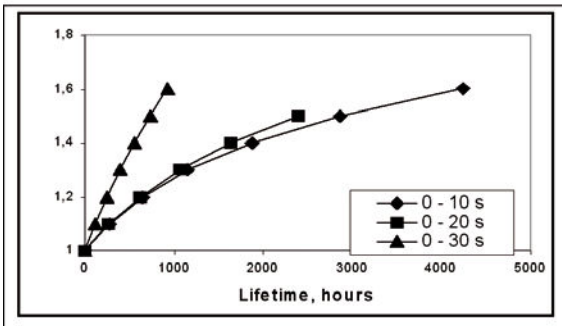


Fig. 3a non representative signal on 10 seconds

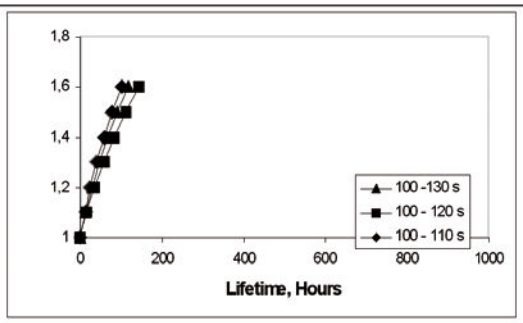


Fig. 3b representative signal on 10 seconds

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# Fatigue design of stamped parts

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Automotive chassis part design is expected to check several criteria such as: stiffness; noise, vibration and harshness (NVH); reliability and fatigue; crash behaviour; … In particular, as most of axle parts are heavy duty high safety ones, fatigue requirements are of prior concern and actually drive the part design.

Axle components are usually obtained by stamping of steel sheets, before to be assembled. Thus, an effective fatigue design is expected to take into account for the forming process, as already described in [1]. In this communication, we address stamped parts fatigue design from several points of view:

- first of all, the forming process assessment by a so-called "local approach" [2,3] : such an approach provides effective data based on elementary solid mechanics and plasticity, as proven by comparison to measures on stamped parts;
- thanks to the "local approach", sensitiveness of macroscopic occurrences of stamping like thinning and curvature on fatigue design computations is analyzed;
- at last, some applications in the automotive industry, e.g. heavy duty high safety grade parts like suspension arms, spring and axle supports, … are considered.

This study comes from a common research project supported by PSA Peugeot Citroën, ARCELOR MITTAL and ENSIETA.

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# A new methodology for designing forged components in fatigue

*Etienne Pessard (LAMPA ENSAM PariTech Angers), France*
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Forged components are recognized as having good mechanical properties, in particular for fatigue applications. This is mainly due to the microstructure induced by the forging process which leads to: the improvement of the material compactness, a finer and more homogeneous microstructure (e.g. a broken dendritic structure) and a grain flow orientation (fibering).
The latter can result in considerable variation in the fatigue limit, depending on the fiber orientation. This variation has been reported as being 35% for 42CD4 steel [1] and 15% for a duplex stainless steel [2].
In order to correctly design a forged component in terms of fatigue strength, the thermo-mechanical history leading to the fibering orientation, the size and orientation of grains or inclusions should be taken into account. Nowadays, process simulation software makes it possible to predict the fibering of a forged component.
Besides, some high cycle fatigue models have been proposed so far to account for the effect of residual stresses, or the nature, size and orientations of defects (or inclusions) with respect to the principal loading direction.
The first objective of this work is to describe an original multiaxial criterion able to reflect the anisotropic behaviour in fatigue. It is used here to predict the fatigue behavior of a bainitic steel: the Metasco MC. It is experimentally demonstrated that its anisotropy is due to elongated manganese sulphide (MnS) inclusions oriented along the rolling or forging direction. Crack initiation mechanism observations showed that the bainitic microstructure fatigue behavior as well as the defects effect must be taken into account to predict the fatigue behavior in any fibering direction and for any multiaxial loading. A probabilistic fatigue model based on two mechanisms competition is then proposed.
The second objective of this work is to integrate this anisotropic fatigue criterion in a numerical model for design applications. First, a method is developed to define the fibering orientation created during the forging operation. Then some fatigue simulations with the proposed criterion are presented and show the interest of this methodology for the design of forged components.

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# A comparative study of fatigue criteria for defective materials

*Gaelle Leopold (LMPM- ENSMA), France*
*Co-authors : Y.Nadot, J.Mendez*

Casting process is often used to manufacture safety components. In order to compute reliability, fatigue resistance is a major parameter: defects have a strong influence on fatigue properties. Authors propose various approaches which generally distinguish themselves through "geometrical" defects description and mechanical quantities used to represent stress distribution around the defect. It is interesting to compare several methods for uniaxial or multixial loadings and various defect sizes and morphologies. The capability of each model to predict fatigue limit or fatigue lifetime of specimens having defect is analysed through experimental results for a various metallic materials. Artificial spherical or elliptical defects are subjected to fully reversed or pure tension or torsion loading paths.

Billaudeau et al. [1] show that fatigue mechanisms from defect are mainly governed by shear mechanisms similarly to defect free material. These authors define the initiation stage like the number of cycles necessary to create the crack that totally surround the defect. A multiaxial fatigue criterion [2] shows interesting results for 2 materials under tension, compression or torsion with or without mean stress: C35 steel containing artificial surface defects and a nodular cast iron containing micro shrinkages. This criterion takes into account for the defect by the mean of the equivalent local stress gradient around the defect. A finite element calculation allows estimating this equivalent stress gradient using non linear kinematic hardening. This gradient is estimate over a characteristic length: $\sqrt{area}$ [3]. Many experiments under multiaxial loadings have been conducted on defective metallic materials in order to show size defect impact on fatigue limit and fatigue lifetime. Murakami's parameter $\sqrt{area}$ gives a good representation of the defect inside its validity domain (Figure 1).

The aim of the paper is to compare various methods in order to find relevant quantities depending on loading, material and defect type. Murakami's empirical approach [3] and a Linear Elastic Fracture Mechanic (LEFM) based method are compared to current approaches of Vallellano [4], Susmel and Taylor [5] and Gadouini [2]. Defects influence on fatigue properties is considered through materials properties, defect description (morphology and size), microstructural factors and stress distribution around the defect. Analytical or finite element calculations are used to estimate models' prediction for materials having artificial, spherical and elliptical, surface defects under various loading paths: fully reversed or pure tension and/or torsion loadings (R=-1, R=0)

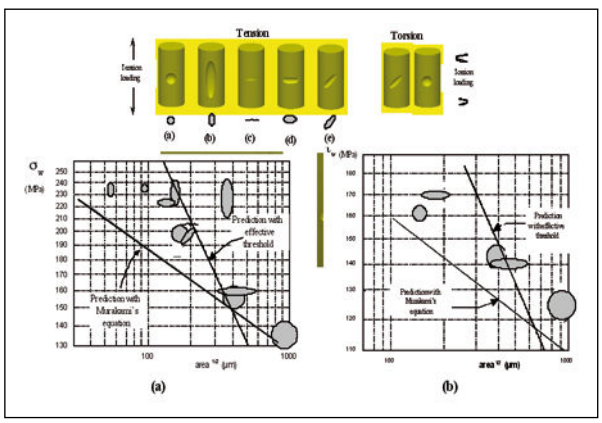


*Fig. 2 : Evolution of fatigue limit with defect size ($area^{1/2}$) C35 steel (a) Tension, R=-1 (b) Torsion, R=-1 [1]*

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# Analytical and Experimental approach of Residual Stress induced by the manufacturing of mechanical parts, and their stability in fatigue

*Hervé Michaud (CREAS-Ascométal), France*

A significant share of the production of ASCOMETAL relies to the supply of alloy steels used for the manufacturing of components like leaf springs of tracks, coil suspensions of cars, crankshafts, or common rails. The damage of such component is mainly due to fatigue. Its understanding requires simulating the different steps of the industrial process: forming of the part, presetting operations and shot peening. In this work a complete analytical model of elastic-plastic bending, tension, torsion or autofrettage has been developed to simulate the manufacturing operations. A special procedure was also implemented to model mechanical surface treatments such as shot peening. These models allow predicting the plastic strains and residual stresses induced by successive loadings of the part. Our approach required however first defining the mechanical behaviour of the material. The constitutive laws of the employed steels were therefore identified starting from cyclic loops recorded for tests carried out at various imposed strains. These laws were then introduced in the plasticity model to simulate the different steps of manufacturing and the elastic-plastic shake down produced by the first cycles of fatigue. In order to validate the model, residual stress maps were also characterized by X-Ray diffraction. However, to retrieve the maximum of information from this kind of measurement, the experimental data has been analysed through a global method which processes the whole acquired diffraction peaks at once.

# CDM approach applied to fatigue crack propagation on aeronautical metallic alloys

*François Hamon (LMPM-ENSMA), France*
*Co-authors : G.Henaff (LMPM-ENSMA), France, D.Halm, M.Guegen, T.Billaudeau (Airbus France)*

This paper deals with a work conducted in collaboration with AIRBUS France. The aim is to develop a numerical model to predict the behaviour of cracked panels, in place of expensive and complex experiments. In particular, the model has to simulate R-curves and fatigue crack propagation at high level of $\Delta K$ for a wide variety of metallic alloys including aluminium alloys, titanium alloys and steels.
The proposed model is based on thermodynamic approaches within the framework of Continuum Damage Mechanics which provide numerical robustness as well as a precise description of the physical micromechanism of fracture. Up to now, CDM models have been only applied separately to low cycle fatigue and high cycle fatigue. This study examines the possibility to use such models to simulate fatigue crack propagation. Instead of classical CDM theories, using a single damage variable, two distinct scalars called cyclic damage and static damage have been introduced to take into account experimental observations. Scanning Electron Microscopy has been used to differentiate the two types of damage which appear on fatigue crack propagation. While the static damage evolution law is consistent with the classical Lemaitre's model, the cyclic damage is assumed as a consequence of cumulated plastic strain and does not influence plasticity. Then, an energetic equivalence criterion has been inserted to model crack propagation and to reduce the mesh dependency. This method, originally developed by J.Mazars and G. Pijaudier-Cabot, fills the gap between damage and fracture and avoids the introduction of additional boundary conditions or complex code developments associated with non-locality. The last improvement is the transposition of results from a small specimen to a large one.
This model has been implemented in the commercial finite element code ABAQUS/CAE. Implicit and explicit computations have been performed to highlight drawbacks and advantages of the method. Meanwhile, all the parameters of the model have been identified by simple tests like tensile and cyclic stress-strain tests.

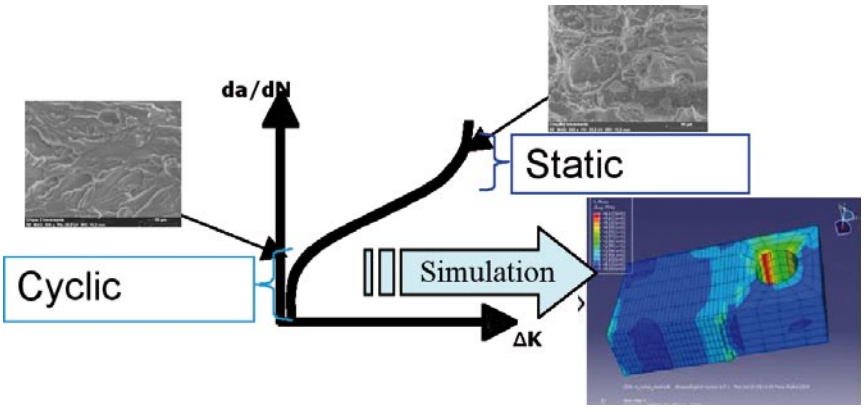


*Figure 3 : Differentiation of two type of damage with a Scanning Electron Microscopy and implementation in ABAQUS/explicit to model fatigue crack propagation.*

# A global model reduction approach for fatigue crack growth with confined plasticity

*Florent Galland (INSA-Lyon), France*
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It is known since decades that fatigue crack propagation in elastic-plastic media is very sensitive to load history since the non-linear behavior of the material can have a great influence on propagation rates [1, 2]. However, raw computations of millions of non-linear fatigue cycles on tri-dimensional realistic structures would lead to prohibitive calculation times. In this respect, we propose here a mixed *a priori – a posteriori* model reduction approach in order to drastically decrease the computational cost of this type of problems.
First, the small scale yielding hypothesis is assumed, and an *a posteriori* model reduction of the plastic behavior of the cracked structure is performed. Using an elastic-plastic behavior as realistic as possible, a crack solicited in mode 1 is simulated, and the resulting displacement field is projected on a suitable reduced basis. Pommier et al. remarked that a basis of dimension 2 is sufficient to describe accurately the elastic-plastic displacement field of a steady crack: one vector for the elastic part and another one for the plastic part of the field [3]. Moreover, they managed to build constitutive laws for the evolutions of the corresponding variables. Thus, the parameters of this evolution laws are numerically identified in a first step and after that, this *a posteriori* model reduction can be applied to any two or tri-dimensional test-case, handling efficiently the plastic behavior of the structure. At this point, even if the non-linear computations are avoided, describing realistic variable amplitude loadings over millions of load steps requires millions of linear elastic computations to provide the stress intensity factors to this reduced model. An additional *a priori* model reduction approach is then used to accelerate even more the time to solution of the whole problem [4]. This *a priori* approach consists in building incrementally and without any previous calculations a reduced basis specific to the considered test-case, by extracting information from the evolving displacement field of the structure. Then the displacement solutions of the updated crack geometries are sought as linear combinations of those few basis vectors.
A good indicator of the minimal dimension of such a reduced basis for a given test-case is to simulate some propagation steps, to store the resulting displacement vectors, and then to perform a singular value decomposition on this set of vectors. The number of significant singular values gives an idea of the necessary number of vectors to build a good basis. Such an analysis is presented in figure 1, on a semi-elliptical crack in 3D. The results show that 140 propagation steps can be efficiently described by only 5 vectors.

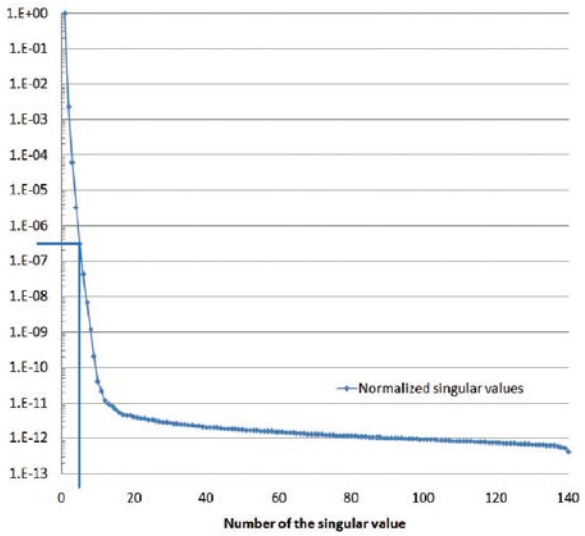


Figure 1. Normalized singular values of a set of 140 displacement solution vectors of a crack propagation problem.

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# Numerical estimation of the macroscopic plastic energy dissipates during fatigue tests

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The life prediction of mechanical components in industrial systems or transportation is always a topic of interest. To understand how the fatigue phenomenon occurs in a material, the crack propagation behaviour is studied. Most of the works about crack propagation are lead by meaning experimental tests. The cost-effectiveness (in time and facilities) of such prediction could be important. This is the reason why numerical approach of such problems becomes interesting.
It has been shown that the theory of crack growth is correlated to the plastic energy dissipated at the crack tip [1]. The work focuses on the determination with numerical tools of the local (near the crack tip) and global plastic energy dissipated in one cycle of fatigue test. Lot of experimental and some numerical works deal with this theoretical approach ([2], [3], [4]). As said before, the microscopic energy estimation is made with experimental tools and the numerical calculations are most of time made for 2D models or considering the closure effect (not studied in this paper).
The principle of virtual work gives the equality between the global and the local plastic works. In help with a numerical model based on script and FEM approach the local and global plastic energies are calculated on a specific CT specimen. The equality of these two numerical results is obtained. These numerical results are compared with analytical results which permits to validate the model. Then the differences between the plane stress, plane strain and 3D models are investigated. The influence of different loading cycles on the dissipated energy is also studied.
As a conclusion, the model gives for elastoplastic material the plastic energy dissipated during one stabilized cycle fatigue test. It is also unnecessary to calculate the microscopic mechanical field (which is more difficult to estimate) because the macroscopic one provides the result. Moreover experimental fatigue tests on such material are not really useful to estimate the energy because the numerical model could estimate it on different geometries.

# Numerical evaluation of a dual-mechanism model for fatigue crack growth under flight load spectra

*R. Sunder (Biss Research), India*

A new fatigue crack growth prediction model was developed that incorporates two independently acting load interaction mechanisms, crack closure and crack-tip residual stress. Crack closure affects crack driving force, while history-sensitive instantaneous hydrostatic stress at the crack-tip affects instantaneous threshold stress intensity. These are together modeled on a cycle-by-cycle basis, by numerically simulating both the compressive stress distribution in the crack wake, as well as the local inelastic stress-strain distribution ahead of the crack tip. The method for obtaining model constants is described. The quality of crack growth life predictions is assessed through tests on laboratory coupons using different aircraft wing load spectra. It is shown that accounting for crack-tip residual stress effect has a dramatic impact on near-threshold crack growth rates.

# Probabilistic initiation S-N curves in C35 steel : influence of loading and surface defect

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*Co-authors : Y.Nadot, Ch.Bouraoui (ENSMA Futuroscope), France,*
*R.Fathallah (Ecole Ing. De Sousse), Tunisia*

Theoretical and experimental investigations were combined to characterise the influence of surface defects on the Stress Number of cycles (S-N) initiations curves for C35 steel. A spherical artificial defect has been machined at the surface of each fatigue sample. Initiation crack length definitions are proposed for defect free and defective material. They are justified by the carried out and the previous experimental investigations. The initiation mechanisms have been observed using Scanning Electron Microscope (SEM). The replica technique was used to follow the evolution of the crack length with the number of cycles. The parameters of the Paris law were identified. A coefficient of variation was imposed on these parameters. The iso-probabilistic S-N initiations curves are produced by using the Monte Carlo random selection. For each selection the propagation life was computed with the effective Paris law by integrating crack growth law from the initiation size up to failure. Therefore initiation S-N curves were produced by deducting the propagation part of the total fatigue life. For defect free material, torsion loading allows relatively earlier initiation compared to tension loading. In the case of defective material, it is observed that, for the both loadings, the fatigue life initiation is not negligible by comparison to total fatigue life. It is concluded that defects are match more detrimental to fatigue life in the range of high cycle fatigue zone. However, for the limited fatigue lives (between $10^4$ and $10^5$ cycles), the free defect and defective material S-N curves seem to be comparable.

# Fatigue propagation of short crack near a V-Notch TIP

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*Co-author : C.Z. Cheng, Zhong-rong Niu (Efei Univ. of Technology), Republic of China*

Used in classical Fracture Mechanics Analysis, the Williams expansion allows determining the stress field close to the notch tip region of a V-notch by introducing the boundary conditions of free surface at the notch faces. Nevertheless, except for a crack, the Stress Intensity Factor (SIF) is meaningless.

In this work, a general methodology to study the crack initiation from a V-notch was established under mode-I loading. This methodology is established on the basis of a set of criteria showing how the fracture criterion interacts with the local near notch tip analysis.

A new criterion is developed in this work in order to predict the crack initiation and the crack propagation. The effect of the notch angle on the crack extension angle and on the crack propagation is analyzed.

On the basis of this approach, the fatigue of Welded Joints considering the V-notch effect of the weld toe can be done.

A comparison between V-notch case and real crack case is done in term of fatigue life using a crack propagation law.

In the present paper we will present a method as an attempt to improve to the weld notch approach: The weld bead is considered as a sharp V shaped notch with a given angle. The radius is set to zero, see figure 1. From this assumption it is possible to determine the Stress Intensity Factor (SIF) associated with the weld toe notch.

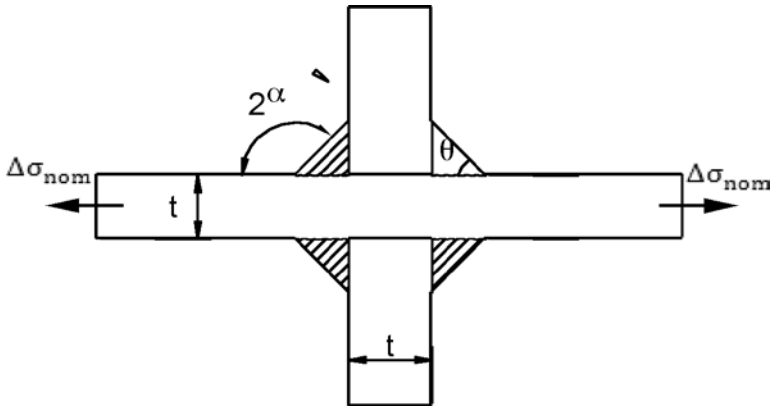


**Figure 1**-Definition of speciemn and toe geometry for a fillet weld

Based on the approach, the stress intensity for range can be found on a closed form solution:

$$\Delta K_1^N = k_1 \cdot t^{1-\lambda_1} \cdot \Delta\sigma_{nom} \qquad (1)$$

where $k_1$ is a non-dimensional coefficient, t, is the plate thickness and $\lambda_1$ is the Williams eigenvalue which denotes the degree of singularity (DOS). $k_1$ and $\lambda_1$ are the amplitude and the exponent of the first term of the stress field expansion.

If we now relate the fatigue life (N) to the average variation of the Stress Intensity Factor (SIF) we have in fact accounted for the entire stress field in the vicinity of the weld toe.

For practical applications of the N-SIF method, the average variation of the Stress Intensity Factor should be related directly to the geometry parameters of the joint.

# Deep water stinger Polaris cast joints fatigue design

*Romain Mille (ACERGY), France*
*Co-authors : A. Chabod (CTIF), France*

A dynamically positioned derrick lay barge, the Acergy Polaris is the ideal barge for pipelay and construction activities in deepwater fields. Equipped with both "S" and "J" configuration pipelay capabilities, this barge can undertake the installation of deepwater moorings, subsea structures and pipelines. It can also perform tie-in and support functions. The Acergy Polaris is ideally suited for deepwater construction tasks in West Africa, the Gulf of Mexico and Brazil.
This study deals with the triangular tubular truss beam named stinger, attached to the stern of the Acergy Polaris via an A-Frame. The stinger is dedicated to deep and intermediate water depth projects and is used to install various pipe-lines, supports the pipe loads, the hydrodynamic effects of wave and inertia loads due to the barge movements. A preliminary stinger fatigue analysis with a global beam model shows high damage ratio at 3 welded tubular joints.
The solution is to use cast joints in order to improve the fatigue life. Indeed, cast joint material (GSMn5V cast steel) has better fatigue properties than welded connections ones. The second advantage is to minimize stress level by increasing connection radii, which are greater in a cast part than in a welded assembly. And the third advantage is to remove bending moments due to eccentricities at joints, which are inevitable with welded connections, as soon as overlaps are forbidden for inspection purpose. A new design of these 3 joints is put forward, meeting cast parts requirements. Material soundness and mechanical properties are warranted by taking into account this technical choice during design step and by writing non-destructive controls and fabrication specifications.
The calculation method is the following. Load time series are extracted from dynamic analysis done with the global beam model. On the whole, fatigue assessment is a combination of 8 elementary cycles, corresponding to 4 wave's amplitudes and two load directions ("beam sea" and "quartering sea"), which represent 648 static load cases. Indeed, each cycle must be discretized in 81 time steps, in order to identify accurately maximum and minimum applied load. A local 3D model of each cast joint is built and the hypothesis of balanced loads applied to ends is checked. Then korn shell written routine generates automatically static analysis input files. Finally, a damage accumulation is made with NCODE software to obtain fatigue capabilities of these 3 parts.

# Evaluation of effective shear stress amplitude and assessment of fatigue damage under multiaxial service loading

*B. Li (Instituto Supérior Technico), Portugal*
*Co-author : M. De Freitas, L.Reis*

Due to the increasing pressure of market competition, computational durability analysis of engineering components and structures is more and more used in today's industrial design for preliminary design optimisation and reducing prototype testing. Since it is widely recognized that about 80% of mechanical component failures are related to fatigue, structural fatigue life has become the primary concern in design for durability.
This paper presents an efficient and easy-to-use approach for fatigue damage evaluations of ductile structural materials under general multiaxial service loading. Further developments and implementations of the MCE (Minimum Circumscribed Ellipse) approach developed and previously published by the authors for multiaxial fatigue are carried out, which uses the normal/shear stresses on the octahedral plane (stress invariants) to define damage parameters and takes into account the non-proportionality of the loading path in an efficient and easy way. For multiaxial stresses with sinusoidal waveforms, analytical solutions are derived and much better predictions are shown by comparisons with experimental results. For multiaxial stresses with general non-sinusoidal waveforms, an efficient algorithm is implemented in C language. By applications to some typical examples, very interesting results are obtained, which can explain why the conventional approaches underestimate the non-proportional multiaxial fatigue damage. A simplified equation is proposed to predict fatigue damage under multiaxial service loading, which can predict the fatigue damage under the worst-case combinations of the multiaxial fatigue stresses. A comparison with experimental results of multiaxial fatigue tests with a wide range of loading paths is presented and discussed.

# A multiaxial endurance criterion for HCF/LCF complex cycles

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*Co-authors : Sylvie Pommier (LMT-ENS Cachan), Arnaud Longuet, Caroline Mary (SNECMA, Moissy-Cramayel), France*
*François Vogel (TURBOMECA, Bordes), France*

A multiaxial fatigue criterion that takes explicitly into account the defect size was developed in a previous study [1]. The material is assumed to contain defects modeled as cracks. The criterion is developed within the LEFM frameworks. Non-singular terms in the asymptotic developments of stresses at crack tip were considered. A critical elastic distortional energy is used as a yield criterion for the crack tip region. The elastic domain of the crack tip region is viewed as an endurance domain. With this approach, the defect size effect in the Kitagawa and Takahashi diagram [2] and the hydrostatic stress dependency in the Dang Van [3] criterion are both successfully reproduced.
However, this model neither accounts for mean stresses effects nor for history effects. Therefore the centre of the elastic domain is introduced as an internal variable that represents history effects induced by plasticity. The FE method is used to analyse plastic deformation in the crack tip region and to build the evolution law of the centre in a (T,KI,KII) diagram. An incremental formulation is used to make easier the simulation of the effect of variable loads on the fatigue resistance. This approach is applied to the Ti-6Al-4V alloy and compared with experimental results obtained with HCF and CCF (HCH+LCF) cycles at different stress ratios.

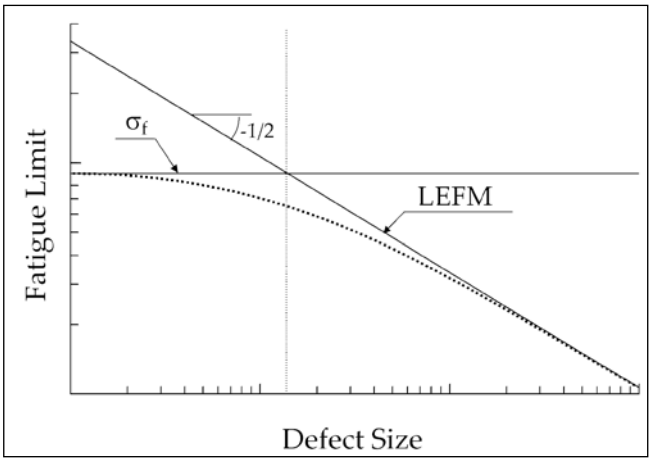


*Figure 1. Schematic of the proposed model in the Kitagawa-Takahashi's diagram, see [1].*

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# The reliability approach in fatigue design : deffi project

*André Bignonnet (Consultant), France*
*Co-authors : Henri-Paul Lieurade, Isabel Huther, Fabien Lefebvre, Alain Carcan, Eric Babaud, Jean-Claude Escoffier,Daniel Marquand (CETIM, Senlis) France*

With the DEFFI project, *Démarche Fiabiliste de conception en Fatigue pour l'Industrie,* CETIM developed Method and Tools for the reliability analysis in Fatigue design to answer the industrial need. The project was built with industrial partners, SNECMA/CNES, MECALAC, VOLVO CE, POMAGALSKI, AGCO and SNCF. The Fatigue Design Reliability Approach has been experienced on five industrial components proposed by the partners.
The method based on the Stress Strength Interference Analysis allows defining the minimum Fatigue Design requirement to reach a reliability target. The main operational fallouts are on three levels: tools, integration in the design and validation processes, evolution of the engineer though with regards to fatigue problems.

The tools developed allows analyzing
- the statistical aspect of in service loading based on elementary situation of life
- the statistical distribution of the fatigue strength with regards to the fabrication scatter
- the reliability target; it conducts to define the minimum Fatigue Design Requirement.

The Reliability is introduced as one of the Product Functions in a System Engineering approach. Each of the five industrial sub project were conducted following a Design and Validation Procedure.
The project demonstrates that the Keystone of the Reliability approach is the ability to capitalize Load data and Fatigue Strength data. This is necessary to increase the confidence in statistical estimators and therefore conduct a true analysis of the reliability with a sufficient level of realism. The project also shows that to integrate the Reliability as a Product Functions in the design processes needs some changes in the way of thinking of the engineers with close link of the contribution of design engineer, measurement engineer and test and calculation engineers.

# Reliability assessment of structures subjected to fatigue failure using kriging methods

*Nicolas Gayton (LAMI-IFMA), France*
*Co-authors : B. Echard, M. Lemaire*

More and more designers are interested in the structural reliability assessment. What is the reliability level of the designed structures? What is the associated security margin? How is it possible to design the only necessary structure without penalizing the structural reliability level? These are the objectives of the ANR project named APPROFI, managed by the CETIM, particularly for structures subjected to fatigue failure.
The proposed paper is in line with the APPROFI project. The only way to evaluate the fatigue strength of complex industrial structures is to use finite element modelling. As the reliability analysis is a succession of mechanical computations for various close configurations, two main problems are met:
· The use of finite element in a reliability analysis increases the computation time
· The critical area can switch from one point to another during the reliability analysis.
The objectives of this paper are firstly to replace the finite element model by a metamodel (kriging model) in order to decrease the computation time. The use of this kind of metamodel will be compared to the classical adaptive response surface. Secondly, the problem of critical point displacement during the reliability analysis will be discussed, and directions of work will be proposed in agreement with the APPROFI Project.
The illustration of this work will be achieved on a relatively simple structure (see figure 1) with a finite element resolution using Ansys. This structure is a metallic bracket loaded by a time variable force at its extremity. The random variables are the geometrical properties (length, width, radius, and thickness), the load amplitude and the material fatigue strength.
The structural failure is considered using the Dang Van criterion.

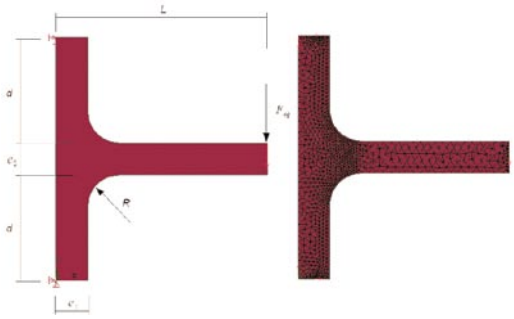

Figure 1: metallic bracket subjected to fatigue failure.

# A strategy to perform reliability analysis using polynomial chaos and resampling: application to Fatigue design

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*Co-authors : N. Gayton (LAMI-IFMA), France, J.L. Dulong (UTC), France, M. Lemaire (LAMI-IFMA), France*

In reliability analysis, the failure criterion is defined as a limit state function which depends on random inputs and response quantities. Since the work pioneered by Ghanem and Spanos on stochastic finite elements, structural computation involving random material and load properties has been intensively investigated and is now well known. Using stochastic finite elements, the response quantity can be written as series expansion which allows an approximation of the limit state function. For computational purpose, the series must be truncated in order to retain only a finite number of terms. In the context of industrial applications, no information is available concerning the smoothness of the model. This way, the accuracy of truncated polynomial chaos expansions cannot be directly computed as our aim is to minimize the number of model evaluations and find the optimal chaos order. Resampling techniques are tools to explore databases and to compute confidence intervals. In this paper, confidence intervals are applied to reliability analysis in order to pilot polynomial chaos expansions. This leads to a resampling polynomial chaos method (RPCM). Nowadays, it is a common practice in the industry to use the finite element method in order to predict the structural behaviour. Particularly, fatigue lifetime predictions are primordial. The randomness comes from the loading process and the fatigue resistance of material. From a general point of view, the objective of this paper is to show the contribution of resampling techniques in polynomial chaos based approaches in the context of fatigue design and reliability analysis. The method is first applied on numerical examples and then on an industrial one taken from the rail industry. Because the estimation of the fatigue lifetime is critical in the industry in order to assess and verify safety margins, we focus on the reliability index $\beta$ linked to the probability $P_f$ of not exceeding a lifetime limit.

# Reliability approach in fatigue design for aerospace industry

*Fabien Lefebvre (CETIM), France*
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The DEFFI project run by Cetim is an ongoing French project whose purpose is to promote the development of industrial stochastic methods and tools for mechanical fatigue design. This paper aims at demonstrating the necessary steps to validate a reliable probabilistic analytical design approach for fatigue in the aerospace domain, and the associated platform tools.

In 2006, as aerospace partners of the project, CNES and SNECMA started with CETIM the study of a rocket engine structure called "blade support", using a simplified but nonetheless realistic model shape. The reliability approach described in this paper is based on the "Stress-Strength" theory where the criterion for acceptability complies with a reliability objective, *i.e.* a required maximum probability of failure. Concerning the Stress analysis, the European rocket flights' database is used and a loading mix strategy is adopted. The launcher mission profile consists of "elementary situations of life" which depend on flight parameters such as velocity, launcher behaviour, aerodynamic loads, launcher's trajectory deviations, etc. At the end, the reliable Stress distribution curve is calculated. For the Strength distribution analysis which integrates material and manufacturing variability, sufficient fatigue test results up to failure on representative specimens and components are considered. Reliable fatigue life curves are developed based on these experimental fatigue data tests on the one hand, and sensitivity analysis performed on the model and material law on the other hand. All these results are achieved thanks to the platform tools which afford technical support to this case study. Finally, the estimation of the "blade support" structure failure rate is calculated, enabling a comparison to the previously defined reliability objective. The results fulfil the requirements of the acceptability criterion.

The use of a reliable probabilistic approach for the fatigue design in the aerospace domain has been demonstrated but further investigations on real loads and damage experienced by the structure in service are necessary. It is a must to have good understanding of the physical environment and the life cycle of the product, from its manufacturing to its operational use. This non-deterministic approach can help the traditional design approach and can also provide a better management of uncertainties and risks. This method could be used to realise acceptance files for waivers in production. It could be useful to obtain the necessary changes in the engineering know-how in order to manage industrial projects by mastering their technical risks and at the same time to develop an engineering probabilistic culture in a project team.

# POSTERS

## A strategy based on $LDL_T$ decomposition to speed up Monte Carlo simulations

*Alban Notin (CETIM), France*
*Co-authors: J.L. Dulong (UTC), France, N. Gayton (LAMI-IFMA), France, P. Villon (UTC), France*

Since the work pioneered by Ghanem and Spanos on stochastic finite elements, structural computation involving random material and load properties has been intensively investigated and is now well known. The proposed paper describes the use of the stochastic finite elements approach for predicting structures fatigue lifetimes with confidence intervals computation on the probability of not exceeding a lifetime limit.
In the industry, the estimation of fatigue lifetime is critical in order to assess and verify safety. Moreover, obtaining results from a mechanical model could be very time consuming. The number of calls to the mechanical model must be as weak as possible and we have to deal with available data. As resampling techniques supply information on the robustness of the results; this is why these techniques could be combined with polynomial chaos in order to have a confidence index on the reliability results. It will provide more information on results validity considering the selected initial sample for polynomial chaos computation. It implies an alteration to the computational procedure because of the resampling.
Concerning fatigue lifetime computation, the Dang Van criterion is used. The Dang Van criterion is expanded onto the so-called polynomial chaos. We focus on the computation of the reliability index for the lifetime limit. Confidence intervals are evaluated for the reliability index with a level of 95%. The objective is to deal with industrial problems. That is why in this paper, a non intrusive method based on a regression procedure is used to compute chaos coefficients allowing the use of classical finite element software. This consists in three steps: (1) Development of the Dang Van criterion on the polynomial chaos basis from a design of experiments (Latin hypercube sampling, composite sampling …). (2) Experiments resampling in order to compute confidence intervals for chaos coefficients and then first fourth statistical moments. (3) Confidence interval on the reliability index. The proposed method is first illustrated on an academic example and then on an industrial one from the rail industry . These two examples demonstrate the feasibility and accuracy of the computation chain.

# From design to optimization: how to consider shot peening and laser benefits

*Edouard Daniel (Metal Improvement Company), France*

Shot peening and laser peening are used to increase fatigue life and fatigue limit of the parts and mechanical structures mainly due to introduction of residual compressive stress. It is done by air blasting of steel, stainless steel, glass or ceramic for shot peening and by the shock wave created by a high energy laser beam (several GW) for the laser peening. Those two processes are very efficient on fatigue, fretting-fatigue, fretting-corrosion, pitting and stress corrosion cracking on limited or full surface of parts and welding structures. They are used on all metallic materials.

Both exist for several decades and are currently used, especially in aerospace industry.

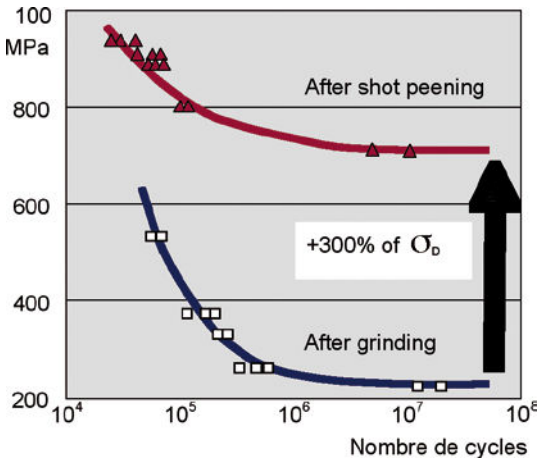
However, they are often used at last and above all, at last moment, when all other possibilities to increase fatigue life, as new design or material change have been tried. This often conduct to use expensive materials and with large design. Then, their fatigue design is not optimized.

Then, when considered from the beginning of the part design, shot peening and/or laser peening are useful to get the fatigue life required by the specifications combined with lighter parts and allow to avoid redesign.

Finally, they are used to reduce material purchasing costs and delivery time significantly. For instance, it avoids to use expensive and/or difficult to purchase materials.

Even if the benefits of shot peening and laser peening is not easy to include in FEA models, it is possible to characterize in fatigue materials after those treatments and to insert the data in the calculation models.

Those different approaches of shot peening and laser peening will be developed and illustrated by industrial cases.




Fretting-fatting on 35NCD16 steel samples after grinding and shot peening

# Validation of the prandtl damage operator approach for durability prediction a turbocharger turbine housing

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In the last two decades the development time of vehicles has been drastically reduced from eight to three years due to the application of advanced numerical and experimental methods. The specifications concerning comfort, driving behaviour and durability for every new model improve for every vehicle. The development responsibility is passed on to the supplier who, at the start, with limited information, makes a commitment with a fixed price for the production lead time. The aim of the paper is to validate the Prandtl damage operator approach integrated into the LMS Virtual.Lab Durability thermal fatigue module. The subject of the investigation is a turbocharger turbine housing that is exposed to high mechanical and thermal loads leading to considerable creep during its usage. The presented strain-life approach is based on the isothermal cyclically stable stress-strain and Manson-Coffin-Morrow strain-life curves. The finite element model of the turbocharger turbine housing is analysed numerically. The resulting time-dependent stress tensor and temperature histories are transformed into the equivalent uniaxial stresses by applying the signed von Mises and the critical plane approaches. Further, the stresses are transformed into uniaxial elastoplastic stress-strain curves and the fatigue damage is assessed continuously by applying the operator of the Prandtl type. The influence of the mean stress correction of the Morrow and the Smith-Watson-Topper type upon damage accumulation is studied, too. Based on the isothermal master curves, creep damage is assessed. Different damage assessment techniques are compared to the experimentally obtained values at four significant critical spots on the turbocharger turbine housing.

# Identification des fissures par la méthode des éléments de frontières et algorithme du simplex

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*S. Rechak, (Laboratoire GMD, Ecole Nationale Supérieure Polytechnique, El Harrach), Algérie*

The paper deals with the application of the dual boundary element method (DBEM) and the Downhill simplex algorithm for inverse problems in fracture mechanics. The problem of crack identification is formulated as the minimization of the difference between the measured and computed values of strains at selected boundary sensor points. Measured values are evaluated numerically by solving the direct problem using DBEM for the actual position and size of the crack. Several tests of identification are presented.

Nevertheless, it was noted that the algorithm does not converge in some cases or converges towards a bad solution. To highlight these cases, some preliminary results concerning the influence of some parameters are established (number of sensor points, initial solution, identity of cracks with respect to the boundary, direction of loading compared to crack position, interaction with interior obstacles. Solutions are proposed to circumvent those problems and to improve the robustness of the method.

# A numerical study of the fatigue proneness of flange thickness transitions in welded bridge girders

*A. Lechner (Graz University of Technology), Austria*
*Co-authors: Andreas Taras*

A number of factors have contributed to the increased use of comparatively large plate thickness changes -with ratios of $t_1 : t_2$ exceeding 2.5- in the design of large, welded bridge girders. The increased availability and enhanced weldability of larger plate thicknesses due to the developments in steel making processes are certainly two main factors. Another important criterion, however, is the fact that these joints are attributed to a much higher FAT class in current structural design codes when compared to the more traditional girder reinforcement technique using doubling plates.
A (not exclusively fatigue-related) case of damage at one such plate thickness transition in the compression flange of a newly built composite highway bridge triggered the study presented in this abstract. It takes a critical look at the current design practice for this common constructional detail and points out the vast discrepancies between the different fatigue design concepts based on nominal, geometrical/structural and notch stresses as well as modified FAT classes based on notch stresses.
These discrepancies derive from a combination of stress-raising factors that come together at this presumably simple constructional detail, i.e.:

- a global increase of longitudinal stresses in the thinner of the joined plates (when compared to the beam-theoretical stresses) caused by the sudden change of flange forces.
- a local increase of these longitudinal stresses due to plate bending resulting from the plate thickness eccentricity.
- high shear and vertical stresses in the web fillet welds surrounding the thickness transition.
- the simultaneous presence of a larger cope hole in the web plate, caused by the fabrication requirements during the welding of the transverse butt weld.

All of these effects vary greatly with the geometric parameters of the problem at hand. However, none of them enter the design concept currently suggested in the codes for the fatigue design of constructional steelwork. Therefore, the study presented here points out the need for further guidance of the structural design regulations and gives recommendations for flange thickness transitions.

# Fatigue life estimation of aircraft damaged structural component with surface crack

*Stevan Maksimovic (VTI Military department Aeronautical Institute), Serbia*
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Part-through cracks such as a corner cracks or surface are one of the most common cracks in structural components. The paper focuses to develop analytical expression for stress intensity factor (SIF) for à surface crack in 3-D solid structural component and its crack growth. Generally it is considered that damages in structural components are assumed to have an elliptic shape and that and are loaded with cyclic loads and other load spectra. The propagation of semi elliptical surface initiated fatigue cracks has been considered. Analytical model for the stress intensity factors, derived in this work, are used for crack growth analyses and fatigue life prediction. Semi elliptic surface cracks frequently initiates and grow in vicinity of high stresses, stress concentrations, thermal stresses and other non-linear stress fields. Accurate stress intensity factors for such cracks are necessary for reliable prediction for fatigue crack growth and fracture. The slice synthesis approach is used in this work to the computation of the surface flaw intensities. To validate the analytic derived stress intensity factors for semi elliptic surface cracks, finite elements method is used. The propagation of semi elliptic of surface initiated cracks has been considered. Analytical model for stress intensity factors, found in this work is used for crack growth analysis and fatigue life estimation. Good agreement between developped analytic expressions for stress intensity factors and numerical results based on finite element method are obtained.
Key words: Surface crack; Stress intensity factor; Weight function; Finite Element; Crack growth.

**Plastic work in fatigue design: illustrations and applications**

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In LCF and in thermomechanical fatigue, crack initiation criteria based on plastic and/or elastic energy were proposed since many years [CHA 00, PAR 00, AMI 06]. Charkaluk et al. [CHA 00] proposed the dissipated plastic energy per cycle as a damage indicator in thermomechanical fatigue. This proposition has the particular inconvenient, in a classical deviatoric plastic framework, to be independent of mean stress effects as do not depend on hydrostatic pressure. Park et al [PAR 00] propose then to combine the plastic dissipated energy with the deviatoric elastic energy and triaxiality factors To take into account mean stress effect, Amiable et al. [AMI 06] proposed recently a more simple indicator inspired by the linear relation between the shear stress amplitude and the maximal part of the hydrostatic pressure proposed in HCF by Dang Van. A new plasticity-damage based approach in HCF has been recently proposed by Monchiet et al. [MON 06] which can easily extended to LCF and TMF. In this case, the plastic dissipation depends on the classical deviatoric plastic but depends also explicitly on the hydrostatic pressure. The objective of this paper will then consist in a comparison of this theoretical expression of the plastic dissipation with experimental results coming from literature.

[CHA 00] Charkaluk, E. and Constantinescu, A., « Energetic approach in thermomechanical fatigue for silicon molybdenum cast-iron », Mater. High Temp., vol. 17, p. 373-380, 2000.
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[MON 06] Monchiet, V., Charkaluk, E. and Kondo, D. « A plasticity-damage based micromechanical modelling in high cycle fatigue ». C.R. Mécanique, vol. 334, no. 2, p. 129–136, 2006.

# Probabilistic approach to fatigue life estimation of low pressure turbine blade

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To unsure an relaible fonction of the steam tubine , it is necesarry to investigate about the blade element state . As the blade is one of the most charged element in the turbine and it is also an functionnaly significant item. It must carfully studied in the porpose to unsure the most reliable fonction. This work estimates the safe life by a probabilistic approchs of the X22 CrNiMoV failled blade.
Several failures were noticed on blade made from X22CrNiMoV, in the last row of low pressure turbine before their designed safe life . Fractogarphies of the dammge showed that the failure is a fatigue corrosion damage. To estimat safe lives of the low pressure turbine failed blade, this study started by analyzing the defect of the blade wich presented a crack at the root of the blade. The stressses state was invistigated by finite elements method (FEM). The stresses found due the severe mechanical conditions that affect the blade during its normal function, were high in the edge of the blade because of the effect of the geometrical notch( Fig 1). This region of the turbine may have high probability to concentrate some condensate dirty steam, in corrosive solutioned water. The chemical elements coming from eroded and damaged tubes in the complicated thermodynamical water cycle after some functionel time. The mechanical proprities of the X22CrNiMoV stainless steel had changed in the standards and shown some variation the carbon concentration for the same materiel in some investigations. This leads to uncertainities in the avaluation of the ultimate strength thus in the endurence limit. Those conditions do not unsure the needed reliabilty of such item.
This study includs a probabilitic frame work. To estimate the safe lives for steam turbine, the number of starts over a period of ten years have also several uncertainties a statistics performed over some plant gives informations used in this study (Fig 2). The limite state function defined for a safe functionel time over ten years using the stress life approach and the strain life approach for the damage up to initiation. The random data were taken as normaly and lognormaly distibuted. The simulation is done by MonteCarlo method. The results found are to be considred for both, the design consideration and for the maintenace strategy to be adpted by the tubine user.
Key words: Relability , Probabilistic approach, steam turbine crack initiation, fatigue, corrosion, blade, finite elements, Number of starts.

# An extension for cohesive zones to model fatigue failure in metals

*Steffen Brinkmann (Ruhr University Buchum), Germany*

The deformation in the vicinity of a fatigue crack tip is governed by the microstructure surrounding the crack tip. Moreover, this microstructure's evolution is determined by the presence of the crack tip. Solving this coupled problem numerically requires a novel approach with intrinsically connects both processes. In this work, we study how the fatigue crack tip interacts with the dislocation density, which is responsible for crack advance as well as for crack tip shielding. To this end, we introduce a novel cohesive zone model for the description of fatigue crack growth in metals in Abaqus. The model incorporates the stress fields due to dislocations into the constitutive model. Crack growth for constant amplitude loading and the overload case is computed. Significant crack closure is observed. A fatigue crack growth threshold and Paris law dependence of the fatigue crack growth rate on stress intensity factor range are outcomes of the model. Overload is discussed with respect to the dislocation density distribution and the resulting fatigue crack growth retardation. These results compare well with experimental findings of fcc metals.

# Surface integrity and fatigue life of high precision turning AISI 52100 steel

*Nabil Jouini (Laboratoire Roberval-UTC), France*
*Co-authors: P. Revel, M. Bigerelle, A. Gautier, H.P. Lieurade (Cetim)*

In order to improve contact-fatigue life of hard steel, the relationship between turning process parameters, surface integrity characterized via roughness parameters and residual stresses was investigated. High precision hard turning process can produce low surface roughness and induces compressive residual stresses in a deep subsurface, which increase the fatigue life of the workpiece. Hard bearing steel AISI 52100 steel (60-62 HRC) samples were machined by High precision turning using cubic boron nitride (CBN). Residual stresses and roughness parameters were evaluated respectively by X-ray diffraction and Scanning White Light Interferometry.
Firstly, the effect of cutting speed, feed rate and cutting depth on surface roughness was experimentally investigated. Then, the effect of process parameters on residual stresses was analyzed. The optimal turning parameters combination was selected by choosing the higher and deeper compressive residual stresses and low roughness parameters. Finally, the contact-fatigue test machine from CETIM was used to evaluate the fatigue life of selected samples, and therefore, the effect of surface integrity and process parameters on fatigue life were quantified. The results show that the residual stresses and roughness parameters have significant effects on fatigue life.

# The Mechanisms of the Strepy-Thieu ship lift: fatigue in heavy mechanics field

*Donatienne Portugaels (Service public de Wallonie), Belgium*
*Co-author : G. Janssen (Global Design Technology), Belgium*

The Strépy-Thieu ship lift is the highest boat lift in the world. It allows ships up to 2000 tons to move between the downstream and the upstream reach. The level difference is 73 meters.
The Strépy-Thieu ship lift consists of two cages balanced by counterweights which are linked to the cages by 112 suspension cables and 32 command cables. The suspension cables roll up on 4.8 m diameter sheaves, 224 in total for both cages. Many of the mechanisms of this ship lift are extremely large. All the parts are specific, none of them is usual.

Now, after 7 years of service, some fatigue problems have occured :
- Cracks in a weld of the 4.8 meter pulleys,
- Fretting corrosion of the assembly between the out torque shaft of the low speed reducer and the hub of the drum,
- Pitting of the teeth of the first shaft of the low speed reducer,
- …

Moreover, the ship lift has to continue to operate while we try to deal with these fatigue problems.

The objective of the proposed paper is to present the fatigue problems which have appeared on the mechanisms of the Strépy-Thieu ship lift and the analyses, measurements and studies made to solve these problems.

From the results of these operations, it is possible to determine why the usual rules used for the design of the fatigue resistance are not valid for such a mechanism.

# Effect of Hot-dip galvanization on fatigue properties of advanced high strength steels for automotive applications

*Sophia Aden-Ali (ENIM), France*
*Co-authors: J. Gilbert, E. Petit, Z. Azari*

Nowadays, ecology and economy constitute an important concern in car design. Improvements in car lightweight can significantly contribute to fuel savings, and so CO2 emission reduction. To meet these requirements, the use of Advanced High Strength Steels (AHSS) is well-fitted. Indeed, AHSS exhibit good crash performance and formability, thanks to an interesting elongation-resistance combination. In this way, the production of steel sheet with lower thickness, for equivalent mechanical resistance, is possible. However, the corrosion risk is all the greater since the sheet is thin. Here, hot-dip galvanization remains the most cost-effective technique to prevent corrosion degradation phenomena of mechanically welded assembly or finished parts with complex shape. The hot-dip galvanization industrial process involves surface preparation, immersion of the parts in a liquid zinc bath at 450 °C, and the solidification of zinc in air at room temperature. Galvanizers can guarantee protection against corrosion up to several ten years. The zinc coating is bonded to the substrate through a multiphase multilayered structure. The duration of protection is directly related to the thickness of the coating. Typical coatings, 40 to 80 µm thick, are mainly made of intermetallic Fe-Zn compounds. These Fe-Zn phases are hard but brittle. Fatigue toughness is a mechanical property related to surface properties. Then, the fatigue lifetime of hot-dip galvanized steel may differ from those of uncoated steel. Previous papers reported either a negligible or, for most of them, a significant reduction of lifetime under cycling loading. For this reason, the sizing of the parts should be carried out taking into account the fatigue behaviour of the galvanized steel.
Our experimental study is devoted to the measurement of the fatigue properties of galvanized AHSS steels, including Transformation Incuced Plasticity (TRIP) and High Strength Low Alloy (HSLA) steels. A significant reduction of the fatigue lifetime of these steels after standard galvanization was shown. We work in order to ascertain the assumptions usually cited as explanations for the drop of the fatigue limit. The expected evolution of the steel microstructure due the thermal treatment, undergone during galvanization, is not responsible for the degradation of the fatigue endurance. The mechanism involving the propagation of a pre-existing crack pattern in the intermetallic layer during the fatigue test, cannot account either for our observations in most cases. Effects of the surface preparation steps are presently under study.

Keys words : Lightweight improvement ; fatigue behaviour ; hot-dip galvanization ; TRIP; HSLA

# Applications of selected NDT procedures for more detailed identification of crack initiation stage at fatigue tests of aluminium alloys

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*Co-author: F. Vlasic*

Aluminium based alloys are widely used in technical practice. In many cases, products made of these materials have to meet high requirements; that is why it is necessary to obtain detailed information about their mechanical properties.
The paper describes some basic results of AlMg alloy (EN-AW-6082) behaviour change during high cycle fatigue loading which were detected using AE method and analysis of load frequency changes of the electromagnetic loading device. These procedures allow basic identification of different stages of fatigue process. The main attention is targeted on more exact identification of the first stage of fatigue cracks propagation. AE signal plots obtained with use of the newly developed AE analyser device called DAKEL IPL are commented in detail. This apparatus allows for continual recording and processing of data from the acoustic emission sensors. Compared to the up to date commonly used AE analyser devices, the major advantage of this type of analyser is that it is capable of continually sampling and storing the whole AE signal for as long as there is space to store it.
Some changes of AE signal and loading frequencies are identified also in the stage of fatigue damage cumulation. For explanation of this phenomenon the method of X-ray diffraction analysis of the structure is used.
Acoustic emission method seems to be a very valuable tool for evaluation of damage degree. This method enables monitoring of changes of damage processes directly in the course of loading cycle, which is its big advantage, compared with other identification methods.

This paper originated with support from a Grant Agency of the Czech Rep. project nr.: 106/07/0508 - Detection and research of the development of cyclic damage of modern AlMg alloys with the application of specific NDT procedures.

# Optimisation of fatigue design in wind towers

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In the last two decades, driven by the demand of more sustainable and cleaner energy sources, there has been a great expansion of wind energy technologies. This has led to the development of specific design procedures/codes for the different components being involved. Among the latter, the wind towers are one of the most critical in terms of safety, efficiency and economy. These components are subjected to challenging loading conditions, specially caused by wind effects, whose random nature generates fatigue processes which are one of the determining phenomena in the design.
The design of wind towers against fatigue is generally performed by using traditional approaches, such as those that combine nominal stresses, FAT classes and S-N curves. However, also in the last years, there have been significant improvements in fatigue tools that can be applied in the design of wind towers, providing more adjusted structural sizing.
This paper applies the Fatigue module of the newly developed FITNET FFS procedure. This module provides different assessment routes (Routes 1 to 5), some of them gathering new fatigue assessment tools. Two of these routes have been applied for the assessment of a wind tower: Route 1, as a traditional approach using nominal stresses; and Route 2, using the hot spot stress or the notch stress obtained through finite element modelling and ,theoretically, providing more adjusted results. The differences obtained in the structural sizing when using the different approaches are also exposed.

# Early fatigue damage detection in stainless steel through digital image correlation studies

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Up to now, because most of numerical models developed for the prediction of the fatigue lifetime of a structural component consider either the initiation stage or the propagation stage of micro-cracks, an underestimation of this feature is usually committed. In particular, numerical models that define the propagation of cracks or defects are based on linear or non-linear fracture mechanics that is inappropriate to define the first initiation stage of a crack, which would require a finer analysis relatively to the volume element.
For the development of an innovative numerical approach taking into account the initiation and propagation stage at once, it is, thus, necessary to obtain some specific understanding drawn from experimental observations of the relevant micromechanisms coming into play. To this aim, the experimental observations have to reach several objectives: first, to allow an early detection of the initiation of cracks, then, to follow the evolution of these cracks and finally to yield quantitative measurements in relation to these aspects. A microscopic strain mapping technique using in-situ optical microscope device coupled with digital image correlation has hence been chosen. Using austenitic stainless steel as experimental material, after electropolishing, the natural revealed texture is used as pattern to directly apply a digital image correlation technique at the microstructural scale. During fatigue test, damage micromechanisms can thus be observed and followed through strain fields measurements and directly related to the microstructural features of the materials. In particular, strain gradients indicate potential microcrack initiation sites. This technique is coupled with other means as acoustic emission to help in early damage detection.
Since the experimental procedure is mainly based on the information given by the strain distribution (at the grain level) throughout the fatigue test, it is essential to control the committed errors inherent to the derivative operation performed for strain calculation. A filtering method based on diffuse approximation (weighted local least squares) has therefore been proposed. Basically, starting from a discrete number of data points (given by the correlation calculus), the diffusive approximation defines a continuous field from which the strain fields can be directly deduced. Previously developed in 2D, the filtering capacity depends on the size Rx of the spatial area used for each local regression. In the case of fatigue loading, we take advantage of the fact that data points given by the correlation calculus, can also be obtained and varied regarding the time. A filtering tool has therefore been developed by filtering along the time as well and adding a supplementary factor Rt. First results have shown a better filtering capacity of this 3D method compared to the previously used 2D one.

# Fatigue behaviour of 6061-T6 aluminium alloy welds obtained by MIEA welding technique

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We present experimental results on the fatigue behavior of welded 6061-T6 aluminum alloy specimens by means of Modified Indirect Electric Arc (MIEA). In order to study the fatigue behavior, fatigue testing were performed in specimens with and without weld reinforcement in the as welded condition. For samples with weld reinforcement, the surfaces normal to the welding direction were polished whereas when the welding reinforcement was removed all surfaces were polished. In both conditions, the approximate fatigue limit was obtained employing the Locati method. The calculated fatigue limits were 77 MPa and 102 MPa for specimens with and without weld reinforcement respectively. It was observed that for the samples with weld reinforcement, failure consistently occurred in the transition zone between the fusion zone and base material. This failure mode is attributed to the stress concentration factor caused by the reinforcement shape. In contrast, for the samples where the welding reinforcement was eliminated, failure occurred principally in a soft zone 13 millimeters from the fusion line, but sometimes failure was located in the fusion zone due to weld defects as porosity. Softening is caused by the welding process and is characterized by the microstructural transformation of the strengthening β' type precipitates into coarse β' type precipitates (over aging phenomenon) decreasing significantly the alloy mechanical properties. The fatigue behavior followed by the as welded specimens indicates that geometry is the most important parameter in samples with weld reinforcement. On the other hand, after removing the effect of stress concentration caused by the reinforcement, fatigue limit is dominated by over aging of the microstructure. The fatigue behavior for both conditions (reinforcement and no reinforcement), were represented by means of the *S-N* curves.

# Musica: from the welding simulation to the fatigue life prediction. Methodology, software and application to a T welded joint

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*Co-authors: G. Shi, F. Lefebvre, G. Bremaud, J. Nawrot*

Musica is a multi-partner project aiming to set up a unified methodology for welding, inspection and assemblies design.
Welding processes generate changes in microstructure, residual stresses and distortions that play an important role on the fatigue strength of joints. These stresses and distortions, mainly due to temperature gradients and phase transformations occurring during the welding process, must be evaluated and incorporated into a fatigue life prediction. Simulation tools are now available to conduct these analyses; however, as part of an integrated approach, based on different softwares, gateways are needed to transfer essential information to each solver. This study was conducted with the objective to establish and use a software chain starting from the structure meshing, continuing with the welding simulation and ending by the fatigue analysis. During the different steps of this process, emphasis was placed on the information needed as input for each code and the results produced by each code. This chaining is illustrated in the figure 1.
For the fatigue life prediction, this study focused on a local approach, more able to take into account local effects induced by the welding process. Local stresses or strains determination needs an accurate definition of the weld's local geometry, particularly at the potential crack initiation site as the weld toe. The local approach considers the weld as a structural detail with features taken into account by the fatigue calculation. This allows to predict the strength of new assemblies and to optimize the welding process.

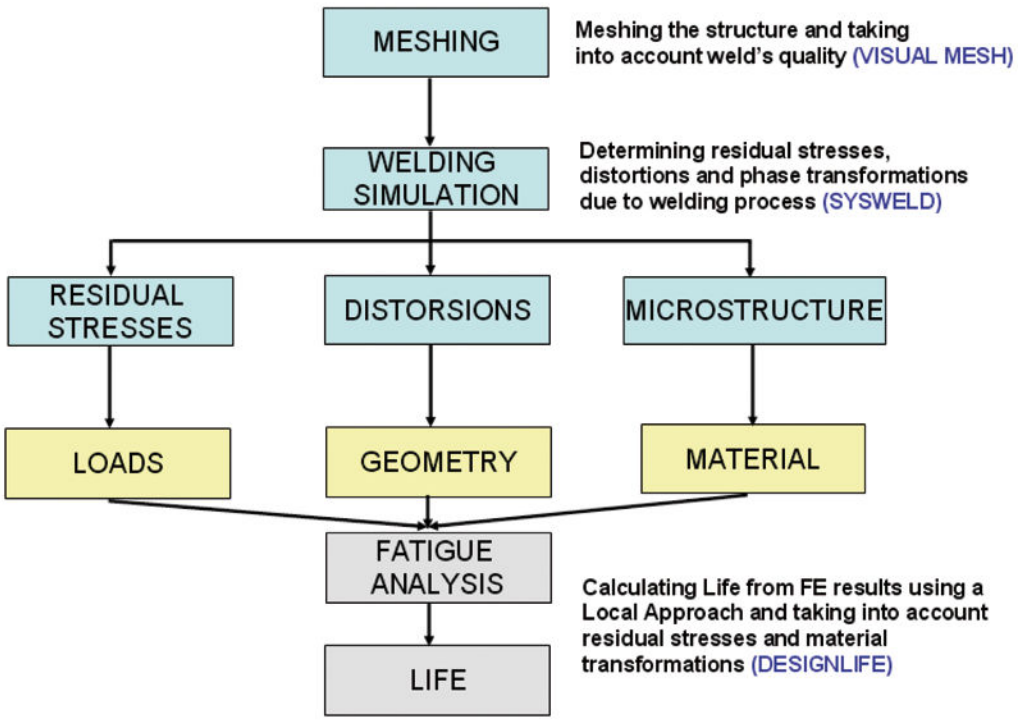


Figure 1: Analysis process and software chaining

# A cyclic plastic strain based wear model

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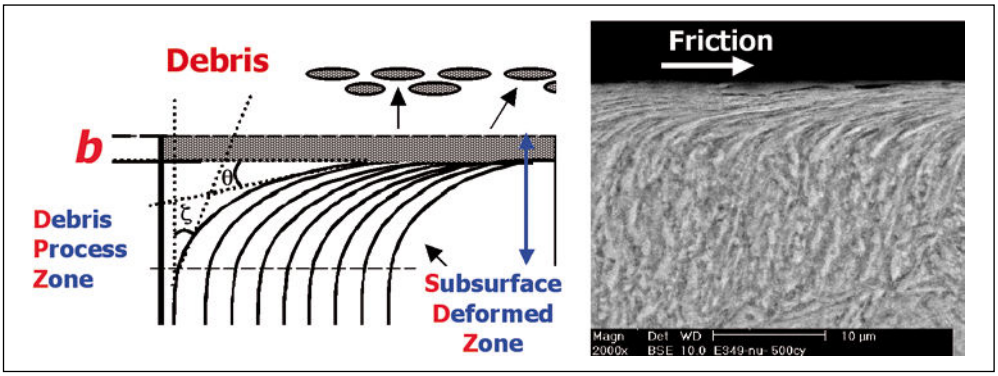
*Keywords: high temperature tribology, high temperature friction, wear model, plastic deformation, ratchetting, tool steel, tempered martensitic structure*

The surfaces of bodies experiencing cyclic thermo-mechanical solicitations in relative movement are very much prone to wear. The origin of the wear strains and stresses is basically the heat transfer between two antagonists bodies and also the load transfer between the bodies, such for example the forming efforts to produce a part. In general phenomenological classical or modified-Archard models are used to estimate the wear height or volume.

A new wear model based on cyclic plastic shear strain accumulation is proposed. The basic idea is that when the cumulative plastic-shear strain at sub-surface attains a critical limit (*shear strain rupture ductility*), the sub-surface micro-porosities form and coalesce into the micro-cracks. These cracks propagate and form the debris that are rejected out-off the wearing tracks.

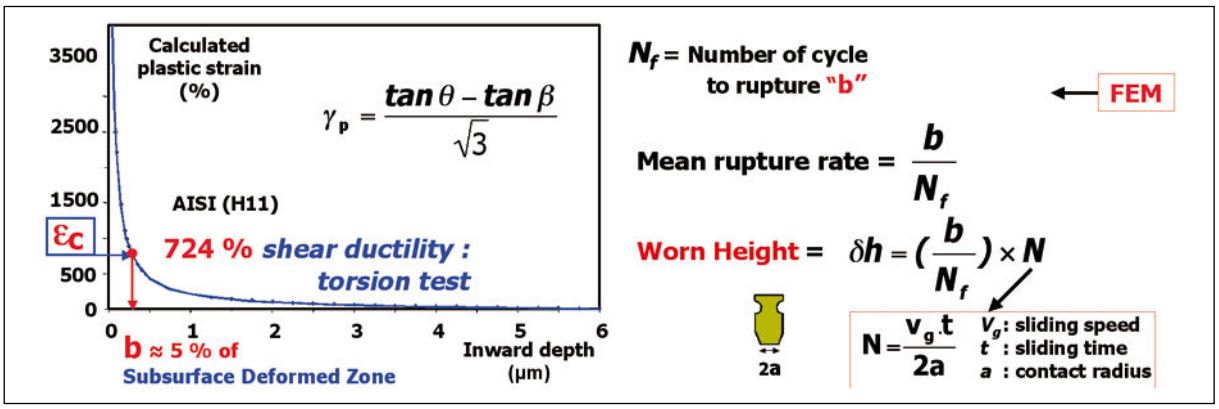
An Equivalent Damage Cycle (EDC) is introduced. It is considered that:

- Sub-surface zone is deformed by plastic shearing (SDZ)
- Deformation accumulates by cyclic incremental plastic, ($\Delta\varepsilon_p$, estimated via FEM analysis
- When the strain accumulation achieves the critical *shear strain rupture ductility* ($\varepsilon_c$) the debris are emitted
- $\varepsilon_c$ is achieved only in a limited part of SDZ (" b")

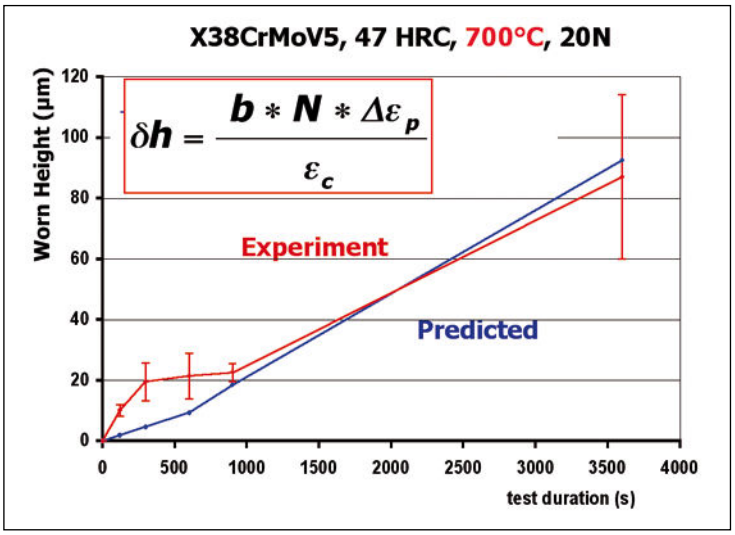



The wear experiments are carried out under dry friction constant load and velocity on a high-temperature pin-on-disc tribometer with different disc temperature and test duration. The well-known double tempered martensitic tool steel, X38CrMoV5 AISI-H11 (47 HRC, as pin), and mild steel XC18 (as disc) are used as antagonists.

The average strain increment ($\Delta\varepsilon_p$, estimated by FEM analysis), the number of the cycles (N), the material dependant sub-layer characteristic thickness (b, estimated via calculation of sub-surface shear strain distribution of pin, see the following figure) and the shear strain rupture ductility ($\varepsilon_c$, measured by a torsion experiment) are related in a "Manson-Coffin" type law (see the following figure).




A very good correlation between the experimental and predicted worn heights vs. time or vs. number of cycle (1) (see the following figure) in steady state fiction and wear regime. The model underestimates the worn heights for the short time experiments.




(1)Remark: the number of cycle N and test duration time are related via disc's angular rotation speed

# Fatigue behaviour of the austenitic stainless steel 316l in a physiological medium

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*Co-author : Fatah Hellal (Laboratory of Science and Engineering of Metallic materials, Metallurgy Department, Superior Polytechnic National School, Algiers), Algeria*

The austenitic stainless steels are among materials the most used in the field of implantology, considering their high corrosion resistance and their suitable mechanical characteristics. The implants are often subjected to dynamic stresses in a physiological environment which can be aggressive. The goal of this study is to simulate the behavior of the 316L stainless steel in physiological medium, to determine its lifespan. For that, flat specimens were prepared with initial notches in the form of pits obtained by tests of polarization in a solution of $FeCl_2$. These specimens were then subjected to tests of fatigue-corrosion per cross-bending with a frequency of 0,5Hz, in a NaCl 3.5% solution similar at the physiological medium.
The results obtained show the kinetics of cracking according to the number of cycles of request. A small size of initial pit increases the number of cycles to failure, much more in the presence of the chlorinated medium. However, with higher sizes, one can observe a deceleration of the chemical effect.
The curve of Wöhler shows that the mechanical action has much more influence when the loads applied are high. When those decrease, the electrochemical effect becomes dominating and reduces the lifespan of material considerably.
**Key words:** austenitic stainless steel, fatigue, corrosion, pits, crack, lifespan

# Introduction of an optimized conception against Fretting-Fatigue damages: Development of a Fretting-Fatigue Mapping strategy including material and surface treatment properties

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Fretting fatigue induced by combined localized cyclic contact motion and external bulk fatigue loadings may result in premature and dramatic failure of the contacting components. Depending on fretting and fatigue loading conditions, crack nucleation and possibly crack propagation can be activated. This paper proposes a procedure for estimating these two damage thresholds. The crack nucleation boundary is formalized by applying the Crossland high cycle fatigue criterion taking into account the stress gradient and the ensuing «size effect». The prediction of the crack propagation condition is formalized using a short crack arrest description. Applied to an AISI 1034 steel, this methodology allows the development of an original Material Response Fretting Fatigue Map (FFM). The impact of material properties and surface treatments is investigated.

Keywords: Crack nucleation, Crack arrest, AISI 1034 steel, Surfaces treatments, Fretting.

# Methodology for Plastic strain assessment and fatigue behaviour of 304L stainless steel used in cryogenic environment

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**Gaztransport & Technigaz** (GTT) is a highly-specialised marine technology company occupying a leadership position in the engineering and design of membrane containment systems for the storage and transportation of LNG on ships. The objective of this study is to quantify the residual capability of the membrane sheets during all steps of its service life but also after potential accidental loads. Indeed, the corrugated membrane is initially formed at room temperature and then submitted to ship elongation, thermal loads and pressure loads at cryogenic temperature. In extreme accidental case, the corrugation can suffer from important distortion caused by liquid gas sloshing during its service. To achieve this aim, different tests and characterisation are carried out on damaged and undamaged stainless steel membranes, as metallographic analysis, X-ray diffraction analyses, static and dynamic mechanical testing.

With interrupted tensile tests, experimental relationships are determined between X-ray diffraction peak broadening and plastic strain to build calibration curves for different configurations (room temperature, cryogenic environment, pre-straining).

In relation with the calibration curves, X-ray diffraction peak broadening measurements on critical zones of the membrane sheet (large corrugation or knots) are transposed in terms of plastic strain.

When a large corrugation has totally collapsed there is still a fair safety coefficient regarding strength aspects (at least more than two on the plastic strain).

Fatigue tests carried out to simulate the ship bending at sea show that samples submitted to sloshing loads present similar fatigue strength in cryogenic environment than samples directly coming from the forming process. Other tentative fatigue tests to simulate repeated sloshing effect have been also carried out and seem to show a high potential before crack appearing.

# Effect of welding consumables on fatigue crack growth behaviour of armour grade quenched &tempered steel joints

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Armour grade Q&T steels are widely used in the construction of military vehicles. These steels are prone to hydrogen induced cracking in the HAZ after welding. The use of austenitic stainless steel weld metal consumable to weld the above steel was the only available remedy because of higher solubility for hydrogen in austenitic phase. Recent studies proved that low hydrogen ferritic consumables are being used which can give a very low hydrogen levels in the weld deposits and this is a cost effective process when compared to the austenitic weld metal consumables. The present study involves experimental investigation on fatigue crack growth behavior armour grade Q&T steel closely confirming to AISI 4340 configuration. Single 'V' butt joints have been fabricated using austenitic stainless steel electrodes, low hydrogen ferritic steel electrodes and high nickel steel electrodes by Shielded metal arc welding (SMAW) process. The fatigue crack growth tests were conducted by using Center cracked tension (CCT) specimen with a frequency of 20 HZ and at constant amplitude loading (R=0). The crack growth rate was established from steady state crack growth and the fatigue crack growth parameters were evaluated from the data obtained for all types of joints. It is inferred that the joints fabricated by low hydrogen ferritic joints exhibit better fatigue crack growth resistance than the austenitic joints and high nickel joints.
*Key Words*: Q&T steel, welding consumables SMAW, Fatigue crack growth.