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ABSTRACTS BOOK

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C O N T E N T

Session 1

Methodologies and tools for fatigue life assessment: optimization of the durability process.

Méthodologies et outils d'évaluation de la durée de vie à la fatigue : optimisation du processus de durabilité

S1.1 : **Stiffness and durability assessment using different modeling methods of various joining technologies by means of finite element method**
Evaluation de la rigidité et de la durabilité de diverses technologies d'assemblage, utilisant différentes méthodes de modélisation au moyen des éléments finis.

S1.2 : **Fatigue life assessment for light pressure diesel injection components with large residual stresses**
Estimation de la durée de vie de composants d'injection diesel à haute pression, comportant des contraintes résiduelles élevées.

S1.3 : **Using a common test and simulation environment to optimize the durability process and verify the results**
Utilisation d'un environnement commun d'essai et de simulation, afin d'optimiser le processus de durabilité et de vérifier les résultats.

Stiffness and durability assessment using different modeling methods of various joining technologies by means of Finite Element Method

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Abstract

For lightweight automotive body structures, the stiffness and the fatigue behavior is greatly influenced by the properties of its joints. The used joining technology, the number and the distribution of the joints are of high importance to derive a well engineered and cost effective structure.

Since the drastic raise of fuel prices and environmental pollution in the last time the reduction of the vehicle weight is a basic requirement for the development of new cars, trucks, buses or other vehicles. Nevertheless there can be observed a general tendency in the opposite direction. The reasons for this contradiction are on the one hand additional features for more comfort and safety as well as increased engine torques. On the other hand the potential for mass savings in the basic structure is not enormous.

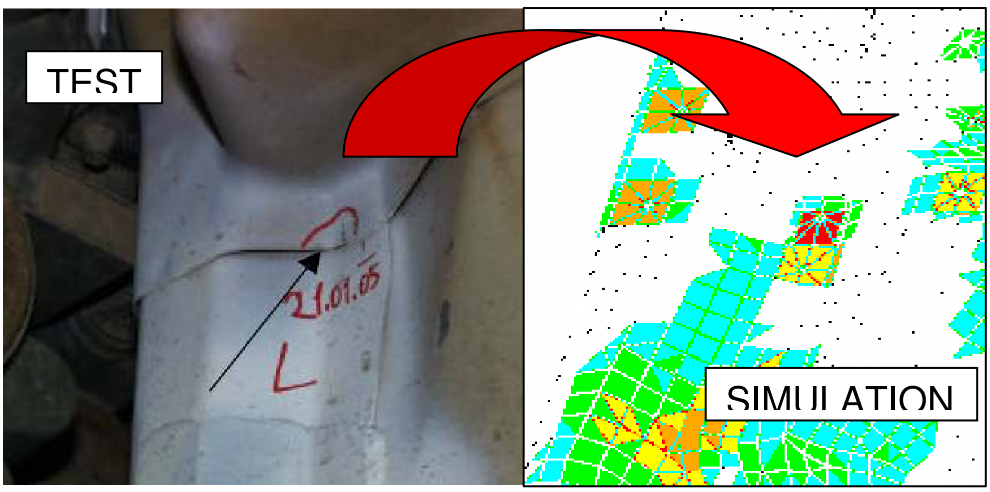
On the market several methods are available to simulate different joining technologies. But it is still often not clear which modeling and assessment method is appropriate for each specific application.

Vehicle bodies have to withstand high dynamic loads while they contain a lot of arc welds, spot joints, bonded joints or other types of joints and notches representing potential crack initiation points.

There are two ways engineers can handle all these important influences during the development process: On the one hand, a very good method is to perform stiffness and fatigue tests with components or total vehicles. Many influences can be considered without any mathematical model, nevertheless the results have high accuracy.
Unfortunately, experimental tests give only poor information about low stressed areas, so it is very expensive and time consuming to minimize a component's mass without significant loss of stiffness and acceptable durability behavior based on testing.

Therefore, numerical simulations, mainly based on the Finite Element Method (FEM) are state of the art to reduce or even avoid testing loops, prototyping and therefore development time and costs. Nevertheless, release tests are necessary before start of production because of risk considerations.

This lecture will give an overview of simulation approaches for spot welded joinings. The advantages and handicaps of the different available modeling possibilities (fast modeling vs. detailed results) will be represented. Differences in the results for stiffness and durability behavior will be pointed out to give simulation engineers hints about which kind of joining simulation best fits to his expectations.



Fatigue Life Assessment for High Pressure Diesel Injection Components with Large Residual Stresses

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In order to meet economic and ecological requirements, maximum internal pressures in Diesel injection systems have been raised to above 2500 bar. Technologies like autofrettage of components considerably raising the endurance limit have made this possible. Nevertheless, the technical methods to further increase the endurance limits are somewhat exhausted. However, it can be expected that a design based on a finite life will allow for the desirable further increase of internal pressure.

In the present paper, an overview on investigations regarding this problem is given. Experimental analyses have been conducted using specimens with a typical, yet idealized geometry under variable amplitude loading. To this aim, a synthetical load sequence has been created based on typical common rail load data. Several approaches to predict the finite fatigue life of such components with increasing degree of sophistication, of accuracy, and of numerical expense, are presented.

As a **first** level, the applicability of the state-of-the-art nominal stress approach used with an appropriate mean stress criterion and the elementary Miner rule is evaluated. Three more approaches with increasing levels of sophistication have been investigated. These aim at calculating crack growth by means of fracture mechanics. Herein, the consideration of residual stresses resulting from the autofrettage process is of outstanding importance, as these are crucially influencing crack growth. In the **second** level, they are treated as mean stresses modifying the local stress ratio R.

The accuracy of crack growth calculations can significantly be increased by taking into account load sequence effects. In the **third** analysis level the well established Newman strip yield model is extended to incorporate residual stress distributions calculated with the finite element method. This approach proves to be appropriate to calculate crack opening stresses taking into account load sequence dependent residual stress redistributions. Thus, the effective load ranges, that dominate crack growth, are accessible with quite satisfying accuracy.

The most sophisticated of the here presented approaches is a finite element crack growth simulation (**fourth** level). This includes a realistic description of the material behaviour by using an appropriate material model. Moreover, the basically three dimensional stress-strain-state in the specimen can be taken into account.

For approaches 1, 3 and 4, results are presented and compared to experimental fatigue data. Their applicability to design autofrettaged components is evaluated, advantages and disadvantages are outlined. Especially with levels 3 and 4, a good agreement with the experimental results can be achieved. It can thus be concluded that fatigue life design can lead to higher admissible pressures. In the present paper, only mean values are given. It is to be expected that the beneficial effect of autofrettage is amplified by the smaller scatter of experimental finite fatigue life data leading to smaller necessary safety factors.

The presented methods all prove appropriate for the further development of a finite fatigue life prediction. The more sophisticated methods have – additionally to being more accurate – the advantage of needing far less experimental data while, on the other hand, consuming significantly more computational resources. However, especially the Newman strip yield model seems to be a promising way to reconcile the need for accuracy and efficiency, respectively.

Using a common Test and Simulation environment to optimize the Durability Process and verify the results

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Manufacturers are under continuous and increasing pressure to reduce the "Time to Market" of new products while assuring a high reliability level of these products. Durability design and analysis is an essential element in achieving these objectives and involves a multi-disciplinary approach.

In order to obtain rapid and realistic life predictions, Simulation and Testing should be used in synergy, each field bringing to the other the necessary information, making the durability process an integrated one.

Products durability was traditionally evaluated late in the design cycle when a prototype was available for measurement & test, but nowadays simulation techniques allow investigating durability design options very soon before physical testing (Virtual Prototyping). This approach reduces development time and costs, by concentrating on only prevalidated designs.

Analytical techniques are available for load generation, stress state calculation, and fatigue analysis. These methods often rely on very complex models and need realistic measured test data as inputs and also for correlation purposes at each stage of the analysis process.

The diagram in figure 1 shows how analytical and physical approaches work in synergy in order to successfully analyse product performance. In this process, it is essential that numerical simulation techniques are employed at the earliest possible stage, so that the design can be developed, optimized and above all understood through analysis. Key elements in making reliable durability calculations, apart from the use of adequate models, is the accuracy of inputs such as: loads – measured, virtually derived or based on previous design - stresses induced by these loads on the structure and material behaviour laws – including manufacturing effects. Simulation allows sensitivity analyses to be conducted until an acceptable durability is obtained. These analysis loops give an insight to the predominant influencing factors and the distribution of fatigue lives.

In parallel to virtual analysis, physical tests are conducted in the field or laboratory. These tests provide the necessary information such as loads or materials data and allow correlation with simulation which is critical to ensure high confidence in the results. Due to the inherent scatter of the fatigue phenomenon and all possible sources of inaccuracy & variability, the physical test represents final validation of the design and is often time consuming. At this stage several test acceleration techniques may be applied in order to further optimize the process.

This paper reviews the main components of the durability process and the way they interact between each other. It also discusses how this process can benefit from an integrated approach in a common analysis interface.

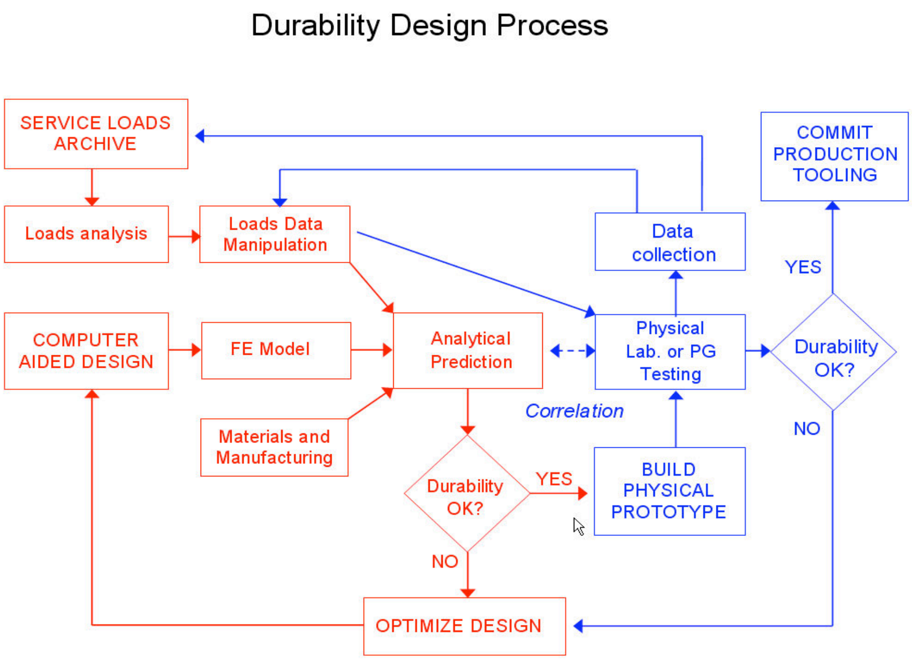

Figure 1. The Durability Design Process

Figure 2 shows an example of a Test and CAE fatigue process in ICE-Flow GlyphWorks from nCode.

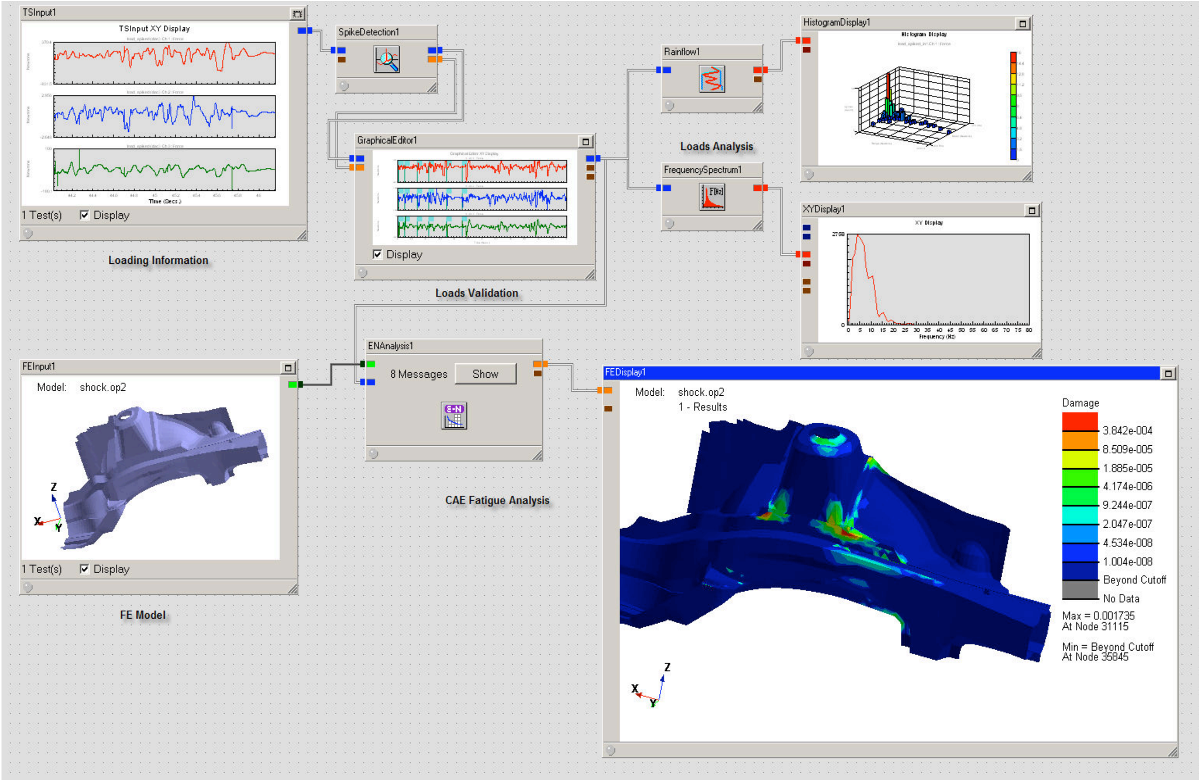

Figure 2. Test & CAE fatigue example analysis flow

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Session 2

Fatigue Design and manufacture process.

Conception en fatigue et procédé de fabrication.

Taking into account the forming process in fatigue design computations

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Fatigue design of mechanical parts may be based on ideal ones, without taking into account for their real geometry (e.g. thickness), the formed material state (e.g. plastic strain and residual stress) and considering fatigue data involving pre-formed materials (e.g. Wöhler curve on laminated steel sheet, instead of finished stamped parts). This approach is pragmatic, but in some cases may lead to uneffective design: failure is expected when it is not supposed to occur and damage is not predicted when it seriously affects the part.

CAE tools have been providing effective coupled FE computation of forming-stage and service-stage for several years, even if some details of this “global approach” are still under discussion, e.g. data mapping from the forming mesh to the fatigue one, transition between different solvers, the choice of material hardening models, … : thus, several hypothesis are simply accepted “as-is”.

Actually, due to simultaneous engineering approach, complete FE forming computations are usually provided when the design of the part is already fixed, say too late; moreover, complete and extensive material data on pre-formed material are not yet available. Definitely, there is a need for an easier fatigue design approach, based on rules coming from essential data, implying a deeper comprehension of the phenomena.

Thus, this work aims to highlight the contribution of every ingredient included in fatigue design computations when taking into account for the forming process (i.e. stamping) and identify their sensitiveness on fatigue life assessment. This study focuses on the design of a stamped part like a suspension arm (figure 1) from a “global approach” point of view. Moreover, it considers the elastic-plastic behaviour of a thin steel sheet subject to elementary deformations and loads in the framework of a “local approach”.

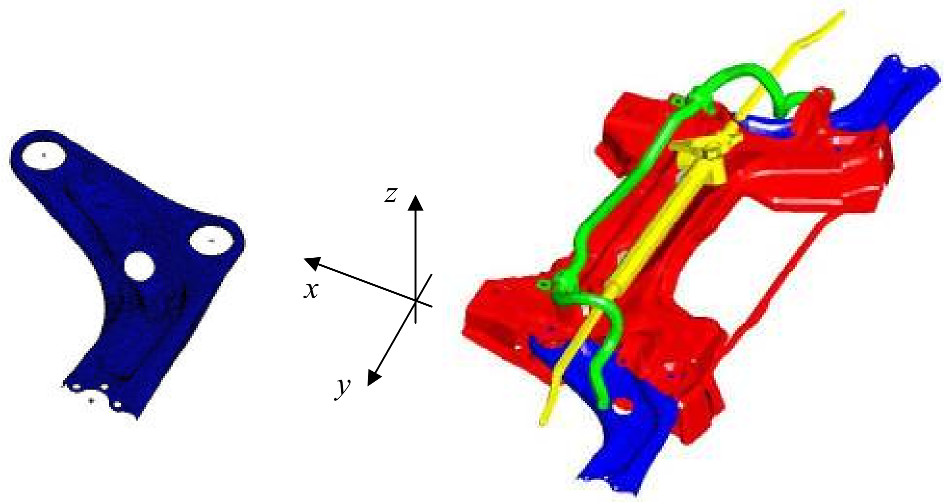

Figure 1. Automotive front axle with engine cradle (red) and suspension arm (blue).

This is an ongoing joint project by PSA Peugeot Citroën, ARCELOR MITTAL and ENSIETA. It does not pretend to be conclusive, but trace the state-of-the-art on this subject and highlight the main questions to address and answer.

Multiaxial fatigue criterion accounting for grain flow orientation in forged components

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Abstract Numerical modelling of fatigue behavior for anisotropic structures has become critical for design applications. This is particularly true for forged components due to the intrinsic anisotropy of the material resulting from the process. Among all forming processes, forging gives raise to the most resistant components withstanding a large number of loading modes. Actually, forging induces a strongly heterogeneous microstructure in the material, resulting in a grain flow anisotropy that can explain such high mechanical properties. The aim of this study is to relate the microstructure scale to the process scale, i.e. the engineering scale. Anisotropy is induced by the forming process and the most relevant feature which results from forging, is the preferential orientation of structural defects and grains in the direction of the deformation. Grain flow is modelled using a fiber tensor at the level of the representative elementary volume. It can then be used to improve and refine the Papadopoulos fatigue criterion by taking into account fatigue limits for each direction of anisotropy. In practice, it is very tedious to determine precisely these fatigue limits and impossible to obtain experimentally all of them for each direction of uniaxial loading. To circumvent this difficulty, we simulate the problem at the microstructure scale by considering fiber tensor as the result of the inclusion and grain orientation. Microstructures are then precisely modelled using ***DIGIMICRO*** software. A representative elementary volume including inclusions is meshed and high cycle fatigue simulation is performed with a classical criterion. Thus, the needed parameters to perform fatigue simulation, which depend on the direction of uniaxial loading, are given by the orientation of inclusions and grains.

Development of a testing method in high cycle fatigue on specimen with foundry skin

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In automotive design, one of the first step is to obtain data materials and judiciously to use them in the structural analyses. In order to guarantee the best link between specimen and materials/process of a selected structure, these mechanical data must be intrinsic with material in its process context. In the particular case of a aluminium casting part, these data must be overall characteristic of the microstructural state (chemical composition, speed of solidification and cooling) and skin of the structure or more generally of the skin quality.

In this document are presented the testing method developed by PSA Peugeot-Citroen and the various applications of this method in design.
The specimen is like a "dog's bone" and is conceived by the foundry experts. It used to characterize the high cycle fatigue resistance of the rough functional zones of the engine and the suspension on aluminium foundry. This fatigue test is bending. The fatigue limit of material is then calculated. These designs data are associated at the structure and at its process, and they allow to feed in data materials the models used for calculations of dimensioning. Thus, this testing method helps to evaluate and compare the potential of several solutions materials and processes. This method is one step of global evaluation of a material and process choice which needs tests on technnologic specimens (which incorporates geometrical specificities common to a family of automotive part) and tests on a structure bench validation.
The operational limits of the "dog's bone" are also approached.

Machining parameters effects on fatigue life of Aluminium alloy aeronautical parts

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Fatigue life of structures is known to highly depend on the surface quality. Consequently, a great attention is paid to the specification and the realization of surfaces of machined parts when those must be dimensioned in fatigue. In engineering design, the effects of surface parameters are commonly accounted for by using empirical reduction factors which modify the endurance limit of the material. Reduction factors are defined for each type of machining process. Moreover, within each category of machining process the use of these reduction factors leads to surface specifications (generally in terms of roughness) linked to machining parameters such as tool shape, feed rate… Even if giving satisfactory fatigue life predictions, the use of this empirical method has obviously limitations due to its restricted area of validity. Indeed, changing machining process or machining parameters must then be accompanied by a new definition of reduction factors and/or surface specifications that must be validated by performing new fatigue tests. This constitutes a real problem as machining processes are in constant evolution in order to increase productivity.

In this context, the present study proposes an approach to directly connect machining parameters to fatigue life without performing time-consuming and expensive tests for an aeronautical aluminium alloy. The objective here is to give tendencies on the machining parameters influence on fatigue life.

For the present 7010-T7451 Al alloy, it has been proved that surface topography is the predominant surface parameter affecting fatigue life. In order to model this effect, surface topography is characterized from a mechanical point of view without the use of geometrical parameters: stress concentration factor K_t is initially calculated by finite element analysis from surface measurements. This so-calculated stress concentration factor is integrated in two different modelling to predict limited fatigue lives and fatigue limit. In addition to this calculated K_t, these two modelling only require basic fatigue crack propagation data (fatigue threshold and Paris law parameters). As shown by the relevance of the results compared to experimental ones (Figure 1), this first approach (measurement of surface topography, determination of K_t, fatigue life prediction) gives a reliable mean to predict fatigue life when changing machining parameters.

Specimen reference	Machining	Ra* (µm)
UL11	shaper	0.5
UL12	shaper	0.5
UL21	shaper	7
UL22	shaper	7
Fine milled	HSM milling	0.25
Slot milled	HSM milling	11.1

* Ra as defined in ISO 4287

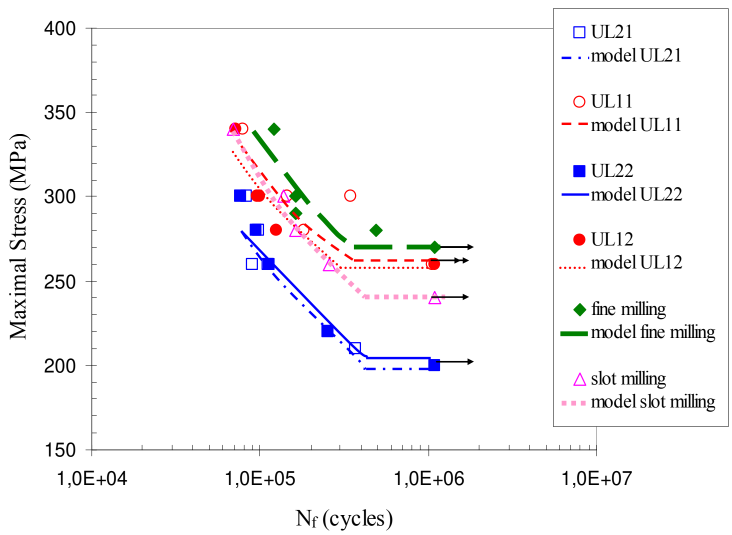

Figure 1. Predicted fatigue life compared to experimental SN curves

In order to provide a predictive tool, a complete modelling of surface generation is then developed coupling a 2D SPH orthogonal cutting model, a Z-Map intersection tool/workpiece model and a 3D mechanistic model. Input data for this 3D surface prediction are limited to a Johnson-Cook material constitutive model and geometrical description. This "numerical" surface is then used as the measured one to calculate K_t and predict fatigue life. The whole process is described in Figure 2.

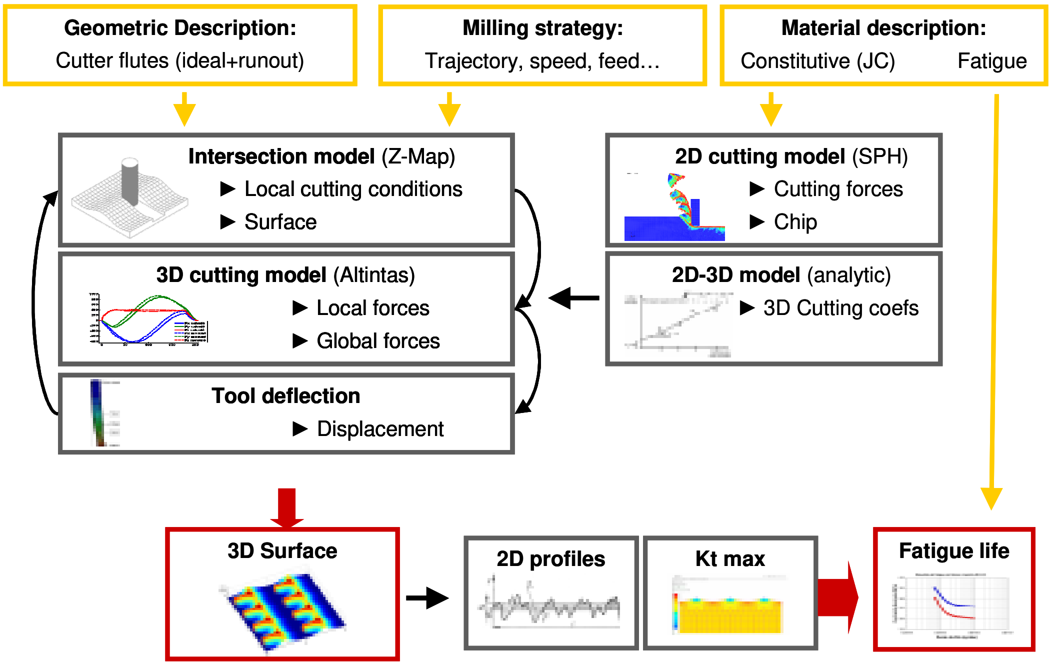

Figure 2. Principle of the predictive modelling from machining parameters to fatigue behaviour

This approach has been validated by comparison with fatigue tests completed with 4 point bending specimens machined by high speed milling with torus cutter. The results are presented in Figure 3. The model predicts the fatigue life with a maximal error of 15% for the nine HSM milling cases that were studied. A strong concentration of predicted fatigue lives around 90000 cycles can be pointed out. This is due to the slight variations of the machining parameters for these various cases.

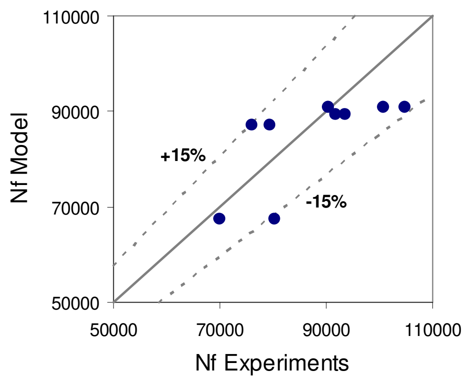

Figure 3. Comparison of predicted and experimental fatigue life time for HSM specimens

The combined approach (from machining parameters to fatigue life) appears to be a useful predictive tool which is able to give tendencies on the machining parameters influence on fatigue life of 7010 Al alloy.

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Session 3

Fatigue Design and manufacture process

Conception en fatigue et procédés de fabrication

Contribution of material and manufacturing process in fatigue design

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To fulfil pollution standards, new motorizations of cars and trucks needs more efficient, more reliable, and naturally cheaper components. To reach this goal, 2 ways are examined by carmakers:

- Lightening of vehicles,
- Increase the efficiency of engine.

So, steel must be more efficient, just-fitted to the application, and contribute to global component cost reduction.

In this article, we will show two examples of development of new methodologies and steel grades to face such increase of fatigue properties, in both side of downsizing (helical suspension springs) or increasing of applied loading for the same geometry (gear steel). At the end, we will discuss about the design of components for very high cycle fatigue domain and the consequence on materials.

1 HELICAL SUSPENSION SPRINGS

The suspension systems of cars are concerned by downsizing. In this respect, the stress level applied on the spring is increased, and the steel used needs to have a good fatigue resistance and also a good sag resistance.

The corrosion resistance is also important for this application. Generally speaking, an increase of mechanical properties decreases the corrosion fatigue resistance. In this respect, a compromise needs to be found. For that, an original device and 3 test procedures have been set up to test in torsion spring steels :

- Fatigue in air,
- dissociated corrosion fatigue,
- coupled corrosion fatigue.

Fig 1 shows, as an example, the SN curves obtained in air and under coupled corrosion fatigue. In this case, no fatigue limit have been obtained.

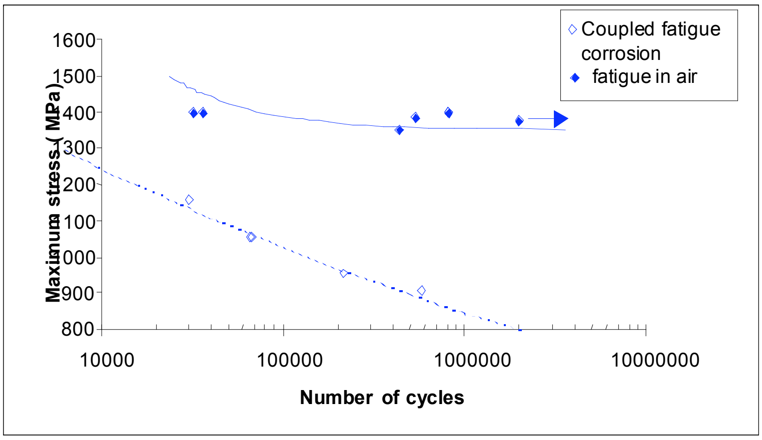

Figure 1 : comparison of S-N curves of 60SCV7 obtained by fatigue in air and in coupled fatigue corrosion

But in the case of dissociated fatigue/corrosion, a fatigue limit could be obtained and estimated by using Murakami approach.

grade	calculated fatigue limit for dissociated fatigue corrosion (MPa)	experimental fatigue limit in air (MPa)	ratio fatigue limit in corrosion / fatigue limit in air
60SCV7+Nb	1061	1325	0.80
45SCV6	1068	1274	0.84

table 1: calculated fatigue limits at 10^6 cycles corresponding to dissociated corrosion fatigue, compared to experimental fatigue limit in air

2 STEELS FOR GEARBOXES APPLICATIONS

In the case of gearboxes, car makers are facing to an increase of the torque. In 10 years, this torque is twice higher than those applied to the original design. In parallel, the weights of gearboxes increase very slowly. Research for new gear steel for high loading application need a precise understanding of the different mechanisms responsible of fatigue and/or mechanical failure. The optimisation of impact resistance , bending and rolling contact fatigue need to find a compromise : i.e., increased case depth improve bending and rolling contact fatigue strength, but it dramatically decreases impact resistance. Fatigue and impact toughness are also strongly dependant on (Steel + thermo-chemical treatment). Rotative bending test have been performed to simulate the bending of gear teeth and impact test on Charpy type specimen have been used to evaluate the impact strength. Fatigue and toughness results obtained on different treatment are summarised in Figure 2.

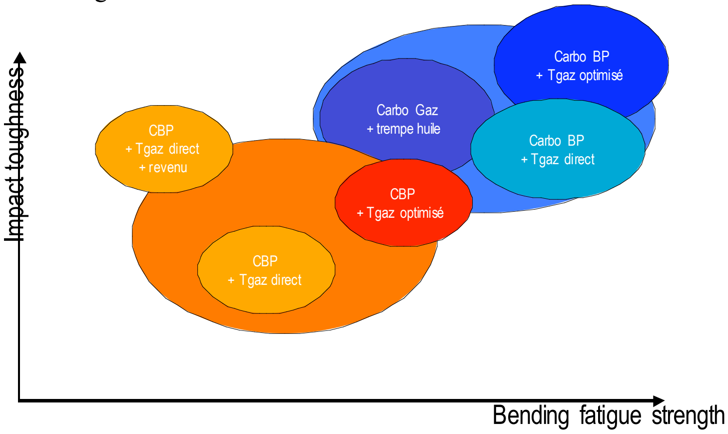

Figure 2: optimisation between bending fatigue strength and impact toughness

Theses results highlight the influence of carburizing treatment and quenching conditions on the optimisation between bending fatigue strength and impact strength, mainly the difference between carburizing and carbonitriding and the influence of hot oil and/or step quenching around 140-180°C.

3 MATERIALS FOR DESIGN IN THE VERY HIGH CYCLE FATIGUE REGIME

During his total in-service life, a car component is submitted to about 10^8 - 10^{10} cycles of fatigue, but current test facilities provides data up to 10^6 – 10^8 cycles. The aim of the study was to develop a new technique of laboratory able to generate fatigue data on main engineering steels and alternative materials up to 10^{10} cycles, to provide data for better design of mechanical parts. Figure 3 presents the preliminary results obtained on a wide range of engineering steels.

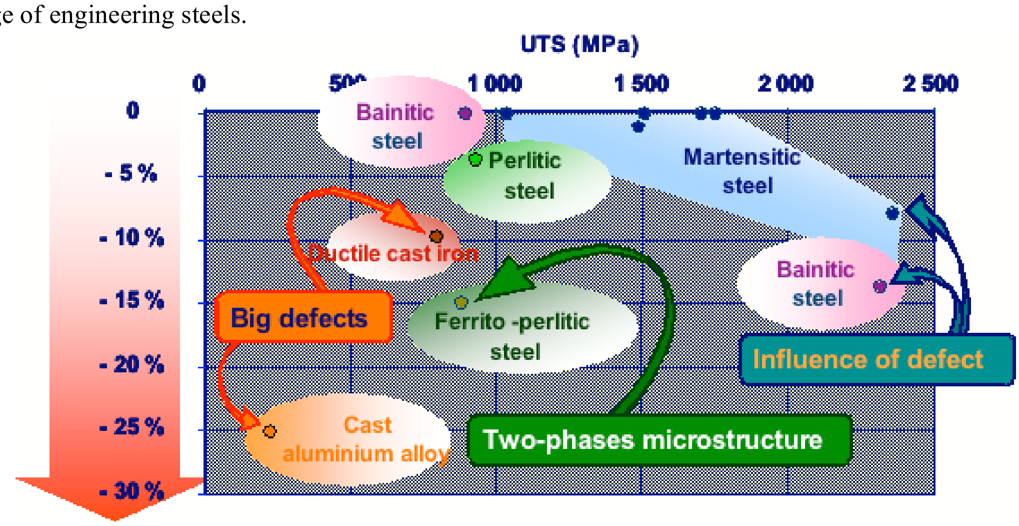

Figure 3 : Evolution of fatigue limit for different materials between 10^7 and 10^{10} cycles, R=-1 - BLE = relative decease of fatigue limit between 10^7 and 10^{10} cycles

An interpretation of all of these results was also proposed in terms of defects and in-homogeneity and/or size of the microstructure. This hypothesis must however be validated.

4 CONCLUSIONS

To reach ecological goals fixed by European Union to carmakers, steelmakers must develop new solutions, based on better knowledge of the damage mechanisms of each component. The (steel grade + cleanliness + heat treatments or surface treatments) must be optimised, by using simple and representative fatigue tests. Obviously, all these developments can only be achieved through a close collaboration with customers, who are the only one able to well know the in-service conditions of the different components.

Acknowledgements

The authors would like to thank A2M Industrie, ARA, CNAM ITMA, ECM and RENAULT for fruitful collaboration in the different subjects presented in this paper.

Two scale approach for the fatigue design of automotive suspension spring

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The aim of this work is to define the allowable defect size for an automotive suspension spring submitted to fatigue loading. Different approaches considering the defect as a crack or a notch exist. However both the approaches are based on 2D description which are limited to uniaxial loading and do not allow to predict fatigue limit accurately under multiaxial conditions. Furthermore, most of the approaches uses macroscopic parameters to describe a very local phenomenon.
To describe the influence of surface defect geometry on fatigue behaviour, a non classical method is proposed: non local approach based on stress gradient is used to describe the defect at the meso scale while the macroscopic scale remains at the elastic level. Cyclic plasticity effects are taken into account by the mean of non linear kinematic hardening at the mesoscale. This method is included in a classical stress based multiaxial fatigue criterion (for example here Crossland formulation); it considers the amplitude of the second invariant of the deviatory stress tensor and the maximum hydrostatic stress as governing variables in the crack initiation process.

$$\sqrt{J_{2,a}} + \alpha\, J^{*}_{1\max} \leq \gamma \qquad J^{*}_{1\max} = J_{1\max}\left(1 - a\,\frac{G}{J_{1\max}}\right) \qquad G = \frac{J_{1\max} - J\left(\sqrt{area}\right)}{\sqrt{area}}$$

The influence of the defect is taken into account through Murakami's parameter $\sqrt{area}$ witch is, in this application, the internal length at the mesoscopic scale. G could be defined as a 'design gradient' because it represents an average of the stress distribution at the tip of the defect.

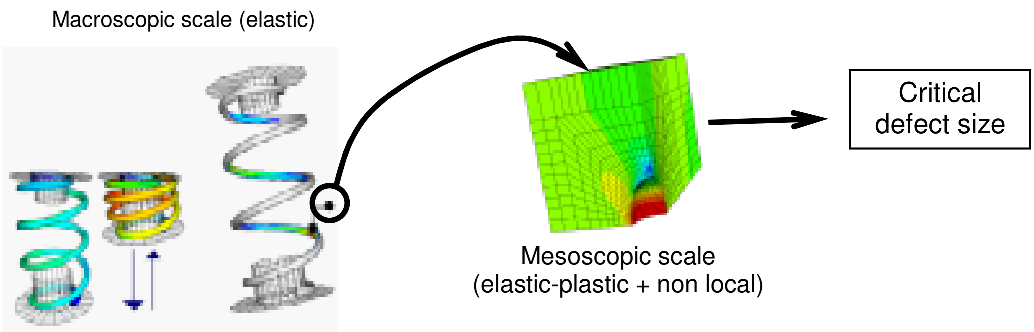

Figure.1 Two scale FEM calculation method to define the critical defect size

This approach allows defining the size of the non damaging defect for a large class of defects and various loading conditions. The approach is applied here on automotive component.

References

[1] Y. Nadot and T. Billaudeau: *Multiaxial fatigue limit criterion for defective materials,* Engng Fract. Mech *Volume 73, Issue 1, January 2006, Pages 112-133*

HIGH CYCLE FATIGUE PREDICTION OF METALLIC SHOT PEENED PARTS BASED ON RELIABILITY APROACH

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Abstract

This paper presents a probabilistic approach to predict high cycle fatigue HCF behaviour of shot peened parts based on the multi-axial HCF criterion of Crossland. The modifications induced by shot peening in the first outer layers of the treated parts were taken into account. They are classified into four categories: (i) the compressive residual stresses, (ii) the surface work-hardening; (iii) the geometrical irregularities and (iv) the surface integrity.

The reliability of the HCF resistance was calculated by using the Strength-Load method with Monte Carlo simulation, by taking into account the dispersions of: (i) the Crossland criterion material characteristics, (ii) the shot peened surface conditions and (iii) the applied loading parameters are taken into account.

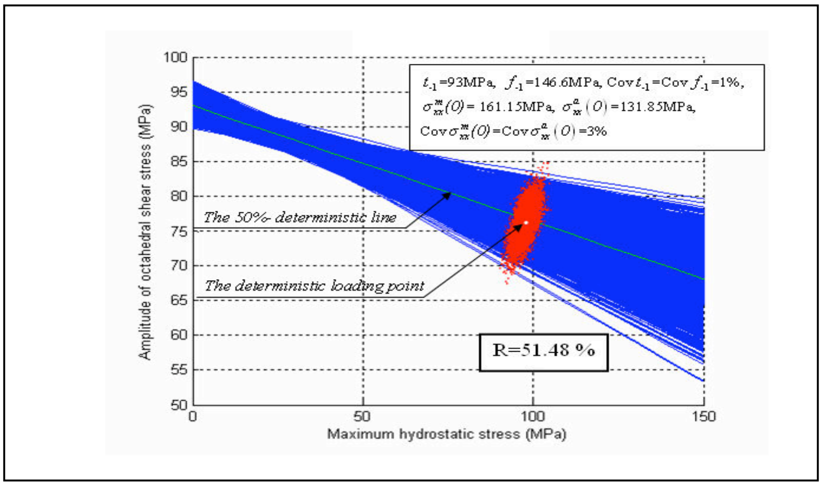
This approach allows, firstly, better evaluation and quantification of the effect of the different input data dispersions relative to both experimental and physical origins, and secondly, the analyse of the quality and the confidence level of the HCF reliability prediction of shot peened parts.

An application has been carried out on shot peened ductile steel SAE 3415 allowing, in a first hand, the validation of the applicability of the proposed model, and in a second hand, the implementation of interesting engineering iso-Probabilistic Crossland Diagrams (PCD). These PCDs are very useful for engineers to quantify the HCF reliability influence of the surface treatment conditions and to have high reliable safe predictive design of shot peened parts.

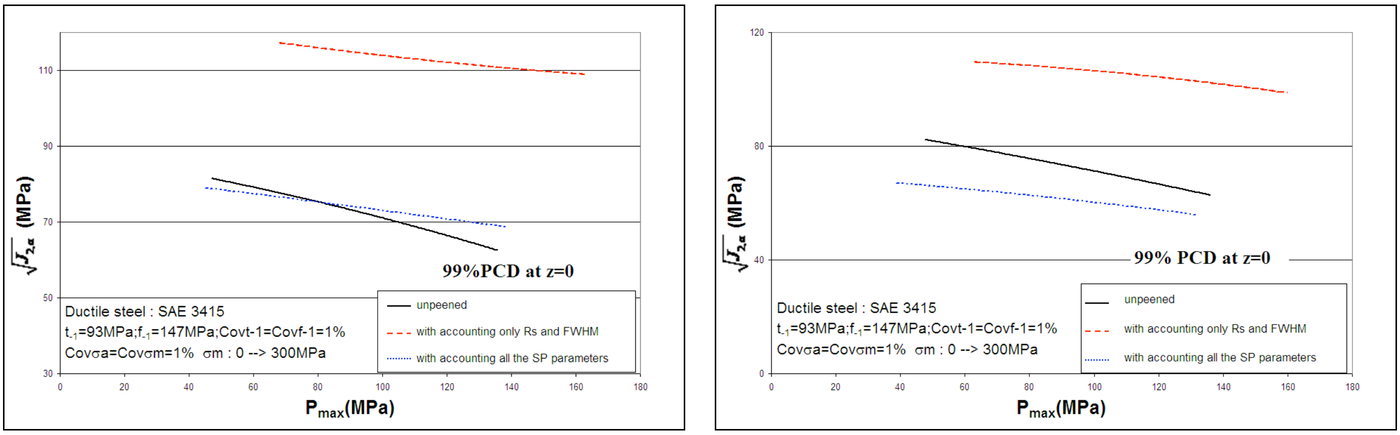
It has been observed that the shot peening HCF reliability predictions and the obtained PCDs are in good agreement with the experimental results. This method has been also used to analyse and to discuss the influence of the surface shot peening properties on the HCF reliability.

***Keywords**:* Fatigue reliability, Monte Carlo simulation, Multi-axial high cycle fatigue criterion, Shot peening, Fatigue scattering parameters.

❖ Some results



Reliability evaluation (unpeened case).



(a) (b)

The zero-depth 99%-reliability PCD of the two shot peening conditions: (a) 100% and (b) 1000% coverage's.

ROBUST AND RELIABLE FATIGUE DESIGN

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While durability simulation methods allow improving nominal product design using virtual prototypes, uncertainty and variability in properties and manufacturing processes lead to large scatter in actual performances. Especially in fatigue the influence of the scatter in material, and manufacturing is important. Uncertainty must hence be incorporated in the durability simulation process to guarantee the robustness and reliability of the design. This paper presents application of both cases – material influence and manufacturing influence using applications from automotive and aerospace.

Product designers worldwide are confronted with highly competitive though conflicting demands to deliver more complex products with increased quality in ever shorter development cycles. Refining and optimizing design performance with purely test-based approaches is no longer an option and numerical simulation methods are widely used to model, assess and improve the product design based on virtual prototypes. Functional performance attributes as durability can already be optimized before entering the expensive test phase.

The use of the Finite Element (FE) method is widely established for the virtual prototyping phase. A major issue is the presence of uncertainty and variability in the material and geometrical properties and manufacturing processes; their effect on the performance cannot be predicted from a single durability analysis. A traditional solution is to apply safety factors on the system parameters, but this typically leads to oversized, too heavy structures. A more promising approach is to include uncertainty in the mechanical simulation process, guaranteeing the robustness and reliability of the design.

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Session 4

Experimental validation: fatigue damage assessment-

Validation expérimentale : Estimation du dommage en fatigue

Early detection of fatigue damage processes by infrared investigation of thermomechanical coupling phenomena

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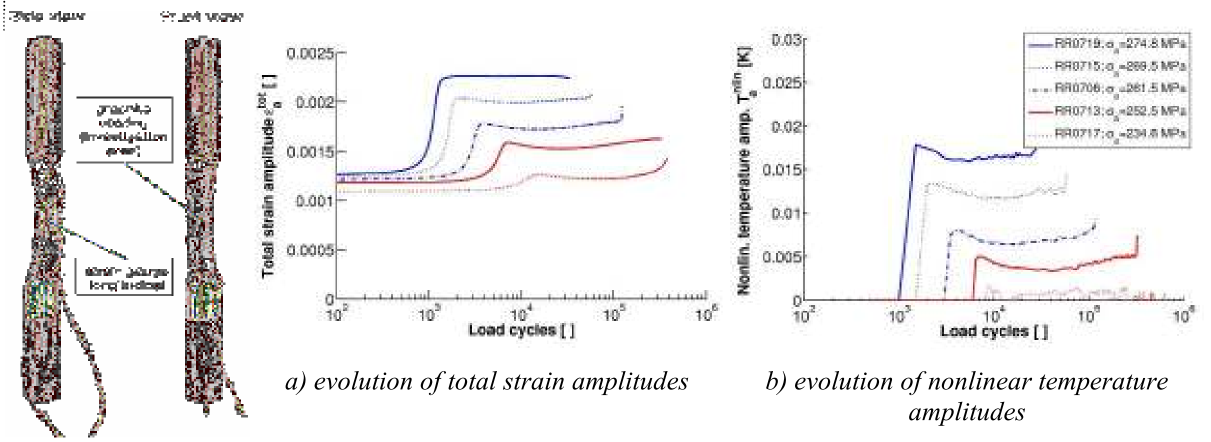
A special issue during fatigue testing is the investigation and identification of continuous damage processes. Typically conventional measurement techniques as strain gauges, monitoring of the forces or displacements, wire-based crack detectors, penetration tests, visual inspection by eye or digital cameras, acoustic emission etc. are applied. These techniques suffer from various disadvantages as time-consuming preparation of the specimens and insufficient spatial resolution or poor online applicability. Due to the rapid advances in infrared technology and falling costs for high resolution infrared cameras the application of thermography as a regular inspection technique during mechanical testing becomes interesting. The idea behind this application is the investigation of thermomechanical coupling phenomena and their analysis with respect to continuous damage processes. The advantages are easy applicability without extensive specimen preparation, full-field resolution and a clear physical meaning of the observed temperature changes. Even though the recording of the temperature changes during mechanical loading is relatively easy, the post-processing and interpretation of the data requires in-depth knowledge of the underlying processes. The governing equation for the study of thermomechanical coupling phenomena is given as the heat equation of a deformable solid body with thermoelastic coupling and thermoplastic dissipation which can be derived from the first and second principle of thermodynamics:

$$\rho C_{\varepsilon}\frac{dT}{dt}-\frac{\partial}{\partial x_j}k\left(\frac{\partial T}{\partial x_j}\right)=T\frac{\partial\sigma_{ij}}{\partial T}\frac{d\varepsilon_{ij}^{e}}{dt}+\sigma_{ij}\frac{d\varepsilon_{ij}^{p}}{dt}-a\frac{d\varepsilon_{ij}^{p}}{dt} \tag{1}$$

In equation (1) ρ is the density, C_ε is the heat capacity at constant strain, T is the temperature, k is the heat conductivity tensor, σ_{ij} is the symmetric Cauchy stress tensor, ε_{ij}^{e} is the reversible (elastic) part of the strain tensor and ε_{ij}^{p} is the irreversible (plastic) part of the strain tensor. Based on numerical simulations of equation (1) the effect of different thermomechanical coupling phenomena on the surface temperature evolution during mechanical harmonic loading is investigated. The findings propose the application of a specialized methodology which allows for the in-situ analysis of typical fatigue processes as cyclic plasticity and crack initiation. In contrast to other well-known approaches e.g. based on the measurement of the mean temperature evolution we focus on the local analysis of the short term temperature evolution during mechanical loading. This offers a very high spatial resolution and allows for the analysis of extremely localized damage phenomena. The approach is based on the extraction of the nonlinearities in the temperature evolution which are typical for local damage processes. For this purpose a specialized data processing technique has been developed which allows for the retrieval of temperature amplitudes as small as 1 to 2 mK. This is sufficient to investigate the local cyclic softening and hardening behaviour as well as the early formation and propagation of fatigue cracks.

The proposed approach has been successfully applied to study the damage evolution during fatigue testing of different welded as well as un-welded notched and un-notched specimens. As an example of retrievable information figure 1 presents the evolution of the total strain amplitudes and the nonlinear temperature amplitudes measured on the surface of a cylindrical specimen of mild steel S355 during load controlled fatigue testing. Figure 1 a) and 1 b) show the evolution of the longitudinal strains in the mid-section of the un-notched specimens during testing and the corresponding evolution of the nonlinear temperature amplitudes. The strains were measured by strain gauges applied to the backside of the specimen. The cyclic behaviour can be roughly distinguished into a linear elastic incubation interval, a phase of primary softening and a phase of more or less stable plastic strains. Figure 1 b) shows the corresponding evolution of the nonlinear temperature amplitudes which closely follows the evolution of the plastic strains. The nonlinearities in the temperature signal become nonzero with the onset of primary softening and similar to the plastic strain amplitudes quickly reach their maximum after softening. Similar to the plastic strain amplitudes the amplitude of the nonlinearities increases due to the softening and hardening of the steel. Further results on the spatial distribution of the nonlinear temperature amplitudes show that the plastic strains evolve in form of cyclic Lueders bands which start at one point of the specimen and spread within hundreds of load cycles.



a) evolution of total strain amplitudes *b) evolution of nonlinear temperature amplitudes*

Figure 1. Evolution of the total strain amplitudes and the corresponding nonlinear temperature amplitudes in the mid section of the cylindrical specimen, F_a=var., f_L=2.5 Hz.

Figure 2 shows the distribution of the linear temperature amplitudes around the front side of a welded specimen and the evolution during fatigue testing. The stress concentrations at the weld toe cause increased temperature amplitudes with respect to the nominal cross-section of the specimen. By contrast the temperature amplitudes within the weld bead are reduced which indicates smaller loading in this area. By direct comparison with visual images of the weld seam we were able to locate the most loaded sections of the weld toe. The fatigue process at the weld toes is governed by crack initiation and crack propagation. No indication on the existence of local elastic-plastic cyclic material behaviour prior to crack initiation could be found. Generally the first cracks could be observed around 10 to 20% of the total fatigue lifetime. The results demonstrate that by contrast to un-notched or mildly notched specimens crack propagation is the dominant process for the fatigue behaviour of the weld seam.

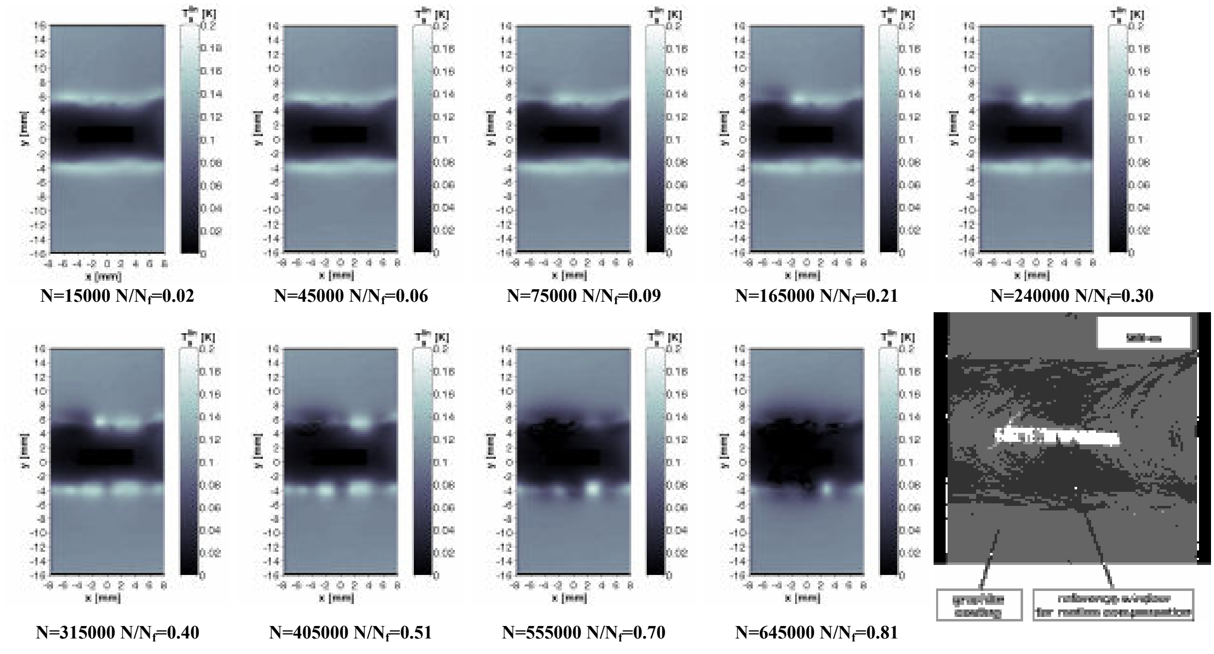


Figure 2. Evolution of the linear temperature amplitude on the front surface of a welded specimen with respect to the applied load cycles, F_a=17.5 kN, f_L=15 Hz.

Conclusion: An experimental approach based on infrared thermographic investigations which allows for the in-situ analysis of fatigue processes during fatigue testing is proposed. By contrast to former approaches only the short term temperature evolution due to thermomechanical coupling is considered and analysed with respect to the underlying damage processes. For this purpose a specialized data processing technique is used which allows for the retrieval of temperature amplitudes as small as 1 to 2 mK. This is sufficient to investigate the local cyclic softening and hardening behaviour as well as the early formation and propagation of fatigue cracks. The new method has been successfully applied during fatigue testing on different specimen geometries and gives unique qualitative insight in the local fatigue damage accumulation.

Fast Identification of HCF Properties by Self-Heating Measurements under Cyclic Loadings

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The industry is one of the domains that needs good design procedures to ensure the reliability of structures. Since fracture of structures is often due to fatigue, probabilistic approaches have been developed in High Cycle Fatigue (HCF) lifing. With these approaches, the scatter of fatigue data can be described, as well as the dependence of fatigue limits with the loaded volume and the type of loading by introducing the so-called effective volume. Consequently, the fatigue limits depend on material properties as well as the effective volume. The identification of probabilistic models is often based on numerous experimental fatigue tests to properly evaluate the scatter. The predictive capability of probabilistic models can be improved by identifying the origin of the scatter. In the present paper, the scatter of experimental fatigue results is assumed to be induced by a heterogeneous microplastic activity.

Some authors have worked on an estimation of the mean fatigue limit based upon temperature measurements [1-6]. This method consists in observing the thermal effect during cyclic loadings. It has the advantage of being performed in shorter time compared with traditional HCF tests. A good correlation can be obtained between the inception of a temperature increase and the mean fatigue limit. If a probabilistic approach useful for HCF life prediction is considered, then the analysis of the temperature measurements cannot be used in a classical way and needs to be revisited. It will be used to identify parameters relevant to a probabilistic model to describe the initiation stage in HCF.

The present paper is concerned with the derivation and identification of a probabilistic two-scale model for HCF that accounts for the failure of samples but also for the thermal effects during cyclic loadings in a unified framework. A two-scale model is used. It is assumed that HCF damage occurs at the microscopic scale and is caused by microplasticity that has a weak effect on the behavior of the material at the macroscopic scale. The development of the model is presented in two successive stages. In the first one, a deterministic viewpoint is chosen to show that the thermal effects can be accounted for by integrating the heat equation in which the microplastic dissipation is included. In view of a single microplastic hardening law, the empirical method proposed to estimate quickly the mean fatigue limits can be described to determine a deterministic (i.e., mean) fatigue limit. The model is then extended by introducing a random yield stress distribution at the microscopic scale. The new model describes more closely the thermal effects than the first one. An identification method of the scatter is proposed. It is based on the analysis of the thermal effects for the scatter and is applied on different metallic materials.

REFERENCES

1. M. P. Luong, SPIE **1682**, 1992, 222-233.
2. J.-Y. Bérard, S. Rathery and A.-S. Béranger, *Mat. Techn.* **1-2**, 1998, 55-57.
3. J.-C. Krapez, D. Pacou and C. Bertin, 5th AITA, Int. Workshop on Advanced Infrared Techn. and Appl., Venezia (Italy), Ed. E. Grinzato et al., 1999, 379-385.
4. G. La Rosa and A. Risitano, *Int. J. Fat.* **22** [1], 2000, 65-73.
5. C. Mabru and A. Chrysochoos. Photomécanique 2001, 375-382.
6. C. Doudard, S. Calloch, P. Cugy, A. Galtier, F. Hild, *Fat. Fract. Engng Mater Struct*, 2005, 28, 279-288.

Damage estimate in high cycle fatigue by energy balance

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This paper presents an experimental protocol developed to locally estimate different terms of the energy balance associated with the fatigue of DP 600 steel. The method involves two quantitative imaging techniques. First, digital image correlation provides displacement fields and, after derivation, strain and strain rate fields. A method, based on the integration of the local equilibrium equations is used to estimate the stress fields. We used both stress and strain field measurements to compute the mean volume energy rate per cycle corresponding to the mean hysteresis area over a whole number N_c of cycles A_h. Under the plane stress hypothesis, we computed:

$$\tilde{\dot{w}}_{\mathrm{def}} = f_{\mathrm{L}} A_{\mathrm{h}}(x,y) = \frac{f_{\mathrm{L}}}{N_{\mathrm{c}}} \int_0^{N_c f_{\mathrm{L}}^{-1}} \sigma_{\mathrm{ij}}(x,y,t)\, \dot{\varepsilon}_{\mathrm{ij}}(x,y,t)\, \mathrm{d}t \qquad (1)$$

where σ is the Cauchy stress tensor, ε the linearized strain tensor (hypothesis of small perturbations), f_{L} the loading frequency and N_c the number of cycles.

Secondly, infrared thermography provides thermal images which are used to separately estimate the thermoelastic source amplitude and mean dissipation per cycle distributions. The image processing uses a local form of the heat diffusion equation: and a special set of approximation functions that take the frequency spectra of the sought sources into account. Regarding the dissipative effects, we considered dissipation averaged over a whole number n of complete cycles:

$$\tilde{d}_1 = \int_{n f_{\mathrm{L}}^{-1}} n^{-1} f_{\mathrm{L}}\, \bar{d}_1\, dt \qquad (2)$$

Finally, the preliminary results obtained on DP 600 steel were presented. The tests involved two series of short loading blocks performed at increasing stress range. Between the two series, a block of 100 000 cycles was performed in the maximal stress range. In Figure 1, the energy balance was performed for all blocks by considering the mean anelastic energy and dissipated energy values over the sample gauge part. These results showed that the amounts of deformation energy corresponding to the stress-strain hysteresis loop were systematically greater than the dissipated energy per cycle. A thermodynamic analysis led us to interpret these differences as internal energy variations. Dissipation and stored energy data will now be used to propose state and evolution equations to describe the kinetics of the fatigue progress.

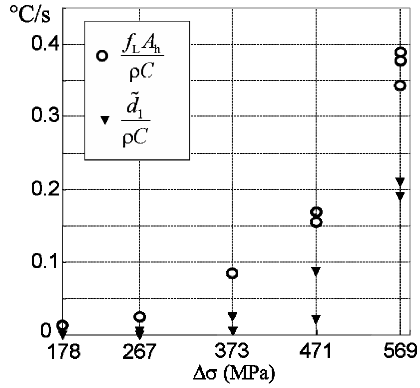

Figure 1: Mean $f_{\mathrm{L}} A_{\mathrm{h}}$ and $\tilde{d}_1$ values over the gauge part and per block

Limite de validité des règles de cumul (linéaire et non linéaire) en fatigue et proposition d'une règle de cumul intégrant l'effet de préchargement.

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Résumé : le cumul linéaire et non linéaire ainsi que l'effet de séquence sont analysés. On montre l'acceptabilité d'un cumul linéaire pour les matériaux à courbe cyclique unique. Pour les matériaux avec courbe cyclique dépendant de l'histoire du chargement on propose de combiner la règle linéaire avec l'effet du pré-chargement sur la courbe cyclique. On montre que les effets en contrainte contrôlée et en déformation contrôlée sont opposés et que la séquence grand-petit réduit la durée de vie en déformation contrôlée mais l'augmente en contrainte contrôlée, ce qui est en opposition avec les règles du cumul non linéaire n'utilisant pas le comportement élastopalstique. L'analyse précédente est étendue au cas des chargements en amplitude variable, on montre que dans le cas d'un chargement par bloc la règle de Miner peut être conservative en contrainte contrôlée mais non conservative en déformation contrôlée.

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Session 5

Advanced design tools and approaches : contribution of the fatigue crack propagation stage.

Outils et approches en conception avancée : contribution à la propagation des fissures en fatigue

Computation of life expectancy of Aeronautical structures

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ABSTRACT

Ageing aircraft structures are susceptible to a very typical and dangerous form of fatigue damage named Multiple Site Damage. It is defined as the simultaneous presence of fatigue cracks in the same structural element. It generally occurs in areas where a lot of critical sites (fastener holes for example) are subjected to the same stress level, as in the riveted joints of a fuselage.

An overall assessment method has been developed in order to improve the understanding of this phenomenon. A full deterministic approach has been completed first. An automatic numerical process, using the Dual Boundary Element Method and Fracture Mechanics laws, computes the crack evolution until failure of the structure. Then, in order to take materials scatter into account, a probabilistic approach has been developed based on Monte-Carlo simulations. Initial cracks scenarios are randomly defined and cracks evolution is computed for each of them. Thus statistical results are provided.

The results obtained are in good agreement with experimental results carried out at the EADS research center.

REFERENCES

1. C.A. Brebbia, J. Dominguez, 'Boundary elements: an introductory course'. Mc Graw-Hill, 1989.
2. H. KEBIR, J. M. Roelandt, 'Modélisation de structures multi-fissurées par éléments de frontiere singuliers', Actes du 5 eme Colloque Maghrebin sur les Modeles Numériques de l'Ingenieur, Rabat, Novembre, 1995.
3. Aircraft accident report: Aloha Airlines, Flight 243, Boeing 737-200, N73711, near Maui, Hawaii, April 28, 1988. Washington: U.S. national transportation safety board, 1989.
4. Portela and M. H. Aliabadi, ` The dual boundary element method: effective implementation for crack problems ', International Journal for Numerical Methods in Engineering, 33 : 1269-1287, 1992.
5. Portela, M. H. Aliabadi and D.P. Rooke, ` Dual boundary element incremental analysis of crack propagation', Computers & Structures, 46 : 237-247,1993.
6. H. KEBIR, J. M. Roelandt and J. Foulquier, “A new singular boundary element for crack problems : Application to bolted joints”, Engineering Fracture Mechanics, V62, 497- 510, PERGAMON, 1999.
7. H. KEBIR, J. M. Roelandt and J. Foulquier, 'Dual boundary element incremental analysis of crack growth in bolted joints', MAT-TEC 96 Improvement of materials, 233-230, 1996.
8. J. Schijve, 'Multiple-site damage in aircraft fuselage structures', Fatigue & Fracture of Engineering Materials & Structures, 329-344,1995.
9. D. Y. Jeong, J. C. Brewer, 'On the linkup of multiple cracks', Engineering Fracture Mechanics, vol. 51, No. 2, 233-238, 1995.

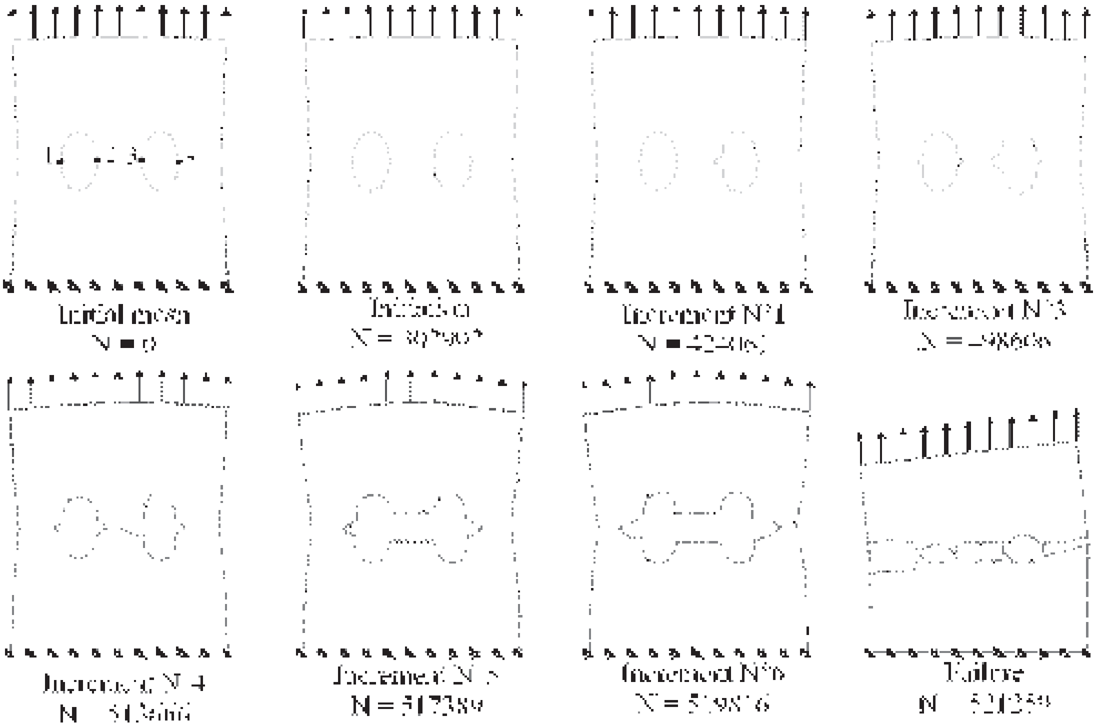

Fig. 1. one scenario of Monte-Carlo Simulations

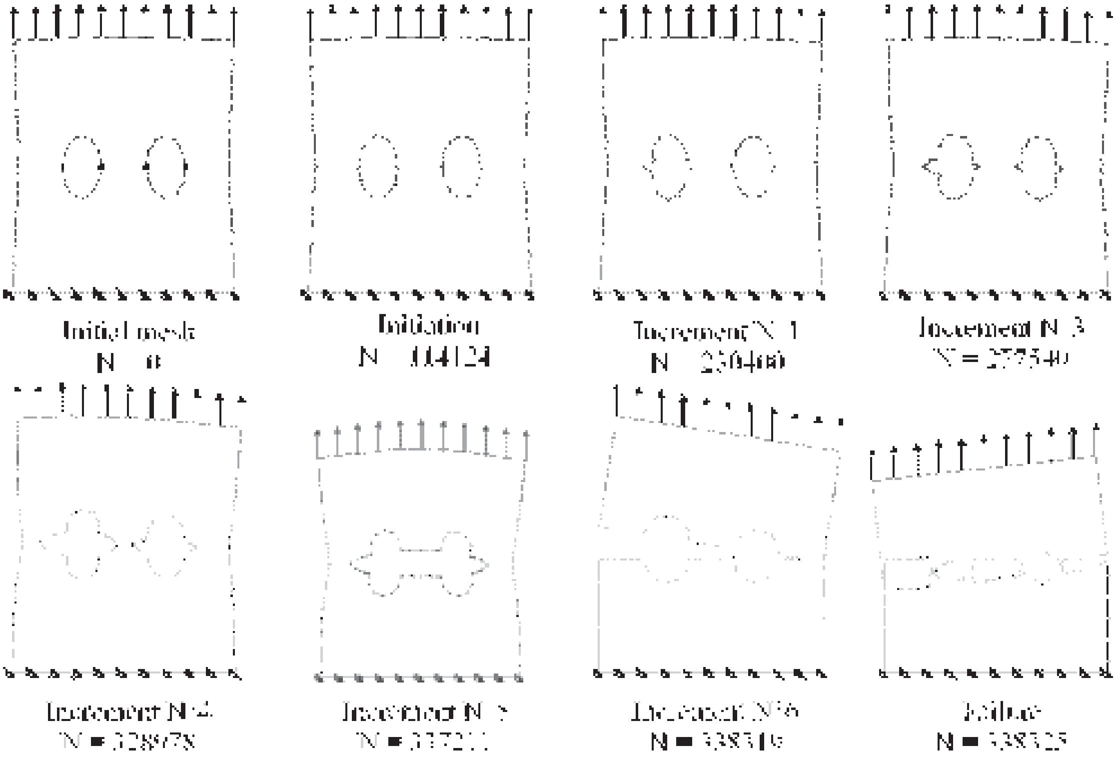

Fig. 1. Second scenario of Monte-Carlo Simulations

Crack Box Technique for Fatigue Design of Welded Structures

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Abstract

The aim of a fatigue analysis on welded complex structures is to evaluate the life duration to initiate a crack and to propagate it, until the failure of the structure occurs. Those structures as ships, FPSO, armoured vehicles, cars, are submitted to variable amplitude loads. The results of such a calculation is to help operators to take decisions for inspection, repair and maintenance processes [1].

In this paper we will introduce a methodology (see flow chart Figure 2) and results obtained thanks a research partnership between Bureau Veritas, CETIM, Nexter-Sytems and LaMI (Clermont-Ferrand – France). In this collaboration, we have developed a complete multi-scale tool called VERICRACK [1] allowing to calculate crack initiation and crack propagation in industrial welded structures submitted to complex loading environment.

It is based on the use of finite elements from the global cartography of the damaged zones (see Figure 1) to the local calculation with cracks inserted in the models. It's to be noted that shell assumption is considered for global geometry and 2-D elements or 3-D brick modelling are used for local approaches. Crack initiation is calculated thanks to the local approach [2], taking into account the residual stress fields, notch and plastic corrections. Multi-initiation of fatigue cracks is considered as damage is accumulated during simulation. The crack propagation is performed using the Line Spring model introduced by Rice and Levy [3] to take into account the flexibility due to cracks. Crack Box Technique (see Figure 3) allows to precisely calculate the stress intensity factors for various loads. To limit computation time, industrial rules are used to determine the crack path. This path is checked during the crack growth. Also, automatic crack box re-meshing coupled with ABAQUS code is used for 2-D and shell elements if needed. Furthermore, sets of tools have been developed to predict crack bifurcation and take into account the influence of the loading history on fatigue crack growth, such as crack growth retardation effect, as consequence of overloads.

In this context, we will present the use of a Crack Box Technique to calculate SIF and crack path in linear elasticity for an overall aluminium welded structure experiment, which has been designed to allow several cracks to initiate and propagate. A phenomenon of crack growth deceleration and arrest has been observed and explained thanks to simulations. So, the results are in good agreement with calculations and point out :

- the industrial necessity to measure the local characteristics of welds and to control the quality for fatigue design.
- the importance to take into account the flexibility due to cracks in order to calculate the crack growth. In fact, the propagation of cracks modify the global stress field.
- and finally, the necessity to couple local and global approaches to simulate crack propagation.

References

[1] Lebaillif D., Huther I., Serror M., Recho N. Fatigue Crack Initiation and Propagation : a complete industrial process compared with experiments on industrial welded structure. Fatigue Design 2005. Senlis. France

[2] E. Petitpas, H.P. Lieurade, D. Lebaillif, L. Dupont, I. Huther, Virtual Prototyping of Mechanical System using a Multi Scale Approach. Conference untitled : Betriebsfestigkeit in der virtuellen Produktentwicklung 11-12/10/2006 Austria.

[3] Rice J.R. and Levy N., The Part-Through Surface Crack in an Elastic Plate, Journal of Applied Mechanics, March 1972,185-194

Figures and tables

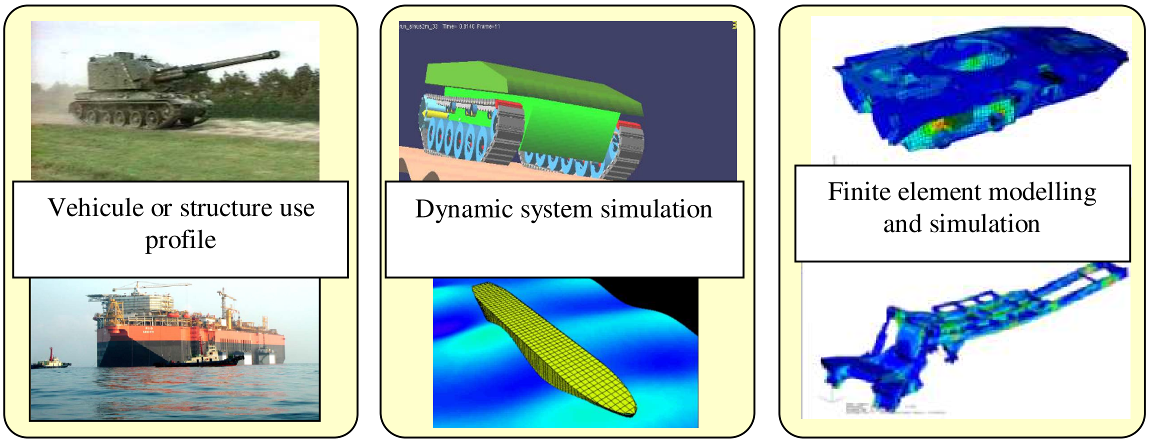

Figure 1 : data and simulation needed before damage and crack propagation calculations

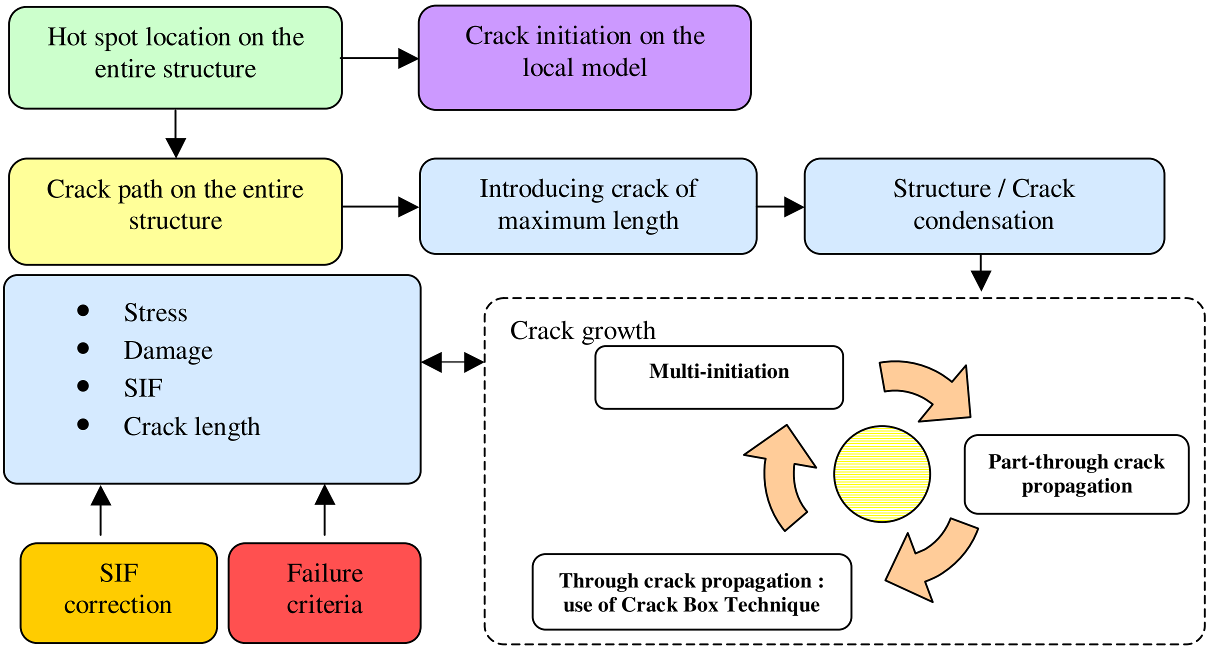

Figure 2 : flow chart of the entire methodology

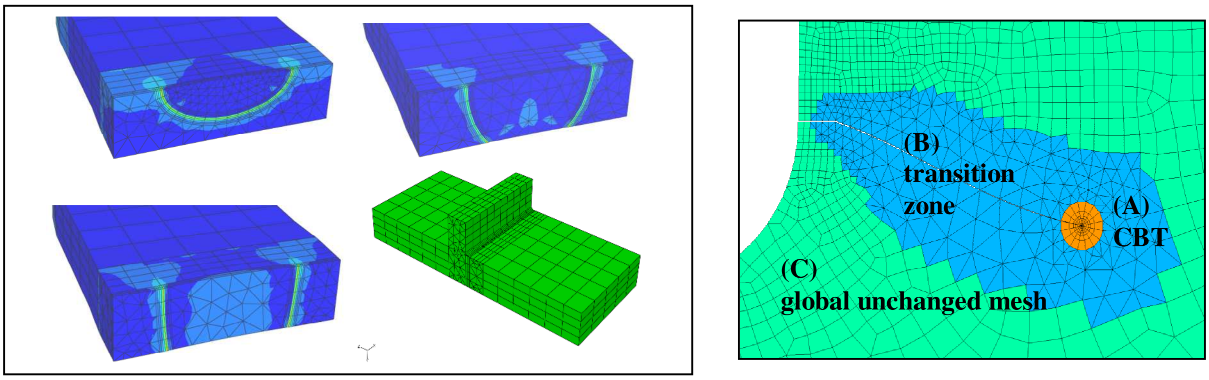

Figure 3 : automatic 3D or 2D Crack Box Technique (CBT)

Numerical simulation of crack propagation in pressure equipments

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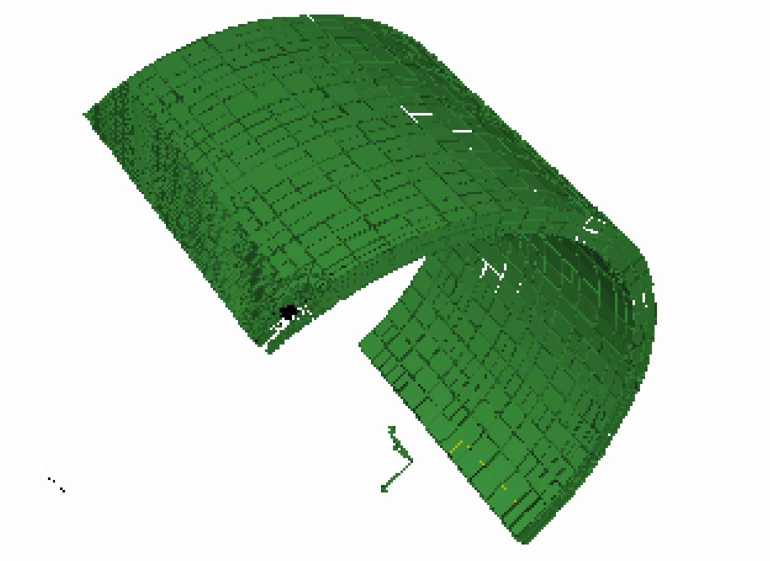
Abstract. The present study deals with the severity of cracks in pressure equipments, where such defects are often involved. The objective is to assess the growing harmfulness level of a given propagating defect, in order to predict the residual lifetime of a pressure equipment. The stress intensity factors are thus performed at each step during the crack front propagation. Our work is particularly concerned with the problems of shells including almost all sorts of practical defects, namely both internal and external, longitudinal or transverse semi-elliptic cracks. Use is made of a specific adjusted crack-block so as to mesh the vicinity of the crack front, in the framework of the finite element method. Moreover, the Paris' law is generalized to the case of 3D fatigue crack extension. Finally, a Python program is particularly developed to automate the calculation process, only involving a local remeshing and jointly using Abaqus and Castem softwares.

Simulation numérique de la propagation de fissures dans les structures sous pression

Résumé. *L'objectif de ce travail est de déterminer l'évolution du degré de nocivité d'un défaut dans un équipement sous pression durant sa propagation. L'estimation du degré de nocivité d'une fissure passe par le calcul des facteurs d'intensité de contrainte à chaque état d'avancement du front de fissure. Les fissures considérées sont semi-elliptiques. Les géométries et chargements peuvent être complexes de façon à couvrir la majorité des cas industriels. La modélisation numérique par éléments finis s'appuie sur la création d'un bloc-fissure, représentant le maillage optimisé du voisinage de la discontinuité. La loi de Paris permet de décrire le comportement en fatigue sous chargement cyclique. Un programme spécifique (Python), alliant les avantages des codes de calcul Castem et Abaqus, permet d'automatiser la démarche de propagation et facilite l'évaluation de la durée de vie résiduelle d'une structure sous pression fissurée.*



Numerical simulation of the fatigue crack growth with history effects. Complex non-isothermal loading conditions.

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When complex loading conditions are encountered, the fatigue crack growth rate remains difficult to model because of various coupling effects. The problem that was considered in this research, is the growth of a crack at high temperature (450°C - 650°C) in a nickel base superalloy under variable temperature, stress amplitude and stress rates loading conditions. This material has been widely studied in the past under isothermal conditions. The mechanisms leading to dwell time effects at various temperatures, for instance, are well understood. The main objective of this research is to use this knowledge to model the fatigue crack growth rate under complex "missions". An incremental model was previously developed specifically to take into account variable amplitude loading conditions. In this research, this model was extended so as to consider also variable stress rates and non-isothermal loading conditions.

The incremental model aims at modelling the variations of the fatigue crack growth rate induced by plasticity. As a matter of fact, crack tip plasticity in metals is known to be at the origin of spectacular history effects in fatigue. Because plastic deformation at crack tip is constrained, residual stresses appear at unloading within the crack tip plastic zone and modify the subsequent fatigue crack growth rate. The fatigue crack growth rate in mode I, for instance, is significantly reduced after the application of an overload. Compressive residual stresses in the crack tip region reduce the efficiency of subsequent fatigue cycles. Therefore, modelling continuously the evolution of internal stresses in the crack tip region is very useful so as to predict the fatigue crack growth rate. For this purpose the finite element method (FE) was shown to be very efficient, since it allows taking into account the specific features of the cyclic elastic-plastic behaviour of each material through its constitutive model. Besides it allows testing various loading conditions. However, elastic-plastic FE computation times remain prohibitive for industrial applications, as soon as more than a few thousand cycles are encountered.

Therefore, a multiscale approach was proposed so as to transpose to the global scale the very detailed data computed in the crack tip region using the finite element method. The method consists in partitioning the displacement field at crack tip into plastic and elastic parts. Each part is the product of a reference spatial field and of an intensity factor. If the plastic zone is well constrained, the intensity factor of the elastic part, K_I^* is close to the nominal stress intensity factor K_I. Besides, the intensity factor of the plastic part, labelled ρ, measures, at the global scale, the development of plastic deformation within the crack tip region. The error associated to that partitioning hypothesis is determined and remains below 10% for loading conditions consistent with a fatigue application. Using the finite element method and a post-treatment procedure, this method allows generating evolutions of K_I versus ρ, where K_I is the "load" and ρ a global measure of plastic deformation. Then a global cyclic elastic-plastic constitutive model, labelled *f*, for the crack tip region is identified using the generated data. It consists in introducing an elastic domain at the global scale for the crack tip region, which is defined by a criterion function and by a set of internal variables (size and position of that elastic domain). The internal variables of the model allow accounting for plasticity induced history effects. The model contains also evolution laws for these internal variables as a function of the rate of variation of ρ and of the crack extent. The material parameters (m_{pi}) in this model are identified using the finite element method through an automated procedure. The input data needed is the constitutive model for the material, which can be identified using cyclic push-pull tests.

So as to extend this method to non-isothermal conditions, the constitutive behaviour of the N18 nickel base superalloy was identified at 450°C, 550°C, 600°C and 650°C. Then for each temperature, using the multiscale approach discussed above, the parameters (m_{pi}) of the global cyclic elastic-plastic constitutive model *f* are identified. The equations that are employed in this model were chosen so as to ensure the identification of a unique set of parameters for each condition, which ensures that the interpolation is possible. As a consequence, by now, the global cyclic elastic-plastic constitutive model for the crack tip region contains a set of material parameters that are defined as piecewise linear functions of the temperature.

Besides, a crack propagation law is also introduced that defines the rate of creation of cracked area per unit length of the crack front (*da/dt*) as a function of dρ/dt. It is typically proposed that: $da/dt = \alpha \mid d\rho/dt \mid$, where α is a parameter to be adjusted using at least one constant amplitude fatigue crack growth experiment. Gathering the global cyclic elastic-plastic constitutive model for the crack tip region, that predicts $d\rho/dt$ as a function of the loading conditions and history and the crack propagation law that predicts da/dt as a function of $d\rho/dt$ yields finally a crack propagation model which accounts for plasticity induced history effects.

This approach was applied to mode I fatigue crack growth at low temperature and validated using constant amplitude and complex fatigue crack growth experiments. However, since fatigue crack growth at high temperature is aimed to be modelled, the phenomenon of oxidation that assists fatigue crack growth should also be considered. This mechanism is responsible, for instance, of the detrimental effect of dwell times. At high temperature, the grain boundaries are oxidized ahead of the crack tip. It is observed that the crack path changes from transgranular to intergranular when a dwell time at maximum stress is added to the fatigue cycle. This mechanism is thermally activated. Besides, the material is designed to develop a passivation layer of oxides which protects the material against grain boundary oxidation. This second mechanism is also thermally activated. Thus, at the beginning of a dwell time, grain boundary oxidation takes place at crack tip and the crack propagates, but as soon as the passivation layer has grown this propagation stops. It was shown, by Chassaigne et al. that only the very first seconds of a 300 sec dwell time contribute to crack growth. However, if the crack tip is stretched the passivation layer breaks, and the competition between grain boundary embrittlement and the growth of a passivation layer takes place again. Therefore this competition is driven by the mechanical loading. This explains, in particular, why the crack growth rate is not only sensitive to the duration of the fatigue cycle but also to its shape. For instance, two types of cycle were defined, slow-fast and fast-slow, with the same duration but a different shape. During a fast-slow cycle, the passivation layer is broken at loading, but the loading phase is short and the detrimental effect of the environment is small, at unloading the passivation layer grows within a few second and protects the material during the unloading phase. On the contrary, during a slow-fast cycle, the passivation layer breaks and grows continuously during loading and the loading phase is long enough so that oxidation can assist fatigue crack growth. It is observed therefore that the crack growth rate is much higher using slow-fast cycles than using fast-slow cycles. These phenomena are modelled as follows. The crack growth rate is the sum of the contribution of crack tip plasticity and of the time during which grain boundary oxidation takes place :

$$\frac{da}{dt} = \left(\frac{\partial a}{\partial \rho}\right)\frac{d\rho}{dt} + \frac{\partial a}{\partial t} \quad \text{where} \quad \frac{d\rho}{dt} = f\left(\frac{dK}{dt}, K, \text{int.var.}, mp_i(T)\right) \quad \text{and where} \quad \left(\frac{\partial a}{\partial \rho}\right) = \alpha(T) \qquad (1)$$

The global cyclic elastic-plastic constitutive model *f* that provides the plasticity rate as a function of the loading conditions and of the status of its internal variables, is a function of the temperature through the dependency of its material parameters (m_{pi}) to the temperature. Besides, the adjustable parameter α was determined at 450°C, 550°C, 600°C and 650°C using high frequency fatigue crack growth experiments (sinus) for which the crack path is transgranular. Then, so as to account for stress rate variations (such as dwell times, for instance), grain boundary embrittlement is modelled as follows:

$$\frac{\partial a}{\partial t} = m.\beta \quad \text{where} \quad \beta = \beta_o.\exp\left(-\frac{Q}{kT}\right) \quad \text{and where} \quad \frac{\partial m}{\partial t} = -R_G.m \quad \text{and} \quad \frac{\partial m}{\partial \rho} = -R_F.(1-m) \qquad (2)$$

The crack growth rate β by grain boundary embrittlement, in absence of a passivation layer, is thermally activated and modulated by a variable *m* that stands for the state of the passivation layer. When m =1, the passivation layer is broken, when m =0, the passivation layer is thick enough to fully protect grain boundaries. In between, two parameters R_G and R_F control respectively the rates of growth of that passivation layer versus time and its rate of fracturation when the crack tip is stretched due to crack tip plasticity. This happens only at opening, when dρ is positive. This model was validated using complex isothermal fatigue crack growth experiments and was also employed to simulate complex non-isothermal loading sequences, yielding to a good prediction of the total crack propagation life.

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Session 6

Methodologies and tools for fatigue life assessment applied to non metallic components.

Méthodologies et outils d'évaluation de la durée de vie à la fatigue, appliqués aux composants non métalliques

FATIGUE BEHAVIOUR OF POLYPROPYLENE FOR AUTOMOTIVE APPLICATIONS

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The fatigue behaviour of semi-crystalline homo-polymers is crucial for the design of polymer-based structural applications. Such materials exhibit a complex behaviour due to time-dependent mechanisms. Scientific literature about this issue widely focused on crack propagation approaches, mainly based on tension-compression experiments performed to compare materials. Only a few works were carried out about high-cycle fatigue approaches. Therefore only a very few data are available on multi-axial high-cycle fatigue behaviour of polymers. This experimental study focuses on this issue.

The mechanical properties of the investigated polypropylene (PP) (crystallinity ratio 41%; glass transition temperature at 10°C and melting temperature at 166°C) are briefly presented first. Then the paper is divided into the 3 following sections.

Experimental device

The first part presents the special experimental device developed for the study. As illustrated in Figure 1, the fatigue sample is a thin extruded tube made of Polypropylene and special grips were used in order to perform test under tension, torsion or combined loading on the same sample. This allows obtaining all results on the same sample (same process, material and geometry). Temperatures were tracked by means of three thermocouples at the inner and outer surface of the specimen, and in the ambient air inside the pipe.

Figure 1: Experimental devicefor tension-compression, torsion and combined fatigue tests on pipes

Fatigue test results

All fatigue tests were carried out with a triangular signal, at a constant frequency of 1Hz and at load controlled constant amplitude. The triangular signal was chosen for constant strain-rate purpose because of the viscosity of the material. Different load ratios R were applied: -1 and 0.
S-N curves are presented and analyzed for both tension and torsion loading. Complementary tests were performed to determine the fatigue limit for two other multiaxial loadings.
No significant temperature raise was observed during tests performed at the lowest stress amplitude. These pipes did not fracture. For tests leading to a low number of cycles to failure, the temperature increased by a 3°C to reach a nearly constant value after 300 cycles, and drastically increased again in the last 100 cycles.
Both tension and torsion tests suggest an influence of the mean shear stress, even if the fatigue limit in torsion appears difficult to be estimated from the S-N. If existing, it is however expected to be lower than measured in tension.

Multiaxial fatigue criterion

The last part is devoted to the mechanical analysis of experimental results by the mean of multi-axial fatigue criteria.

Due to the low frequency of 1 Hz, such tests are very time consuming. For this reason, additional tests based on the Luong's method [1-2] were also carried out to determine the fatigue limit under different multi-axial conditions using one sample only. According to this method, the pipe was loaded at a given stress amplitude (below the estimated fatigue limit) for 500 cycles, the temperature was recorded at the end of the 500-cycle stage. The same sample was loaded again at higher stress amplitude for 500 cycles more with a temperature measurement again at the end of the 500-cycle stage. This procedure was repeated up to the pipe failure. At the end of the test, a temperature vs. stress amplitude can be plotted and the fatigue limit is supposed to be given by the intersection of the two linear regimes. Several tests were performed in torsion and tension at different normalized mean stress levels. Values obtained from the two methods in tension at R = -1 were close, but are rather different in tension at R = 0 and in torsion at R = -1 and 0. The accuracy of the intersection determination may account for this difference. Even if this is a first step that must be largely completed by other tests for different conditions, it suggests that this method would be of interest for fast estimation of the fatigue limit in such material; it can’t be a good experimental procedure to determine the fatigue limit.

Some existing initiation fatigue criteria (i.e. Crossland and Sines criterion) were used to analyze lifetime results from the previously presented multi-axial tests. A modified expression of the Sines criterion that takes into account the mean stress influence on the torsion fatigue limit is also proposed. Only results exhibiting a scatter lower than 20% are interesting to be discussed.
(i) For loading cases without any mean shear stress, the Sines and Sines-modified criteria are the most accurate.
(ii) For loading cases with a mean shear stress, the Sines-modified criterion is the most accurate.
The proposed criterion is a basic modification of the usual Sines criterion that takes into account the mean stress influence on the torsion fatigue limit. This experimental result is important because this effect is not observed in metallic materials. Tests with a classical S-N curve would be useful to get a clear conclusion on that subject.

Conclusions

Several conclusions arise from the presented work.
- Under fatigue loading, the behaviour is influenced by the hydrostatic stress.
- The determination of the fatigue limit using temperature measurement with Luong's method gives estimation of the fatigue limit with up to 40 % error compare to S-N curve.
- The fatigue limit under torsion is influenced by the mean shear stress. This result is important because it is not the case on metallic materials.
- Comparison between Sines, Crossland and the Sines-modified criterion shows that the fatigue behaviour of semi-crystalline polymers seems to be governed by the mean hydrostatic stress more than by the maximum hydrostatic stress. Furthermore, the maximum shear stress is probably a predominant governing parameter in comparison to the amplitude (the fatigue limit in torsion depends on the mean shear stress).

Acknowledgements

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References

(1) Luong M.P., "fatigue limit evaluation of metals using an infrared thermography technique", Mechanics of Materials, 28, pp. 155-163, 1998

(2) Luong M.P., "Fatigue evaluation of metals using infrared thermography", Proceedings of SPIE - The International Society for Optical Engineering, 4317, pp. 297-302

CYCLING BEHAVIOUR OF STITCHED COMPOSITE SANDWICH STRUCTURES

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High technology industries are always in search of materials offering a good compromise between mechanical properties and weight. The sandwich structure is one of the most promising ways to achieve this, even if cohesion skin/core and the transverse properties remain their weak points.

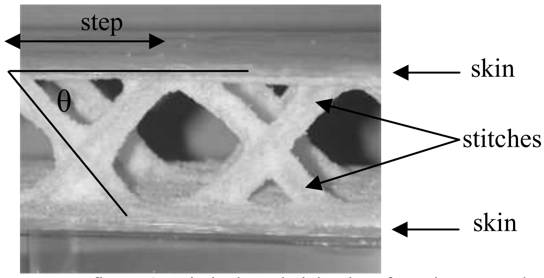

figure 1 : stitched sandwich when foam is removed

By binding together the two skins and the core, the reinforcement in the third direction (figure 1) seems to solve these problems [1,2].
Sandwich pannels are composed of two skins made up with woven glass plies, a polyurethane foam core and glass yarns stitches.
A triangulated structure is created through the foam and the two skins.

The aim of this work is to apprehend the effect of stitching on the mechanical behavior under cycling loading. Thus a four-points flexural testing is conducted at 5Hz until failure or 10^6 cycles. Loading level is deduced from the failure in case of static loading.
A Wohler representation is then adopted (S-N curves).

Rigidity evolution under cycling remains classical even for the stitched structure. After a first phase of fast loss of rigidity where degradations settle, damages remain present but are not propagated any more. In this zone, an apparent stability of the resistance of the structure appears. However the rupture intervenes by decay of the microscopic cracks. Stitches presence enables reaching definitely higher loads while preserving a good resistance to the repeated loadings. A particular attention is given to the specific ruin of such a stitched structure. The weak point of this material already highlighted by static studies is the stitches points of anchoring.

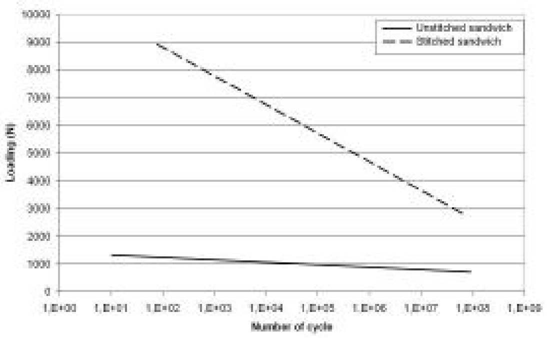

figure 2 : cycling behavior of stitched and unstitched sandwiches

Moreover, the relative positioning of the two stitching yarns is studied. Under loading, the additional degree of freedom of non-dependant stitches allows a better distribution of the efforts by relieving the points of anchoring of the seams or the rupture intervenes classically. Maximum number of cycling could be multiplied by 2.

References

1: **B. Lascoup, Z. Aboura, K Khellil, M.L Benzeggagh** "On the mechanical effect of stitch addition in sandwich panel", *Composites Science and Technology*, *Volume 66, Issue 10*, *August 2006*, *Pages 1385-1398*

2: **P. Potluri, E. Kusak, T.Y. Reddy,** "Novel stitch-bonded sandwich composite structures", *Composites Structures 59* (2003) 251-259

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Session 7

Experimental Validation: reduction of fatigue test duration

Validation expérimentale : réduction de la durée des essais de fatigue

Two different ways for reduction of fatigue test duration

Fatigue design 2007

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Abstract

Today, the safety rules of the automotive industry forbid fatigue failures which can affect mechanical structures. Because this phenomenon is not acceptable, fatigue tests are conducted to validate material behavior with standard spectrum on specimen and automotive components with spectrum signals measured on cars. But, those costly and time consuming tests don't always respect new development schedule targets. That's why, solutions to reduce test duration are investigated.

New technologies, and specially computer calculation of structure (CAD), allow the optimization of component design. Even if the number of tests is reduced with more and more simulation, fatigue tests are necessary to validate material behavior and components and to guarantee the reliability target. Consequently, it is necessary to accelerate fatigue tests by reducing loading signals without changing the fatigue life and the damage or by increasing the test frequencies.

Before continuing we should state the requirement for a successful durability test :

1. The test must be suitable for the item in question , be that a material coupon, a single component or sub-assembly
2. The test must replicate the same failure mechanisms observed in the real loading environment
3. The test should be representative of the real loading environment within known statistical margins
4. The test should be accelerated where possible to improve development schedules and reduce cost ; however ,it should not incur unrealistically high loads that might alter the failure mechanism
5. The test specification should be suitable for rig based testing and Finite Element (FE) based analysis

In this paper we present a comparative study of two different ways to reduce fatigue test duration. One way consist to apply filtering method (integrating material parameters) on real service loads, this method can be used for multiaxial fatigue test on material specimen in advanced project phase and on component in validation project phase. The second way consist to increase frequency loading by using a piezoelectric fatigue system (ultrasonic fatigue frequency), this method can be used only for uniaxial fatigue test on material specimen in advanced project phase.

The study consists to identify strength and weakness of each method and to guide the test engineer towards the most appropriate and efficient form of testing for a variety of situations.

Intégration de l'entropie des sollicitations en service dans l'évaluation de l'endommagement

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Une des grandes difficultés rencontrée dans l'intégration de conditions réelles d'usage lors de la conception d'un composant mécanique, réside dans la capacité à bien analyser et représenter les sollicitations réelles pour les démarches de calcul de l'endommagement et de la durée de vie.

L'entropie selon Shannon, est une fonction mathématique qui correspond à la quantité d'information contenue ou délivrée par une source d'information. Intuitivement, l'entropie de Shannon peut être vue comme mesurant la quantité d'*incertitude* liée à une sollicitation aléatoire ou plus précisément à sa distribution statistique. Notre étude intègre ce concept de l'entropie dans la démarche de calcul de l'endommagement d'une entité mécanique. Cette intégration s'effectue autour de l'analyse de la sollicitation que l'entité mécanique va subir, de l'interaction entre la sollicitation extérieure et l'entité mécanique étudiée et de la réponse aléatoire que cette entité va délivrer. De plus, l'endommagement est considéré comme une probabilité de dégradation des performances de l'entité mécanique étudiée.

Le suivi de l'endommagement s'effectue par son entropie. Des applications seront présentées autour de l'analyse d'essais d'endurance effectués sur un véhicule terrestre. Ces analyses aident à la classification des différentes conditions d'essais et à proposer des indicateurs de corrélation entre les différents environnements d'essais. Cette corrélation est indispensable pour conduire à la réduction du temps des essais sans altérer leurs niveaux de fiabilité et de représentativité.

Dans cette étude, il est proposé de prendre en compte l'entropie de la sollicitation aléatoire que subit l'entité mécanique concernée et de mettre en relation l'entropie de la cause (qui est la sollicitation aléatoire) et la conséquence qui est l'endommagement qui en résulte.

ENDOMMAGEMENT ET ENTROPIE

L'évolution du dommage est toujours calculée à partir du modèle de Miner. On écrit qu'un élément de dommage par fatigue *dD* est dû à un élément de sollicitation *dn*. Selon la loi de Miner $dD = \frac{dn}{N(S)}$ avec *dn* = le nombre d'amplitudes de la sollicitation étudiée dont le niveau est compris entre S et S+ds et N(s) est le modèle d'endurance (ou de durée de vie limite qui est modélisée par une courbe, appelée courbe de Wöhler). Pour une durée donnée T, $dn = N_T\, f_S\,(s)ds$, avec N_T nombre total des sollicitations et $f_S(s)$ densité de probabilité de la contrainte dont le niveau est égal à S. Pour une sollicitation mesurée avec un pas de temps $\Delta t = 1/fe$ (fe fréquence d'échantillonnage), le nombre total des sollicitations est égal à $N_T = fe * T$. Ainsi, le dommage global est la somme des dommages partiels pour toutes les valeurs de S : $D = N_T \int_\Delta \frac{f_S\,(s)}{N(S)} ds$ Avec Δ=domaine de définition de S. Dans le cas où la courbe de Wöhler est considérée selon le modèle de Basquin ($N\ S^b = C$, C est une constante fonction du niveau de sollicitation), l'expression de l'endommagement devient $D = \frac{N_T}{C} \int_\Delta s^b f_S\,(s)ds$, si on pose $u = \frac{s}{\sqrt{V(S)}}$ avec V(S) la variance de S, la relation précédente s'écrit $D = [V(S)]^{b/2} \frac{N_T}{C} \int_\Delta u^b f_U\,(u)du$ Le terme $\int_\Delta u^b f_U\,(u)du$ est le moment d'ordre b ($E(X^b)$) de la variable aléatoire U ou même de la sollicitation aléatoire (S) que le système étudié a subi. Ce moment est directement lié à l'entropie de la densité de probabilité définie selon Shannon. En effet, l'entropie d'une distribution a été définie par Shannon pour les lois discrètes définies par ses probabilités $I_X = -\sum p_i \ln p_i$ et étendue ensuite aux lois continues définies par leur densité selon $I_X = - \int \ln\{f(x)\} f(x) dx$. Mais on sait que ces deux définitions peuvent après coup provenir de la définition de la divergence de Kullback entre deux lois que l'on étend en prenant des mesures de référence convenables pour les lois discrètes et continues. Dans la suite il est naturellement sous-entendu que ces quantités sont définies et finies pour les lois considérées *(à propos des notations, « E » étant pris par l'espérance, nous prenons le "I" d'information pour simplifier un peu nous gardons le logarithme népérien ln).*

L'entropie stochastique a reçu une forte attention en théorie de l'information, avec des analogies physiques bien connues, mais elle possède aussi des propriétés propres à son origine probabiliste. C'est notamment le cas dans les sciences humaines où l'on travaille avec des lois qualitatives ou nominales, les chercheurs ont retenu l'entropie d'une distribution au titre d'un paramètre de dispersion comparable à la variance [22]. C'est aussi une partie du discours de Dacunha-Castelle quand il met ces deux définitions en parallèle.

Dans cette étude deux configurations de lois de probabilités sont traitées (loi Gamma et loi Beta1). Pour ce résumé, uniquement la cas de la loi Gamma est présenté.

La loi $\Gamma(\alpha,\lambda)$ de densité $f(x) = x^{\alpha-1} e^{-\lambda x} \lambda^\alpha/\Gamma(\alpha)$, alors $\ln f(x) = - \lambda x + (\alpha-1) \ln x + \ln(\lambda^\alpha/\Gamma(\alpha))$ et donc $I_X = \lambda E(X)- (\alpha-1)E(\ln X)-\ln(\lambda^\alpha/\Gamma(\alpha))= \alpha - (\alpha-1) E(\ln X) - \ln(\lambda^\alpha/\Gamma(\alpha))$. Pour calculer $E(\ln X)$ on introduit le moment $E(X^b)$. En effet, $E(\ln X) = \frac{d}{db} E(e^{b \ln X})\Big|_{b=0} = \frac{d}{db} E(X^b)\Big|_{b=0}$. Le calcul de $E(X^b)$ est immédiat, $E(X^b)$ est égale à $\dfrac{\Gamma(\alpha+b)}{\lambda^b \, \Gamma(\alpha)}$. On en déduit que $E(\ln X) = \psi(\alpha) - \ln \lambda$ avec ψ la dérivée logarithmique de Γ. Il en résulte que $I_X = \alpha + \ln(\Gamma(\alpha)) - (\alpha-1) \psi(\alpha) - \ln\lambda$. On considère la famille particulière $\Gamma(\alpha,\alpha/\mu)$ d'espérance commune μ, de variance $\sigma^2 = \mu^2/\alpha$ et d'entropie $I_X = \ln\mu + \eta(\alpha)$, en posant $\eta(\alpha) = \alpha - \ln \alpha + \ln \Gamma(\alpha) - (\alpha-1) \psi(\alpha)$. Toutes les lois de cette famille sont centrées sur μ mais au niveau de la variance et de l'entropie, les variations sont respectivement en $1/\alpha$ et en $\eta(\alpha)$: La variation de la variance est immédiate, elle est décroissante en fonction de α et la variation de l'entropie dépend du signe de $\eta'(\alpha) = (\alpha-1) [1/\alpha - \psi'(\alpha)]$. Ainsi le dommage et l'entropie de la sollicitation aléatoire sont liés et évoluent d'une manière directement proportionnelle.

CONCLUSION

Dans cette étude, une liaison est établie entre l'entropie d'information et l'endommagement. Cette liaison s'effectue par l'intermédiaire du moment d'ordre b (réel positif). A partir de cette liaison, une étude de sensibilité est effectuée autour des paramètres des lois de probabilités des sollicitations subies par l'entité mécanique étudiée et leurs influences sur l'endommagement.

PRINCIPALES REFERENCES

LU (J.). – *Fatigue des alliages ferreux. Définitions et diagrammes- Techniques de l'ingénieur* -[BM 5 042]. Base documentaire « Fonctions et composants mécaniques » (2002).

RABBE (P.) et GALTIER (A.). – *Essais de fatigue. Partie I - Techniques de l'ingénieur* -[M 4 170]. Base documentaire « Étude et propriétés des métaux » (2000).

LALLET (P.), PINEAU (M.) et VIET (J.-J.). –*Analyse des sollicitations de service et du comportement en fatigue du matériel ferroviaire de la SNCF*. Revue générale des chemins de fer, Gauthier-Villars éditions, p. 19-29 (janvier 1995).

OSGOOD (C.C.). – *Fatigue design*. Pergamon Press, New York (1982).

KOUTA (R.) et PLAY (D.). – *Durée de vie en service des composants mécaniques- Analyse de chargements aléatoires- Techniques de l'ingénieur*- [BM 5 030] Base documentaire « Fonctions et composants mécaniques » *(2007).*

KOUTA (R.) et PLAY (D.). – *Durée de vie en service des composants mécaniques - Modélisation de chargements aléatoires - Techniques de l'ingénieur*- [BM 5 031] Base documentaire « Fonctions et composants mécaniques » *(2007).*

KOUTA (R.) et PLAY (D.). – *Durée de vie en service des composants mécaniques – Méthodes de prises en compte des conséquences d'une sollicitation aléatoire - Techniques de l'ingénieur*- [BM 5 032] Base documentaire « Fonctions et composants mécaniques » *(à paraître fin 2007).*

DACUNHA-CASTELLE D., DUFLO M., Probabilités et statistique, tome 1, éditions Masson 1994.

REUCHLIN M., Les méthodes quantitatives en psychologie, PUF. 1975.

WHITTAKER E.T., WATSON G.N., A course of modem analysis, Cambridge Un. Pr. 1927-1965

MAURIN M. Jeux de variance et d'entropie, XXXI journées de statistique, 17-21 mai, Grenoble, France, (57-60)

Optimization of an accelerated step-stress fatigue test plan

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The design of a component subjected to fatigue requires an experimental qualification of the couple material/process fatigue characteristics. The current industrial requirements involve that this qualification has to be carried out on the smallest possible number of tests and within the smallest possible testing time to censorship. In the same time, the accuracy of estimations has to remain significant.

To do this, accelerated step-stress fatigue tests are quite efficient. Moreover, the accuracy of this kind of test can be optimized thanks to a good distribution of the steps. We suggest illustrating on a particular example the process to obtain an optimized test plan by this way. Its efficiency will be compared to that obtained with other kinds of plans and the advantage of this method will be shown out for the design of a component.

To begin with, the existing accelerated fatigue testing methods and their application to fatigue design, such as the statistical process of results will be reminded. Then, the advantage of a step-stress fatigue test with a common profile applied to any tested specimen will be detailed. The optimization process used to define this profile will be explained. It will be shown how its efficiency can be evaluated by stochastic simulations. An actual test will be defined with this optimized profile and the specific parameters will be estimated (Basquin parameters, standard deviation, …).

The efficiency obtained with this test will be compared to that obtained with existing testing methods. The focus will be put on the testing times and the sample sizes required with this method to obtain a significant accuracy level.

To show out the applicability of the method in the industrial field and to evaluate its efficiency, the method will be carried out to design an actual mechanical component (a window mechanism) with a reliability approach.

First of all, it can be reminded that an Accelerated Life Test (ALT) consists of subjecting a sample to high stress levels and to extrapolate the estimated lifetime parameters at these levels thanks to a so called "acceleration model". It can be performed with heat, vibrations, or alternative tensions, torsions or flexions. These tests can be carried out on electronic boards, fatigue smooth specimens or mechanical components.

To improve the efficiency of the test plan, a more recent ALT method suggests subjecting all the specimens to the same step-stress test. For fatigue tests, it means that all the specimens are subjected to a given level of stress amplitude during a given number of cycles. Then, the survival specimens are tested at another level and so on. A number of cycles to censorship may be defined to limit the testing time.

In both cases, the parameters of the acceleration model and of the lifetime distribution can be estimated by the Maximum Likelihood Estimation (MLE) method and the accuracy of these parameter estimates can also be estimated.

The step-stress test can be processed like a test at constant stress amplitude by using the Sedyakin model. This model also enables one to define a step-stress test and a constant amplitude test leading to the same evolution of the failure probability.

When first estimations of the fatigue parameters are known, this model can be used to easily define a step-stress test with given fractiles of failures at the end of each step. The quality of the test plan can be verified by random generations of fatigue lives and when its quality is validated, the test can be performed on smooth specimens or on whole mechanical parts.

Let us sum up the results obtained with this process:

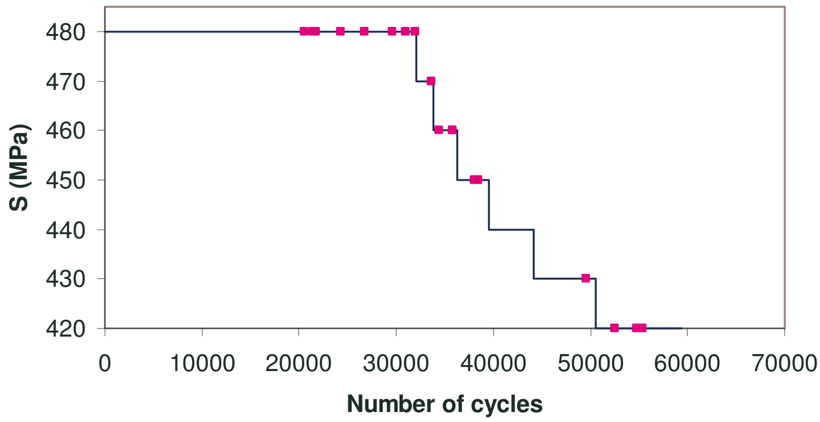
- for a sample of 20 smooth specimens made of C38 stretched steel subjected to rotative bending fatigue tests,
- and for 5 guideways with a stop end subjected to successive pressures.

For the smooth specimens, we carried out a hardness and a tensile test, microscopic and chemical analysis and fatigue tests on 5 specimens at an amplitude slightly beside the yield stress.

It quickly led to first estimations of Basquin parameters and of the standard deviation of the log fatigue life.

Thus, a step-stress test with 5 steps at 5 amplitude levels has been defined so that 10, 30, 50, 70 and 90 % of the specimens fail at the end of each of the five steps. These first estimations have also been used to simulate other step-stress plans and it validated that the first one led to the best estimation accuracy. The test has been censored at 6.10^4 cycles.

The actual tests with the optimized plan have been carried out and the fatigue lives obtained have been processed by MLE (figure below).



The estimates of the Basquin parameters a and b and of the standard deviation σ, the fatigue limits deduced and their accuracy are sum up in the following table:

	a	b (MPa)	σ	S (10^5 cycles)	S (10^6 cycles)
Estimates from short tests	0,08	1110	0,08	442 MPa	368 MPa
Estimates from the usual plan (NF A 03-402)	0,143	2053	0,83	396 MPa	285 MPa
Estimates from the step-stress test	0,14	2059	0,95	411 MPa	298 MPa
Estimated coefficient of variation	4,5 %	3,7 %	17,5 %	5,4 %	7,2 %

It has been verified that, even with fatigue tests at high levels (more than twice the fatigue limit) shorter than the usual ones, the estimations are more accurate.

For the guideways, no short tests were required because fatigue results on similar products were already available. These results have been used to:

- define the optimized test plan like it had been done for the smooth specimens,
- verify the good quality of the plan by simulating other ones (by random generations of fatigue lives),
- define bayesian a priori for the parameter estimates and thus to obtain a posteriori estimates of these parameters.

The bayesian approach was required because no more than 5 guideways could fail during the fatigue tests. This process led to the following results:

	a	b	$F_d(10^7)$	σ
Ref: Usual plan on 100 guideways	0,086 ± 0,8 %	9732 ± 2 %	2503 ± 0.3 %	0.39 ± 8 %
MLE with the classical plan (5 guides)	0,078 ± 11 %	9248 ± 58 %	2107 ± 55 %	0,19 ± 230 %
MLE with the optimized plan (5 guides)	0,079 ± 6 %	9540 ± 39 %	2430 ± 43 %	0,27 ± 82 %
Bayesian estim. (classical plan) - 5 gu.	0,082 ± 5%	9726 ± 5 %	2478 ± 3 %	0,412 ± 21 %
Bayesian estim. (optimized plan) – 5 gu.	0,085 ± 1%	9735 ± 2 %	2509 ± 0.4 %	0.384 ± 11 %

These results show that, for smooth specimens as well as for mechanical components, the proposed method is applicable and more efficient than the usual one. It could lead to save time and money and to easily prevent useless redesign of components.

Notes :

Notes :

Workshop 1

Fatigue design of welded components and structures

Conception en fatigue des composants et des structures

NEW DEVELOPMENTS IN THE IIW RECOMMENDATIONS FOR FATIGUE DESIGN AND ANALYSIS OF WELDED STRUCTURES

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Abstract: The recommendations of the International Institute of Welding (IIW) on fatigue of welded components and structures and on the effect of weld imperfections in respect to fatigue have been published firstly in 1996. A comprehensive recommendation was established, which embraces all current methods of verification, as e.g. component testing, nominal stress, structural stress, notch stress method as well as fracture mechanics assessment procedures. Detailed guidance for assessment of weld imperfections is also given. The safety philosophy covers the different strategies, which are used in various fields of application and gives a specified choice for the designer. The update of the recommendations was finalized in 2006. The main areas of update are the structural hot-spot stress concept, which allows now for an economic and coarser meshing in finite element analysis, the extension of the effective notch stress concept to welded aluminium structures and the numerical assessment of post weld treatments for improving the fatigue properties. It is expected that the new update will exert the same impact on design and codes as the old one.

Fatigue of Welded Connections in Extruded Aluminium Hollow Section Profiles

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Abstract This paper presents a study of the fatigue properties of welded aluminium hollow section joints based on the use of the hot spot stress method. The study includes experimental fatigue test data and analytical results, with a focus on the hot spot stress concentration factors (SCF_{hs}). A welded aluminium rectangular hollow section T-joint forms the basis of the study covering numerical stress analysis (finite element analysis); 3-D laser profile scanning of the welds; experimental stress analysis (strain gauges); and fatigue testing. Finite element analysis was performed on both idealised and actual (scanned) weld geometries. Values of SCF_{hs} were computed for three different load configurations and a comparison made of the effects of the idealised and scanned weld geometries. Differences ranging up to 17.5% were found from the variations in weld geometry alone. The dominant effect lay in the choice of Standards-based guidance for calculating the hot spot stress - causing variations as high as 38%. An experimental programme of some 40 new fatigue tests was compared with tentative design guidance previously drawn from earlier test results. The published database for RHS joints in aluminium remains small and further expansion of the database is clearly advantageous.

Multiaxial fatigue behaviour of hot-rolled crane runway beams with welded block rail

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Abstract Top running overhead cranes belong to the important equipment of modern production halls. Mostly, crane runway beams form the crane supporting structure. Usually, a crane runway beam consists of a hot-rolled I-section with a block rail fixed to the top flange by rail welds (fillet welds). The current fatigue design of crane runway beams according to Eurocode 3 Part 1-9 uses the Classification method (*S-N* method). This approach does not consider the complex multiaxial state of stress in the vicinity of the rail welds to its entire extent (see Fig. 1). At the point of wheel load application the top region of a crane runway beam is subjected to longitudinal stresses σ_x due to bending in addition to local stresses resulting from the load application. The current fatigue verification according to Eurocode 3 considers for the direct load application on the rail welds a very conservative detail derived from a cruciform joint under tension and has to be summed up together with the damage caused by the other stress components in form of the Palmgren-Miner rule leading to an uneconomical design of the rail welds.

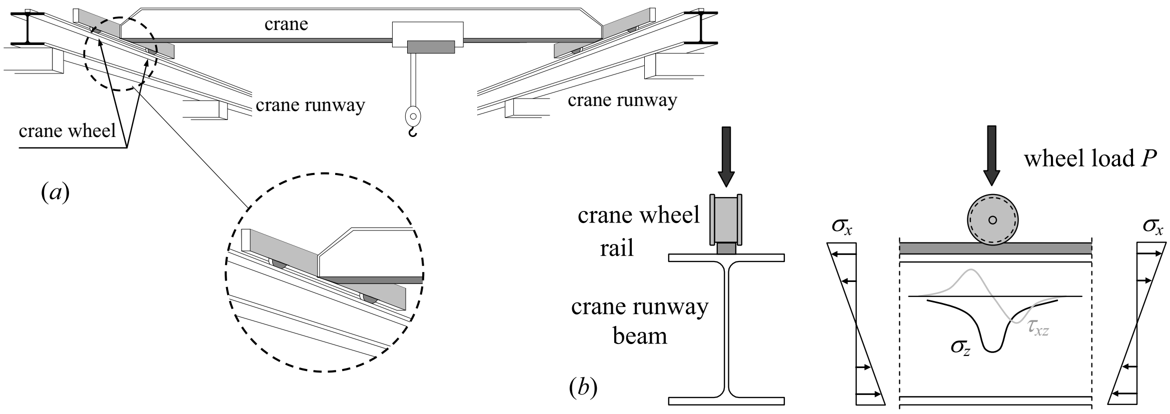

Figure 1. (*a*) Top running overhead crane, (*b*) wheel load application

Here a fatigue verification approach is presented that allows for taking into account the influence of the multiaxial state of stress due to the wheel load application on the rail welds. This approach does not try to determine the damage contribution of the wheel load directly by a damage accumulation formula but tries to assess the damage contribution by identifying the decrease of the fatigue resistance of the longitudinal fillet welds if an additional wheel load is applied (see Fig. 2). The goal of the still ongoing research is to analyse the influence of the wheel load application on the fatigue resistance of the longitudinal fillet weld, a structural detail specified in Eurocode 3 Part 1-9.

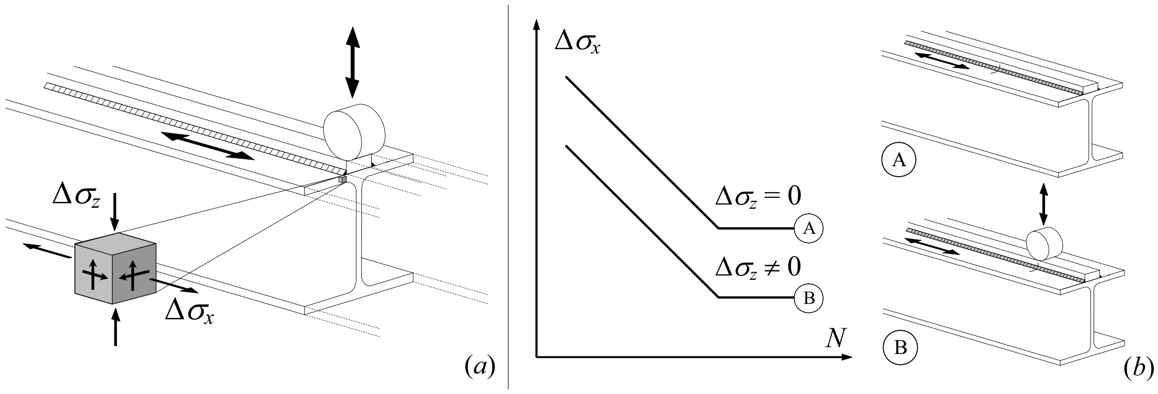

Figure 2. (*a*) Stress field under wheel load, (*b*) schematic diagram of indirect wheel load's influence on the fatigue strength of longitudinal fillet welds in tension

For eight test girders the fatigue strengths of the rail welds in tension (longitudinal fillet welds) under additional crane-wheel load induced transverse pressure were determined. Different types of fillet welds were investigated. By using the described approach the fatigue verification can be limited to the assessment of longitudinal stress ranges. However the fatigue strength of the well-known longitudinal fillet weld in tension has to be modified depending on the magnitude of the additionally acting wheel load.

The determined fatigue strengths of continuous rail welds under wheel loading are reduced compared to the fatigue resistance of a longitudinal fillet weld without wheel load. Nevertheless the reduced fatigue strength seems to be at least fatigue category 71.

For intermittent rail welds the notch at the weld ends dominates. The fatigue strengths of the investigated test girders with chain intermittent rail welds were not lower than the fatigue strength of the longitudinal stiffener with $50 < L \leq 80$ mm.

Compared with the chain intermittent ones the staggered intermittent rail welds behave more unfavourably under wheel loading. Nevertheless the determined fatigue strengths of the investigated test girders with staggered intermittent rail welds in general were not lower than the fatigue strength of the longitudinal stiffener with $80 < L \leq 100$ mm.

The aspect of damage spread throughout the rail and the influence of a non-proportional stressing could not be simulated by means of the research project's test setup. The simulated wheel load could only act stationary on the test girders. Only a test setup including a moving constant wheel load allows for a time-space shift of the loading point. So it has been unrevealed up to now how far the surrounding undamaged material in proximity of the region damaged by the concentrated load develops a beneficial effect.

Up to now the small number of test results has not allowed to formulate statistically confirmed statements. Even so the shown tendencies are very positive. Therefore the longterm goal is to establish an own-standing fatigue detail considering the multiaxial state of stress of a rail weld in Eurocode 3 Part 1-9 based on a more extensive test series.

ACKNOWLEDGEMENT

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REFERENCES

1. U. Kuhlmann and M. Euler, Kranbahntraeger - Wirtschaftliche Bemessung und Konstruktion robuster Radlasteinleitungen, final report of AiF / DASt-research project No. 14173, 2007.
2. Eurocode 3 - Design of steel structures - Part 6: Crane supporting structures, February 2007
3. Eurocode 3 - Design of steel structures - Part 1-9: Fatigue, May 2005
4. G. Sedlacek et al. Background Document to prEN 1993-1-9. 1st Draft, October 2004

The Concept of the Fictitious Radius for the Assessment of Welded Joints of Wrought Magnesium.

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With regard to light-weight design of welded magnesium structures the investigation reported was carried out with three different types of MIG- and TIG-welded joints of the alloy AZ31(ISO-MgAl3Zn1), fully or partially penetrated butt welds, transversal stiffeners. The evaluation of the results showed that the local stress concept using the fictitious notch radius of r_f = 1.0 mm can be applied to magnesium welded joints from plates with thicknesses $t \geq 5$ mm independently from the weld geometries. Design curves are proposed for different stress ratios, i.e. R = -1 as well as 0 and 0.5, which allow the consideration of residual stresses as well as load induced mean stresses. The results permit also the suggestion of $\Delta\underset{\cdot}{\sigma}$= 28 MPa for r_f= 1.0 mm as FAT-value in the IIW-Fatigue Design Recommendations. This FAT-value is compared with the already known data for steel and aluminium joints. A linear relationship between the FAT-values and the Young’s modulus is determined.

THE STRUCTURAL STRESS METHOD FOR THE FATIGUE ANALYSIS OF WELDED STRUCTURES

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The stress concentration in a welded joint dominates the fatigue behavior of the joint. However, traditional finite element methods are not capable of consistently capturing the stress concentration effects due to their mesh-sensitivity.

A robust stress analysis procedure has recently been developed at Battelle and extensively validated by various industries. The method is called Verity™ mesh-insensitive structural stress method and serves as a FE post-processing procedure to commercial FE packages. The Verity™ method has been integrated into fe-safe™ and is available from Safe Technology Limited. The method is based on the mapping of the balanced nodal forces/moments along an arbitrary weld line into the work-equivalent tractions (or line forces/moments). A complex stress state due to notch effects can then be represented in the form of a simple stress state in structural mechanics in terms of through-thickness membrane and bending components at each nodal location. The resulting structural stress calculations are mesh-insensitive as long as the overall geometry of a component is reasonably represented in a finite element model.

In addition to its mesh-insensitivity, the effectiveness of the structural stress parameter has been further validated by collapsing several thousands of fatigue tests available from literature into a single fatigue life curve, referred to as the master S-N curve.

Application of the structural stress method for fatigue design of welded structures

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Abstract A structural stress multiaxial computing method for the fatigue assessment of welded structures is presented. This approach is based on the use of a local equivalent stress, or design stress, derived from the shear stress and the concomitant hydrostatic pressure previously proposed by Dang Van. Associated with a specific shell finite element meshing methodology, the method is successfully used to assess the fatigue resistance of welded structures of complex geometry and with multiaxial loading. The approach also allows the role of the welding process upon the fatigue behaviour to be addressed either by a better description of the influence of the local residual stress state.

1 INTRODUCTION

As for welded structures, the structural method developed for the offshore industry in the 70' and the 80's (AWS and API codes) and particularly following Radenkovic's proposals [3], is without any doubt the one which allows the most interesting industrial calculations. In this method, the welded connection is characterised by a design stress S, more or less clearly defined, and which better describes the local stress at the «Hot Spot». The latter is obtained either by the extrapolation of strain values measured by strain gauges close to the Hot Spot of the structure or by a thin shell finite element calculation. S is a «geometrical» stress which can be deduced from the nominal stress using a Stress Concentration Factor obtained by experiment and parametric formula. This stress is used to predict the fatigue tests on welded tubular nodes submitted to various services loading by means of a unique S-N line.

It is this idea which is considered in the following, giving a clearer interpretation of the design stress based on the Dang Van classical fatigue criterion.

2 DANG VAN FATIGUE CRITERION

This model is presented in detail in [4]; at the same time, different structural applications are given. In this model the *material is considered as a heterogeneous structure* submitted to cyclic loading, and that fatigue corresponds to limit of possibility of elastic shakedown. Thanks to this assumption, local stabilised stress state $\sigma(t)$ can be calculated (see [4]). Local shear $\tau(t)$ and hydrostatic tension $p(t)$, derived from $\sigma(t)$ were chosen as pertinent parameters; the fatigue criterion is a linear relation between these quantities:

$$F(\sigma) \equiv \tau + a.p - b \geq 0$$

where a and b are material constants that can be determined by two simple types of fatigue experiments; b for instance corresponds to the fatigue limit in simple shear.

General application of this criterion requires the consideration of the plane on which the set $(\tau(t),p(t))$ is a «maximum» relative to the criterion. This computation can be done as following: the maximum local shear at any time t is given by

$$\tau(t) = Tresca(\sigma(t)) = \underset{I,J}{Max}\left|\sigma_I(t) - \sigma_J(t)\right|$$

3 FATIGUE ASSESSMENT OF WELDED STRUCTURES

3.1 A structural approach

The classical introduction of the design stress is based on the extrapolation of far field stresses with unclear rules. In order to clarify the description of this design stress we propose an approach deriving from an analogy with the concepts which are at the origin of the Fracture Mechanics. Actually, it is known that the mechanical state in the highly damaged crack tip zone, called the process zone, is inaccessible by the usual mechanics of solids. In this zone, the material is neither really continuous nor homogeneous and the local strains are not small.

Nevertheless, the stress solution obtained from linear homogeneous and isotropic elasticity in small strains allows the correct description of the mechanical state outside the process zone. Although it is erroneous at the vicinity of the crack tip, it makes sense in terms of an asymptotic solution which allows the correct control and the interpretation of the phenomena produced in the process zone. Likewise, we will look for a way to build the asymptotic solution which allows the correct control and interpretation of the phenomena produced in the critical zone of the weld. For that purpose we adopt an approach *which combines testing and calculations* with meshing rules taking into account the local rigidity due to the weld instead of the local geometry of the weld itself (as it is the case in Fracture Mechanics, where the actual geometry of the crack tip is not taken into account) which is a very hazardous data. Therefore, the fatigue design can be based on a structural stress calculation from a finite element analysis. On this basis we can establish design rules for welded structures [5, 7] with a structural approach and a unique S-N curve where S is a local equivalent stress defined from τ and p at the Hot Spot.

3.2 Computing procedure and applications

Some computational methods applicable to the prediction of fatigue strength have been proposed by different researchers [1, 6]. In the automotive industry, J.L. Fayard et al. [5] developed with PSA Peugeot Citroen an efficient numerical tool to evaluate the asymptotic mechanical field which defines precisely the design stress state and allows the prediction of the fatigue strength of continuous arc-welded structures

The failure criterion N has been defined very carefully in order to be transposable to any situation, being independent of the geometry of the structure and of the loading mode. More precisely, the critical crack size is defined as the size from which the crack leaves the influence of the local effects, which are at the origin of crack nucleation. This size is characterized by a significant increase in the crack growth rate. It was observed that the crack critical size for the tested specimens corresponds roughly to a crack depth of 0.5e (e is the thickness of the sheet) and to a 30% decrease of the signal of a strain gauge situated in the vicinity of the hot spot.

Concerning the calculations, in order to take into account the multiaxiality of the stress, the parameter τ_0 derived from Dang Van's proposal was used. In this case, one obtains the following relationship at 10^6 cycles for steels:

$$\tau_0 = \tau + 0.33.p$$

as shown in Fig. 2. Each point of the figure represents the mean value of the fatigue strength at 10^6 cycles. Figure 3 shows the τ_0-N design curve obtained from more than 200 fatigue tests on elementary structures with different geometry, different materials and different loading modes inducing the multiaxial state at the hot spots. This unique fatigue design curve is limited in its upper part by the plastic yield limit of the material.

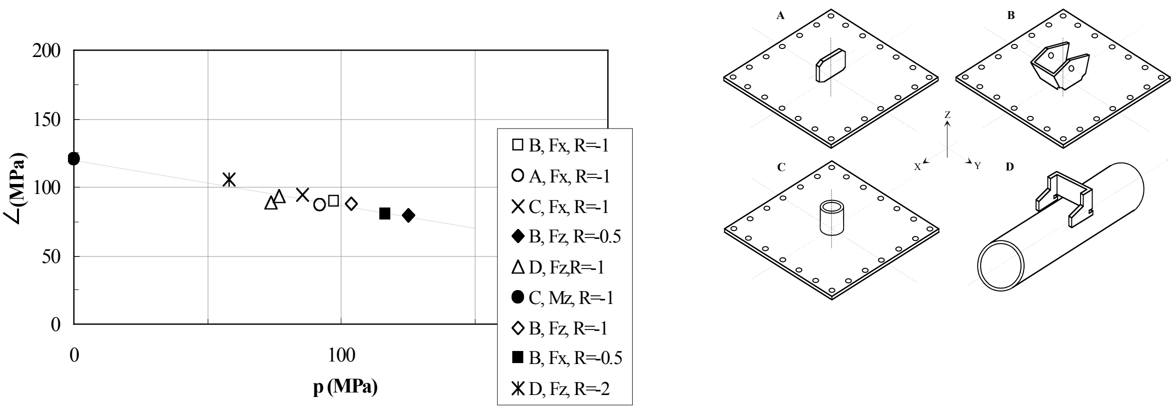

Fig. 2. Mean fatigue strength at 10^6 cycles obtained on elementary arc-welded structures.

Applicability of local strength approaches for the fatigue assessment of welded vehicle components

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Abstract

Within the scope of the research results presented here, the applicability of the structural and notch stress approach is under examination on the basis of different arc welded and dynamically loaded steel structures, taken from the automotive and railway sector. For thin-walled steel structures the fatigue strength of weld seams is in many cases essential for the overall component strength, because the welded joints often turn out to be the weak spots of structures under dynamic loading with constant or variable amplitudes. The assessment of fatigue life allows, in an early point of design, a dimensioning of components appropriate for the expected working loads. Therefore well-defined and in terms of their prediction accuracy reviewed strength concepts are necessary.

The results presented here are developed in the context of the research cluster "applicability of fatigue design concepts for dynamic loaded weld structures", which is promoted by the AiF over the DVS. The applicability of the structural and notch stress approach on the basis of different arc welded steel structures is under examination. In detail these are a transverse control arm and a crossbeam connection from the underframe of a railcar body. Concerning the underframe of the car body, the crossbeam connections are the critical areas. The construction is build of u-profiles with different cross-sections and different sheet thicknesses. This leads within the region of the weld joints to an increase of stress. The construction steel S355J2G3 (1.0116) in a plate thickness of 3.0 mm and the fine grain cold pressure steel S500MC (1.0984) in a plate thickness of 4.0 mm are used for the investigation. To avoid testing a whole railcar body, different types of components and specimen are designed. The critical area of the crossbeam connection is the master for the different types of specimens and components (fig. 1). All specimens were manufactured by manual MAG-welding by the company ALSTOM LHB (Salzgitter, Germany).

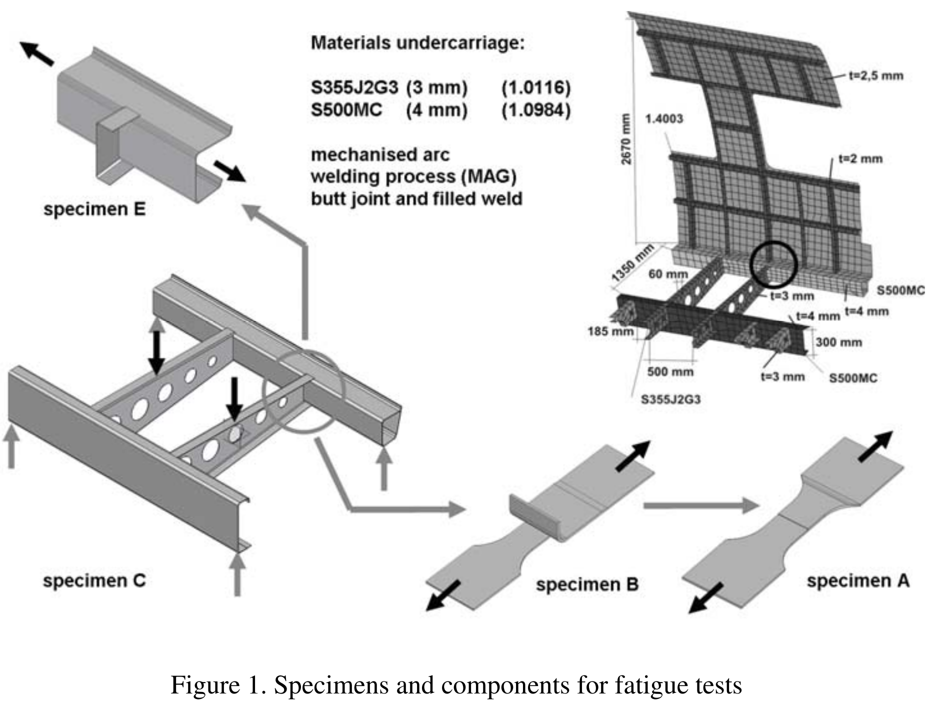

Figure 1. Specimens and components for fatigue tests

In order to determine the fatigue strength behaviour, load-controlled test with constant amplitude and pulsating load (R = 0) were carried out with the different specimen. For each specimen the tests were carried out with a frequency of f = 30 Hz at room temperature in air. With the help of strain gauges, the technical incipient cracks were determined. The end of the test is defined by the fracture of the specimen or by 10^7.numbers of cycles. These results are the basis for application and evaluation of the different concepts for the assessment of fatigue life.

During the load-controlled test with constant amplitude and pulsating load (R=0), the signal of three strain gauges were recorded. The strain gauges were located in a distance of 3 mm from the weld seam, witch is equal to the plate thickness in this area of the specimen. The distance between the strain gauges perpendicular to the load direction was 10 mm and the total width of the specimen was 41 mm. The experiment was stopped after a 10 % change in strain amplitude. This investigation showed that, with the help of strain gauges, it is possible to detect the incipient crack, when the strain gauge is located near the fatigue crack.. So the accuracy of this method depends on the geometry between the crack and the strain gauges.
A further possibility to get information about the incipient crack is given by the ultrasonic-burst-phase-thermography. In this research, a short outlook of this method is given.

The numerical determination of the nominal, structural and notch stresses is performed with proper finite-element models. For a local approach, according to the notch stress analysis, a submodelling technique is used. Existing weld seam and specimen tolerances are included by the usage of parametric models. The FE models are compared with the corresponding experiment by means of an optical three dimensional deformation analysis and strain measurements with strain gauges. These solid models were the basis for the determination of nominal stresses and hot-spot stresses. The models include the misalignment of weld edges concerning the different sheet thicknesses, which leads to an increase of load in one region of the weld seam. To calculate the hot-spot stresses, a linear extrapolation with the evaluation points 0.4 t and 1.0 t is chosen. The notch stresses are determined with the help of a submodelling technique.

The test results for the specimens with butt joint and with the combination of butt und fillet joint are shown in the nominal stress system in fig. 2. The misalignment of weld edges leads to an additional bending load. In this examination, a distinction was made between the fatigue life to crack initiation (technical crack depth a = 1.0 mm) and to final rupture. The results permitted an evaluation according to the concept of uniform SN-curve with a appointed knee point at $N_k = 10^7$ cycles for both specimens, a uniform scatter of T_s = 1:1.24 (specimen A) and a uniform scatter of T_s = 1:1.30 (specimen B) and slopes of k = 7 - 8. For $N > N_k$ the slope of k* = 45 is derived by assuming a fatigue strength decrease of 5% per decade. At the knee point, nominal stress amplitudes of $\sigma_{a,n}$ = 71 MPa for the butt joint and $\sigma_{a,n}$ = 72 MPa for the butt and fillet joint are obtained.

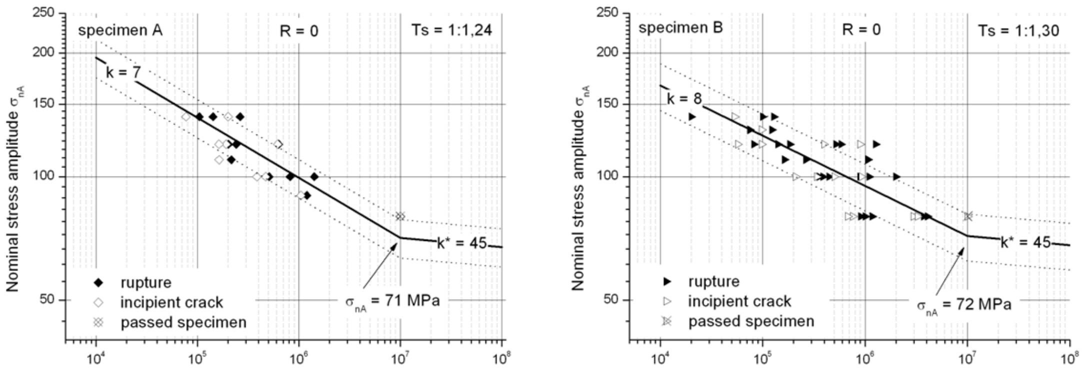

Figure 2. SN-curves of specimen A and B in the nominal stress system under pulsating loading

Biaxial Fatigue of Friction Stir and Laser Beam Welded Stiffened Panels

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Within the framework of the European WelAir (development of short distance WELding concepts for AIRframes) project, cruciform specimens made from both FSW T-joints produced by EADS in Suresnes and LBW T-joints delivered by Alenia were fatigued in the DLR biaxial test rig. To resemble the loading situation of stiffened fuselage structures, proportional loading without any phase shift and different load ratios between the loading components in both directions were applied.

Regardless of the welding process applied, natural crack initiation and subsequent crack growth were governed by the sharp stiffness gradient caused by introducing the stringer. Cracks initiated and propagated at run-in and run-out locations in a direction perpendicular to the weld seam. The shortest fatigue life was observed for uniaxial loading in stringer direction. An additional stress component perpendicular to the joint line reduced deformation in welding direction before crack initiation and diminished crack opening at maximum load after crack initiation both resulting in a higher number of cycles to failure.

Characteristics of a crack propagating from a saw-cut along the weld seam were not markedly deteriorated as compared to crack growth in the base material. However, depending on the load component perpendicular to the joint line, crack growth from the saw-cut competed with the growth of cracks initiated naturally at run-in and run-out locations.

Similar to single stringer panels, increasing the load ratio also increased the number of cycles to failure for FSW stringer-frame structural members, but additionally gives a different location of the fatal crack. When the frame of a stringer-frame panel made exclusively from 2139 was replaced by a high-strength PA765 frame, crack growth behaviour was slightly improved, but did not exceed that of a panel made exclusively from 2024.

Fatigue behaviour of the screwed/riveted joints and the bonded joints

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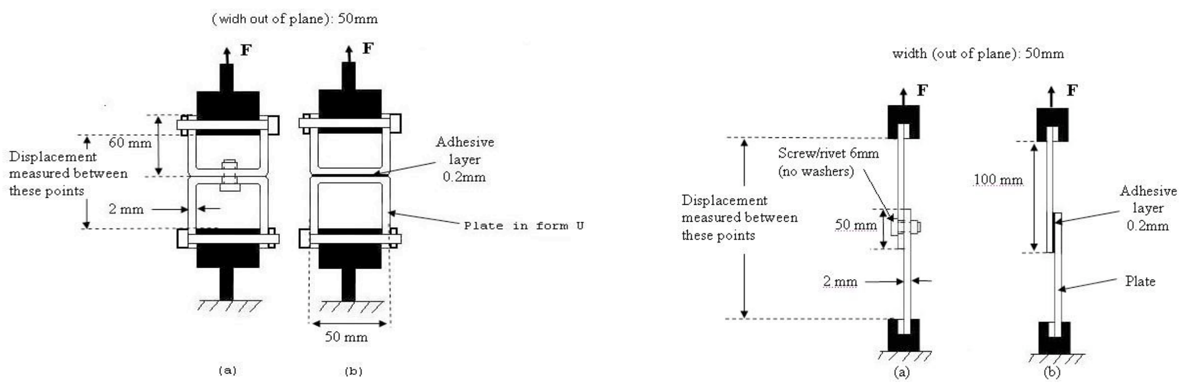
Abstract The origin of this work takes place in the framework of an industrial collaboration in order to study the behaviour of a mechanical connection between two sheets, used in the industry of railway structures. The Technology utilised currently to assemble metal sheets is the assembly by fasteners. The economic interest resides in the reduction of the number of these connections in order to limit the operations of assembly and in the installation of an optimized connection as well in an operational way as calculative.
To strongly reduce the number of the fasteners (screw, rivet) we will introduce bonded joint into the structure, to study and to compare the dynamic behaviours of the joints assembled by fasteners and adhesive, we launched an experimental tests of vibratory fatigue on single lap joint under the traction and the shearing.

In this study we used two configurations to represent the principal behaviours in the railway:

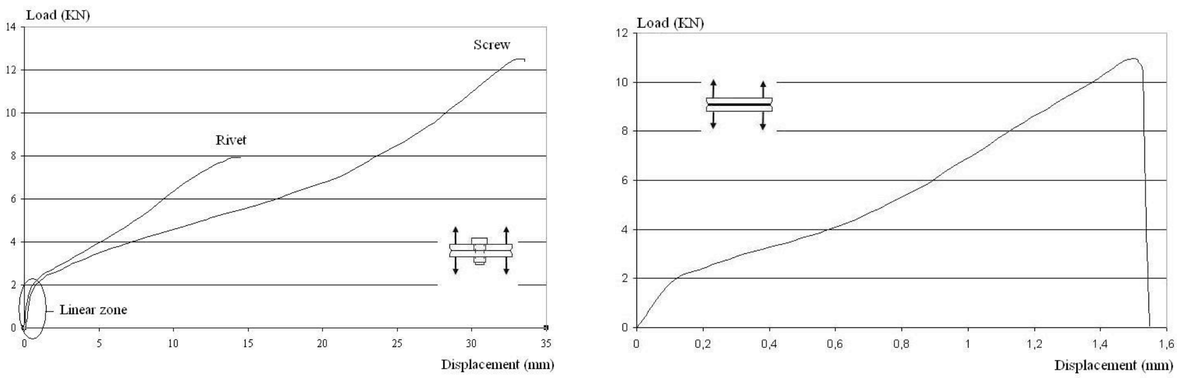
Traction **Shearing**



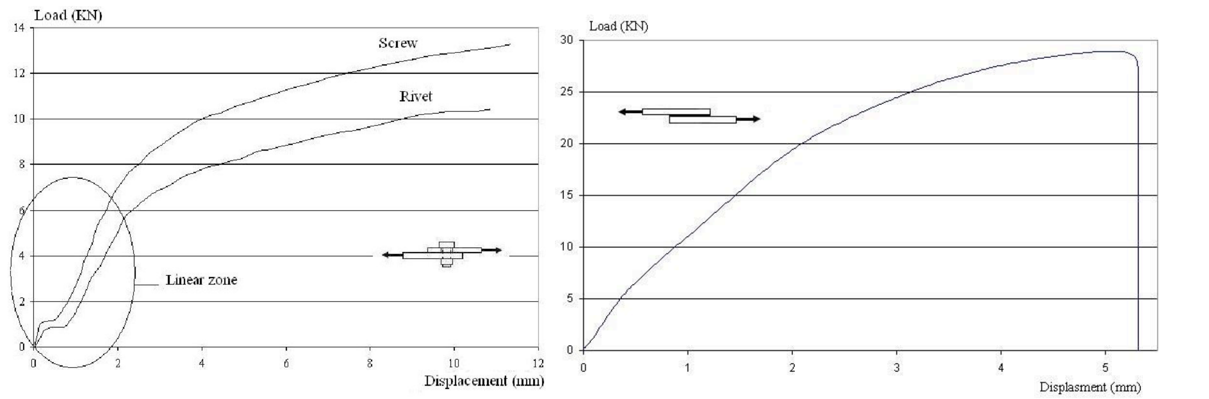
Experimental arrangement for the joint tests (a): screwed or riveted joint, (b): bonded joint.

1 STATIC CHARACTERIZATION OF THE JOINTS

Before beginning the fatigue tests, we carried out tests in static, to identify the behaviours of the joints in traction and shearing.

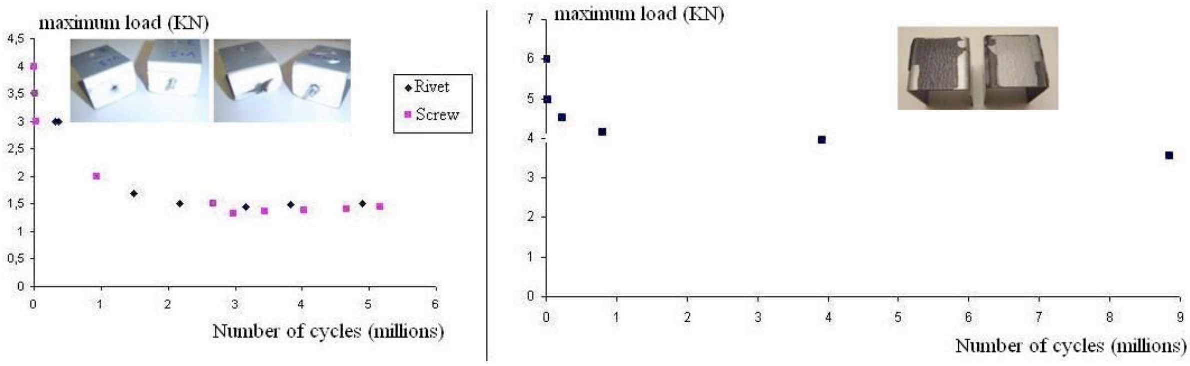


Static tests in traction of the specimens assembled by screw /rivet (a) & by adhesive (b).

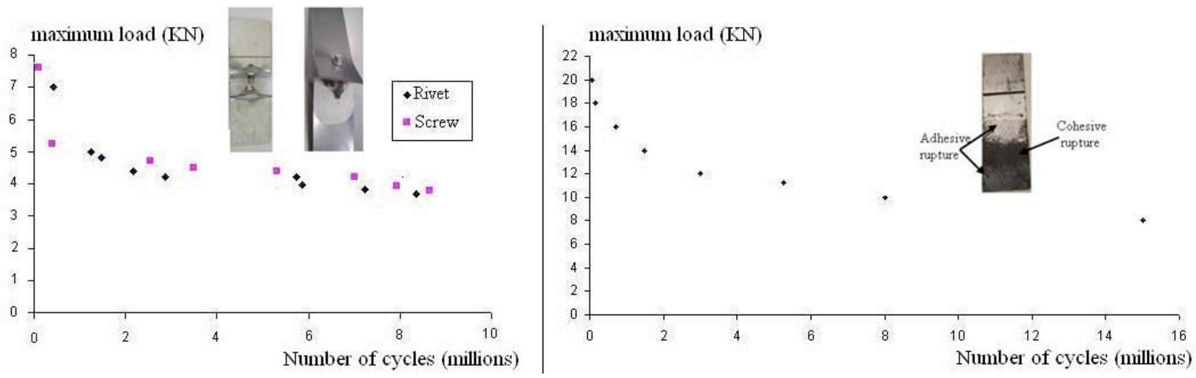


Static tests in shearing of the specimens assembled by: screw /rivet (a),
structural adhesive (b).

2 FATIGUE RESULT



Wöhler's curves in traction, screwed and riveted joints (left) & bonded joint (right)



Wöhler's curves in shearing, screwed and riveted joints (left) & bonded joint (right)

3 CONCLUSIONS

The limits of endurances and the numbers of the cycles, in traction and shearing are more important in bonded joints than in the two other types of joints, so structural gluing can be an alternative solution in the assemblies of the cubicle. This result is obtained with a cyclic loading at ambient temperature and the next stage is to carry out tests according to the temperature.

Influence of welding conditions on the fatigue behaviour of spot welds

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Abstract The influence of continuous or impulse welding current cycle on the fatigue strength of spot welded lap shear specimens is studied. The analysis of the damage mechanism and the fatigue behaviour of the spot welds are based on three experimental investigation techniques. The Potential Drop Method, the fracture surface observation and the metallographic exam contribute to the fatigue damage analysis of tested spot welds. The so called welding range has no influence on the spot weld fatigue resistance. On the contrary the welding cycle pattern and the weld time are the determinant parameters that may strongly improve the spot weld fatigue strength relatively to the welding cycle recommended by the ISO 18278-2:2004 standard. The present study is performed on a dual-phase steel homogeneous assembly.

1 INTRODUCTION

The aim of the present investigation is to show the effect of the welding current pattern on the fatigue resistance of spot welds, and to understand in which way it influences their fatigue strength through the use of accurate observation tools. A potential drop method enables to track the crack, the fracture surface examination gives information on fatigue failure damage mechanism and crack path, and microstructural zones are identified thanks to metallographic exams. Various welding patterns are thus tested. The effect of the current level, the welding cycle and the weld time are investigated and analyzed in this paper.

2 INFLUENCE OF THE WELD CURRENT OVER THE WELDING RANGE

The high strength steel used for this study is the bare cold rolled 600DP grade from ArcelorMittal with a thickness of 1.2 mm.

The mechanical strength is usually performed for Cross-Tension Specimen (CTS) or Tensile-Shear Specimens (TSS). For both loading mode, the mechanical strength is improved with the increasing of the current value. The mechanical strength remains nevertheless constant for splashed point. The general trend is that the nugget diameter, the corona bond diameter and the sheets separation increase with the current level. In terms of notch root shape, the edge is very sharp for a low current level, the greater the RMS current is and the smoother the edge is. However for splashed point, the notch is very sharp because of the expelled metal particle between the faying surfaces.

In order to reduce the scatter and improve the reliability of the results, all the specimens were prepared during the same experimental welding campaign. The TSS are then tested under constant amplitude fatigue loading (maximal loading of 3000 N with a 0.1 load ratio), with a geometry defined by ISO 14234:2003 standard [1] on a servo-hydraulic fatigue machine. All the tests are implemented with PDM measurements. The displacement limit of the actuator is the test end criterion.

The structural stress approach generally predicts some improvement of the fatigue behaviour when the current level increases as the nugget diameter is getting higher simultaneously. The experimental results show that this trend is not verified over the welding range.

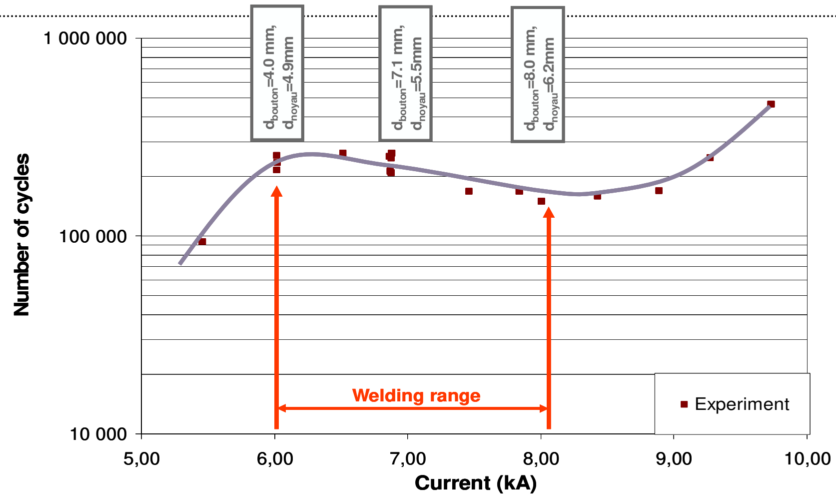

Figure 3. Fatigue life up to complete failure versus current level (maximum load equal to 3000 N and 0.1 load ratio).

3 INFLUENCE OF THE CURRENT PATTERN ON THE FATIGUE BEHAVIOUR

The effect of the current pattern of the welding cycle is investigated in this section. Two kinds of welding cycle patterns are investigated:

- Simple spot welding feature: the current flow passes through the specimens during one sequence with different durations noted Cx where x is the number of period time.
- Pulsation spot welding feature: the current flow is delivered during several sequences separated by hold times. Noted Px where x is the number of pulses.

In order to quantify the improvement in terms of applied load, an equivalent load estimated from the mean lives of each batches is estimated.

The continuous pattern shows a better fatigue behaviour than the multiple impulses one. The hold time is not taken into account here but, as written above, for C42 and C28 welding conditions, the hold time could be stated shorter. As a conclusion, the improvement of fatigue strength is strongly linked to the weld time and to the current pattern. In all cases, this improvement is mainly due to the increase of initiation stage.

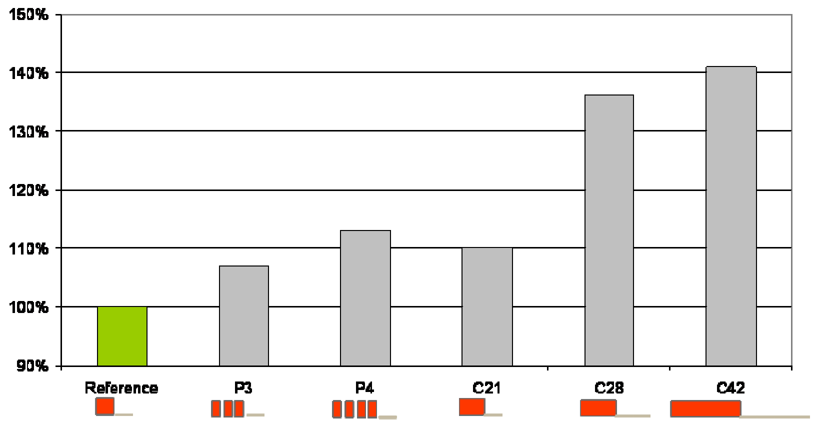

Figure 8. Fatigue resistance improvement on initiation stage in terms of maximum admissible load ratio versus the welding cycle pattern

Integrated fatigue design and manufacturing for welded structures

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ABSTRACT

The primary load-carrying structures for transport vehicles and process equipment are typically complex welded constructions in steel or aluminium. Many Nordic countries have a similar fabrication cultures for welded structures. Production numbers are typically small and competitiveness is attained through innovative product design and high quality production. In order to produce competitive products, the complex demands associated with lead-time, cost-effectiveness, high quality and reduced fuel consumption need to be balanced against those of durability and structural integrity. These demands have led many manufactures to select designs incorporating high strength steels and new approaches to production engineering. Higher nominal operating stresses have increased the sensitivity of advanced structures to fabrication defects and weld geometry variation, i.e., penetration, throat thickness, flank angle and weld toe radius, etc. Improved fatigue strength in traditionally "weak" locations of a structure may simply shift the failure site to the weld root side with little overall improvement in strength. As interest in higher strength materials has increased, the need for integrated research involving high-speed welding processes, cost-effective NDE, and post-weld treatments has become essential. It is increasingly clear that research in manufacturing technology, inspections techniques, fatigue design, etc. can not be performed as separate research fields. Instead, the development of future generations of advanced fabricated structures with reduced weight and higher design stresses will depend on multidisciplinary research efforts. This integrated approach to developing advanced fabricated structures is shown schematically in Fig. 1.

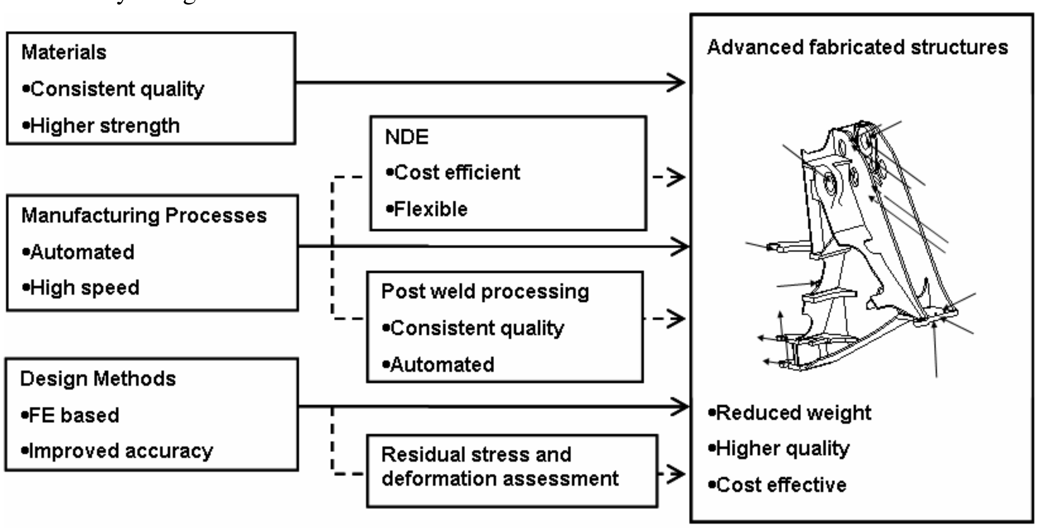

Fig. 1: Integrated research approach to develop advanced fabricated structures.

On the basis of theoretical calculations and comparisons between analytical and experimental results, It has been concluded that local geometrical variations of the weld and weld throat size have only a small effect on the fatigue strength, if the depth of an initial toe crack is deeper than 0.2 mm. As the depth of the initial toe crack increases, the local geometrical effects virtually disappear. The effect of weld angle on the fatigue strength is small when the toe radius is large. For high quality welds, the weld toe radii should be large and the initial crack depth should be very small. If the analytical and experimental fatigue strengths at 2×10^6 cycles (m = 3) are drawn as a function of ρ/T, the corresponding fitted curves are almost identical when an initial semi-elliptical toe crack with depth of 0.05 mm is assumed. Analytical predicted based on fracture mechanics is

$$\Delta\sigma_{mean} = 159.9\left(\frac{\rho}{T}\right)^{0.125} \quad \text{and} \quad \Delta\sigma_{char} = 110.1\left(\frac{\rho}{T}\right)^{0.125} \quad \text{when} \quad \frac{\rho}{T} \geq 0.02$$

A PROPOSAL FOR A NEW WELD CLASS SYSTEM

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Abstract Complex welded structures, such as those in construction equipment, are exposed to tough spectrum loading during their service life. 70-80 % of the main structure are steel structures welded together in highly automated production units. This combination will sooner or later lead to fatigue failures in critical points in the welds. The task for a producer of these vehicles is thus to optimize the design, so that the welds have an adequate quality to withstand the loads during the economic life. The quality systems for welds are described in so called 'weld class systems', such as ISO 5817, where acceptance limits are given for different quality levels. The problem with these systems is an inheritance from old rules and nominal stress based methods, when designers used hand formulas in design, and can be described as being inconsistent, subjective and not well connected to fatigue life. A proposal for a new weld class system, where these problems are removed, is described in this paper. Here three quality levels for fatigue are suggested, where 'as welded' conditions have two levels and post treated welds have one. It contains acceptance limits which are consistent with the expected fatigue life and which can handle revision situations in a more objective way. Furthermore, they can handle not only nominal stress based methods, but also local based ones, such as the effective notch method. The purpose with this new proposal for a weld class system is that it should be able to strengthen the process for welds in a company from the drawing and analysis to the production and final control.

INTRODUCTION

The purpose of having a weld class system, as ISO 5817, ref [10] or Volvo's STD 5605, ref [9], is to define rules for the quality of the welds. The current rules, however, are not well reflecting the fatigue life of the weld geometry. Investigations made, ref [1], indicate that some defects or error types are very important, while others are not. This implies that for a certain quality level the fatigue life can vary one or two magnitudes depending on what kind of error is present. Also, if the quality level is raised, say from D to C in a weld, one can not be certain that the fatigue life will be increased. Another example is the so called "even transition" condition, an important demand often used in the weld class system. This term expresses a requirement of the transition area between the weld toe and the plate surface. The problem is that the control is made visually by the eye and is thus a very subjective method. Here is a clear need of a more objective measure obvious.

Another close related problem is the design of the weld root. The weld classes are within Volvo's system related to the stress levels through a so called Kx-factor (equivalent to FAT-values) and this relation only concerns the toe side of the weld since nominal stresses are being used. This view has the drawback that the root side is neglected and not taken into account. Most of the failures in the supporting structures during the last decades concern the root side of welds and one reason is this described problem. One has to bear in mind that the only important measure for the root side is the size of the root defect that may be present if full penetration is not at hand.

DISCUSSION

The current weld classes, as stated in the international ISO 5817 or in Volvo's STD 5605, have been shown to have a weak relation to fatigue. This is unsatisfactory and leads to a difficult situation especially when the design processes of today drive towards higher performance and optimized geometries. If the process from drawing, analysis, production and control of the welds lack a stable platform (the weld classes) then there is a risk of failures. Especially the use of high strength steel in welded structures, that require high quality welds, will be suffering from weaknesses in the current weld classification systems.

The new weld classes define three levels of quality, two as welded and one post treated. Apart from these three there is also one class for static cases, since the demands on these differs considerably. Some principles have been set before the definition of the acceptance limits were made. First of all, error types in one weld class level should have the same life and second, a shift from one weld class level to a higher, should reflect either twice the fatigue life or an increase of 25% in allowed stress level. Apart from these principles, only error types important for fatigue life are defined in the different classes, other types of errors have the same limits for all classes.

Most important points regarding the fatigue in welds are the toe area and the root area. The new weld class system, as described above, has divided these two points and they are thus treated quite separately. The root side, if not fully penetrated, may serve as starting defect, the greater defect the shorter life. Designing against fatigue is thus depending on the needed penetration. This means that the root side should not be a part of the weld class system at all. Instead, the best way is to define the root side as a measure on the drawing and support the value through analysis. The toe side on the other hand has most of the fatigue failures from the transition area between the weld and the plate. Here the local geometry is the most important factor, especially in form of a too small radius or other defects. This is therefore the main purpose of the new weld class system: define acceptance limits for radius, cold laps and undercuts in order get a fatigue life well related to the expected life. Error types inside the material such as pores etc are also treated in the weld class system since they may serve as starting point for fatigue failures.

CONCLUSIONS

In conclusion the following can be stated about current weld class systems:

- the relation between acceptance limits and fatigue life is weak
- within one class (quality level) some error types have a short life and some a long life
- some error types show no influence on the fatigue life
- the 'even transition' condition is subjective and cannot be measured
-

A new weld class system has been proposed since the current ones are not well reflecting fatigue life phenomena. The new system has three quality levels VD and VC for 'as welded' condition and VB for 'post treated' welds and is built according to the following principles:

- weld classes governs the toe side and invisible defects (like inner pores)
- the root side is governed by measures on the drawing is *not* a part of the weld classes
- only error types important for fatigue loads are described
- different error types within one class (one quality level) have the same fatigue life
- if the weld class is increased one step, twice the fatigue life or 25% higher stress can be expected
- static loaded welds have one class itself (VS)
- the old 'even transition' is replaced by demands on the toe radius

The system is proposed to be Volvo's new standard and will be remitted by the end of year 2007.

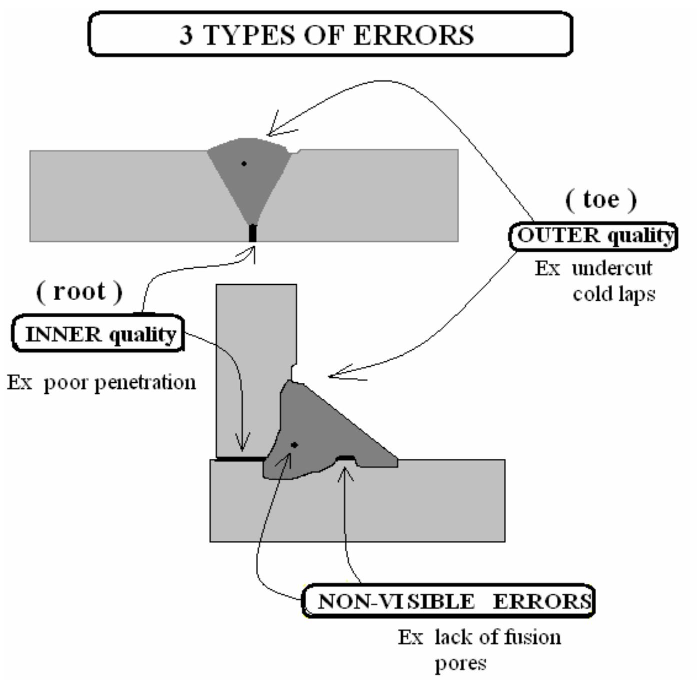

Figure 1 Three different categories of errors. Outer quality and non visible errors are treated in the new weld class system, inner quality is not.

Refined Modeling of the Entire Fatigue Process for High Quality Welds in Steel

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Abstract A Two Phase Model (TPM) for the fatigue process in welded joints is developed and calibrated. The number of cycles to crack initiation is modeled by a local strain approach using the Coffin Manson equation, whereas the propagation phase is modeled by fracture mechanics adopting the simple version of the Paris law. The model is calibrated to fit the crack initiation data for a fillet welded test series subjected to axial loading with a constant stress range of 150 MPa, and the fatigue life data for similar test series subjected to stress ranges below 105 MPa. To make the model fit all test data it is crucial to select a sufficiently low transition crack depth between the initiation phase and the propagation phase. A transition crack depth of 0.1 mm was determined. Furthermore, the material parameters in the Coffin Manson equation were determined directly from the early cracking in the weld toe for full-scale welds and not from test carried out with small-scale smooth specimens. This is essential if the model is to account for the actual surface condition at the weld toe. The model is capable of taking into account the effect of the global geometry of the joint, the local weld toe geometry, applied stress ratio and the residual stress condition. S-N curves are obtained and the practical consequences of the predictions made by the TPM with respect to allowable service stresses and inspection strategies are discussed.

1 INTRODUCTION

Fatigue durability is of major concern in dynamically loaded welded structures. Fatigue life estimates are usually carried out by the S-N method, whereas crack behaviour is described by a fracture mechanics approach. However, the fatigue behaviour of welded joints subjected to typical in-service stress levels is far more complex than conventional bi-linear S-N curves and pure fracture mechanics models predict. These models are based on tests carried out in accelerated laboratory conditions. When the stress range approaches the fatigue limit, the crack initiation period becomes a very important part of fatigue life. Based on this fact a Two Phase Model (TPM) for the fatigue process is developed and calibrated. The model includes both the crack initiation and crack propagation phase. The physical model is suggested as complementary tool to statistical based S-N curves. These curves are only valid for a given joint geometry and loading conditions. It is dangerous to extrapolate them outside the range of the data. The large amount of data pertain to accelerated laboratory condition whereas in service stresses usually are close to the fatigue limit stress region where very few tests actually are carried out. At this stress regime a reliable physical model is useful both for fatigue life predictions and to determine the damage process. The latter gives necessary information for scheduled inspection planning; we must know what crack sizes to look for at various time stages. The S-N curves which do not work with the notion of a crack cannot be of any help on this matter. Furthermore, the present model gives physical insight that statistical S-N method methods do not provide. The practical consequences of the model when it comes to design and inspection planning are illustrated and discussed.

2 MODELLING THE FATIGUE PROCESS

It is assumed that the total fatigue life consists of two major phases:

$$N=N_i + N_p \tag{1}$$

The predictions for the number of cycles to crack initiation, N_i, are based on the Coffin- Manson equation with Morrow's mean stress correction

$$\frac{\Delta\varepsilon}{2} = \frac{\left(\sigma'_f - \sigma_m\right)}{E} \left(2\,N_i\right)^b + \varepsilon'_f \left(2\,N_i\right)^c \tag{2}$$

where $\Delta\varepsilon$ is the local strain range and σ_m is the local mean stress at the weld toe. The parameters b and c are the fatigue strength and ductility exponents, and σ'_f and ε'_f are the fatigue strength and ductility coefficients respectively. When applying the equation it is crucial to determine correctly:

- Local toe geometry and stress concentration factor
- The transition depth
- The parameters in Coffin-Manson law

The propagation phase is modeled by linear elastic fracture mechanics adopting the simple version of the Paris law:

$$N_p = \frac{1}{C}\int_{a_0}^{a_c} \frac{da}{\left(\Delta S\,\sqrt{\pi\, a}\; F(a)\right)^m} \qquad (3)$$

where a_0 is the initial crack depth, a_c is the critical crack depth, whereas ΔS is the nominal stress range. C and m can be regarded as material parameters. This type of modeling has matured into the application stage and guidance on the choice of model and parameters is given in the literature. Hence, description of this model is not emphasized in the present article.

3 CONSTRUCTING S-N CURVES WITH THE TPM

The TPM was used to construct S-N curves and the results are compared with test results and the bi-linear curve found in the building code, see figure 1.

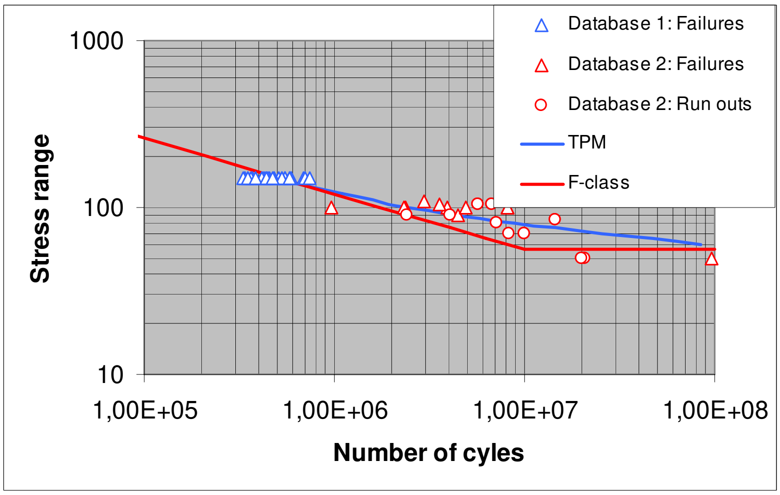

Figure 1. Constructed median S-N curve together with life data and the F-class curve

As can be seen, we have constructed an *S-N* curve which is nonlinear for a log-log scale and that predicts substantially longer lives at stress ranges below 100 MPa than does the F-class linear curve. Furthermore, at these long fatigue lives (more than 5×10^6 cycles) the initiation life is at least 70% of the entire fatigue life. Another conspicuous difference between the F-class curve and the TPM curve is that the latter does not results in a fatigue limit. The obtained curve continues to decrease with a more and more shallow slope. As can be seen the curve obtained from the TPM model is more in accordance with the fatigue life data close to the knee point of the F-class curve. It is obvious that the conventional bi-linear F-N curve does not fit the experimental facts in this stress region. The TPM curve fits the F-class at high and low stress levels, but not in the range just above the fatigue-limit defined by the F-class curve. The conclusion is that the fatigue behaviour of high quality welded joints in steel is far more complex than conventional bi-linear S-N curves and pure fracture mechanics model predict. At typically low in-service stress ranges the crack initiation period, defined as time to reach a crack depth of 0.1 mm, represents the dominating part of the fatigue life.We demonstrate by a simple examples the practical consequences of these results with respect to predicting fatigue life for selecting dimensions of a joint and with respect to crack growth evolution for in-service inspection planning.

Conception en fatigue d'une liaison soudée tube-sur-plaque sous chargement sismique

Fatigue design of a tube-on-plate welded joint under seismic loading

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The competitiveness of the companies is a subject with mutiple parameters, whose essential parameter relates to the optimization of the products put on the market. This dimension, which is defined in terms of acceptable risk, is critical. Indeed, in design to control the lifespan of an element without over sizing it, requests a thorough knowledge of the calculation methods.
From the study of a concrete case drawn from a real case, the paper presents how computation results by finite elements, treated in a probalistic approach of the method of Neuber or of the structural stress method, make it possible to approach the optimization sought.
Written for the design office, this paper shows the efforts of the profession of hoisting appliances and its technical center,Cetim, to progress in the knowledge of the means making it possible to combine cost reduction and risk control.

Competitiveness of a company is determined by its capacity to optimize the products which are offered to the market.
In mechanics, the concern is to adjust the life time of an elasto-plastic mechanism or structure component, to the bare essential of the envisaged mission and accepted failure risk.

The optimization of a component requires a method and reliable and precise tools to define the forecasted resistance. The use of a finite elements method constitutes a decisive stage, because it provides precise knowledge of stress in all the points of the calculated part.

When we deal with sufficient loadings to generate incursion into the plastic range, with a low number of cycles, then the difficulty of the choice of a calculated FEM stress , arises.
Indeed, the resistance of the part in this respect becomes related to the plastics deformations, and not in reference to the yield stress.

In an elasto-plastic material a local stress exceeding the yield stress, does not impact the dimensioning of the part, if it is only related to a localised area surrounded by an elastic zone. The existing local plastic flow creates a new distribution of the elastic stresses in the affected zone, without consequence on the global resistance of the component.

Calculation by finite elements, because it takes into account the stress concentration in the calculated part, means that this situation is constantly present. It constitutes a difficulty when taking into consideration codes and standards of many professions, which remain dependent on traditional calculations in nominal stress of strength of material and with the yield stress as a reference criterion.

To prohibit going beyond yield stress to stress calculated by finite elements is thus not suitable , if it concerns an elasto-plastic material such as structural steel.

In this article, intended for the design office, we propose to avoid this dead end by using two different methods:

1) Elastoplastic local approach of Neuber, where it makes it possible to specify the moment of the start of an oligocyclic plastic crack.
2) The structural stress method, where it is particularly well adapted to the exploitation of computation results by finite elements and where it is qualified in experiments starting from a thousand cycles.

These two steps are successively implemented within the framework of a probabilistic dimensioning allowing the design decisions to be optimized, according to a quantification of the risk and evaluation of uncertainties on the requests applied and the resistance of the part.

On the basis of a theoretical case drawn from a real case, the article describes a tube-on-plate welded joint. This connection constitutes the base of a gantry of a lifting appliance. This machine is subjected to a seismic action causing, during roughly ten cycles, strong intensity loadings, with local plasticity of the connection.

Finally, the engineer simulates by calculation of the future behaviors of the machines which he builds, starting from more or less relevant models, according to the means he has and of his knowledge of the physical phenomena.

The finite element method gives him a precise knowledge of the local stresses at each point of the component studied.
It is inappropriate to compare these stresses with the yield stress of material,

- insofar as they can be definitely higher, while decreasing quickly by elastic or plastic shakedown and when one moves away from the concentrator which caused them,
- whereas this stress concentration does not have an influence on the total resistance of the part, when it is subjected to a static loading.

When the point checked is subjected to a cyclic loading, two different methods, presented and applied in the paper, make it possible to envisage the fatigue failure:

- the elastoplastic local Neuber approach,
- the structural stress method.

Their exploitation, within the framework of the stress-resistance method and probabilistic design, determines for the companies a significant step towards optimization, as soon as the engineer is able to answer these questions:

- which degree of certainty is to be associated to the loading applied and thus which loading limitation devices are to be provided on the machine ?
- which degree of certainty is to be associated to the manufactured part and thus which particular quality provisions should be applied to it ?
- Which risk objective should be accepted in the design context, considering ISO 2394[6] ?

Such steps are likely clearly put the company in an objective position of referee between technical choices, an accepted risk and economic optimization.

They should constitute a line of thought for the establishment of design standards.

Fatigue life prediction of the automotive exhaust system under RLDA

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More than ever, there is a need to optimize the mass of exhaust systems due to increasing cost of raw materials and fuel coupled with ever stringent environmental regulations. In order to meet the cost, performance and timing requirements, it is necessary to have a fatigue approach which leverages prediction tools, testing equipment and previous & current road load measurements during various phases of product development. The purpose of this paper is to present the fatigue approach used in Faurecia. This approach takes into account the multiaxial and random aspect of exhaust system loading. The loading data is typically leveraged from a vast "living" database during early design phase. An example of the application of this approach on a muffler is described. First the load measurement on test track called RLDA (Road Load Data Acquisition) is presented, followed by the approach used in design and validation of the exhaust system. Typically, early in the design phase, FE modelling of the component followed by fatigue post processing to estimate the safety factor (with respect to the material fatigue limit) is performed. Later during development, as more testing data becomes available, an approach which combines prediction and testing is used. Validation usually involves fatigue testing performed on representative prototypes and establishing the factor of safety of each component, typically followed by full exhaust system rig testing.

Spectrum fatigue of high strength steel joints welded with low temperature transformation consumables

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Keywords: Residual stress, stress relaxation, welded joints, fatigue testing, weld filler, LTT, high strength steel.

Abstract

In the present paper constant (CA) and variable amplitude (VA) fatigue testing have been carried out on out-of plane gusset fillet welded high strength steel joints. The joints were welded with conventional weld filler material and martensitic low transformation temperature weld filler, LTT, in order to study the influence of the residual stress on the fatigue strength. Residual stress measurements were carried out close to the weld toe using X-ray diffraction technique in order to study the relaxation due to VA fatigue. The residual stress showed different level of relaxation depending on the VA spectrum loading used. The LTT joints shows ~40% increase in mean fatigue strength compared to the conventional joints in CA. The LTT joints shows ~12% increase in mean fatigue strength compared to the conventional joints. The LTT joints shows 33% increase in mean fatigue strength in CA compared to VA testing. However, the improvement of the fatigue strength is less significant in variable amplitude testing mainly due to the relaxation of the compressive residual stresses.

Welded structures contain residual stresses due to thermal shrinkage of the weld metal and HAZ in the welding cooling process. The residual stresses are static imposed on the cyclic stresses during fatigue loading. The fatigue resistance of the welded structure is affected by this stress ratio effect [1]. Residual stresses are often tensile at the weld toe region, in the magnitude of the base materials yield strength and reduce the fatigue strength of the welded structure. However, compressive residual stresses have beneficial effects on the fatigue strength since they keep the crack closed during the fatigue loading. An available technique for inducing compressive residual stresses in welds is by utilizing Low Transformation Temperature (LTT) weld filler material. The LTT weld filler exploit the transformation expansion due to austenite to martensite transformation at low temperature (approximately 200˚C down to ambient temperature) [2]. This is achieved by alloying elements e.g. high Cr and Ni content [3]. Figure 1 illustrates the difference between conventional and LTT weld filler material in residual stress and strain during cooling. For the conventional weld filler shrinkage is dominating and a small expansion occurs at 500˚C due to transformation from austenite to martensite, and tensile residual stresses are formed at ambient temperature. For the LTT weld filler expansion is dominated due to transformation at low temperature, 200˚C which continues down to ambient temperature. This low temperature expansion will introduce compressive residual stresses in the weld material and in the vicinity of the weld, i.e. at the weld toe were fatigue crack is likely to start. Many researchers [1-8] have reported the beneficial effects of using LTT weld filler particularly on the fatigue strength improvement.

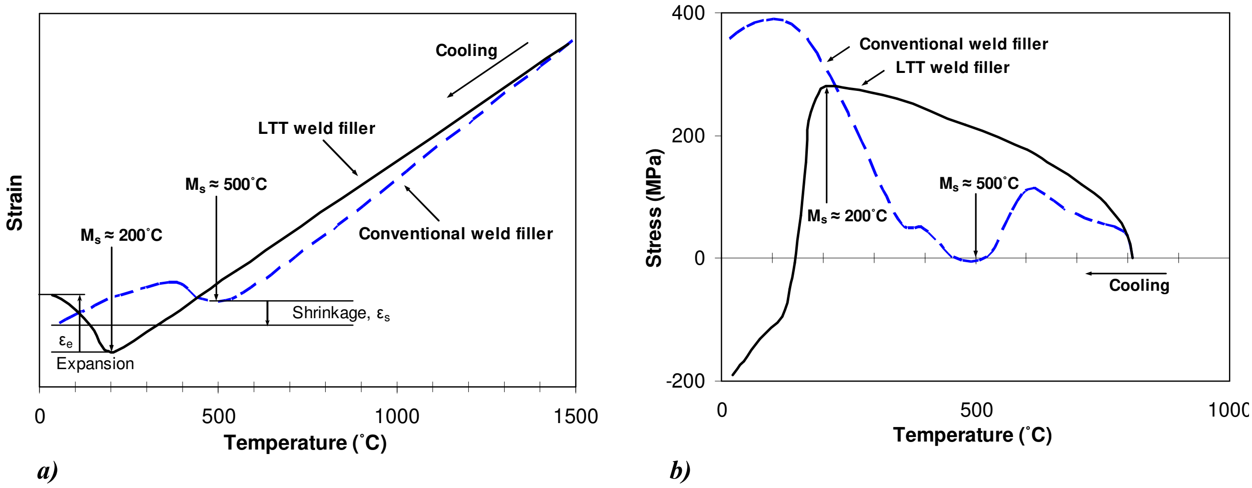

Figure 1. *Variation of strain and stress of weld metal during cooling process: a) strain, b) stress. After [8].*

However, the mainly fatigue strength improvement have been concerned with constant amplitude fatigue loading. Since the residual stress relaxation is smaller in constant amplitude (CA) loading, especially at higher cycles, the fatigue strength improvement is significant for joints welded with LTT consumables. In Eckerlid et al [3] CA fatigue testing was carried out on out-of plane gusset fillet welded joints. The achieved improvement of the mean fatigue strength was 25-90% at 2 million cycles for the LTT joints compared with joints welded with conventional weld filler. In Machida et al [6] CA fatigue testing was carried out on box welds failing from the weld toe. They compared joints welded with LTT versus conventional weld filler. The achieved improvement in fatigue strength was 12% at two million cycles.

In the present study, variable amplitude as well as constant amplitude loading is applied on out-of-plane gusset welded joints welded with LTT filler material. Joints with the same geometry welded with a conventional under-matching filler material are used as reference test series. Residual stresses at the weld toe are measured prior and after fatigue testing at different cycles in order to study the residual stress relaxation.

Fatigue design concepts for welds improved by high frequency hammer peening methods

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Research has been initiated on the effects of high frequency peening methods on the fatigue strength of welded connections. The investigated methods combine an improvement of weld toe profile with an initiation of compressive residual stresses and surface hardening. The results of two different procedures, High Frequency Impact Treatment (HiFIT) and Ultrasonic Impact Treatemnt (UIT) are compared. Laser measurements of the weld seam prove that these methods increase the overall weld toe radii.

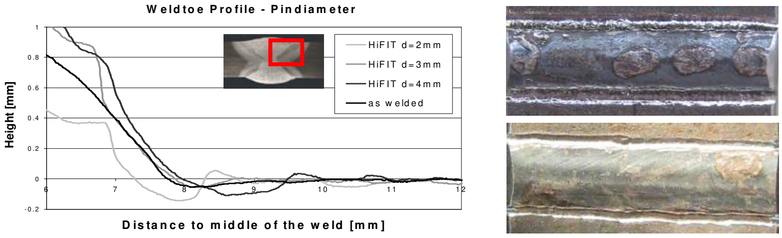

Figure 1. Weld toe profile before and after the treatment with different pin diameters (left), weld toe after UIT(upper right) and HiFIT (lower right)

Further, residual stress measurements verify the introduction of compressive residual stresses at least up to a depth of 1 mm. The values meet the yield strength combined with an increase of the surface hardness. These material mechanical effects cause an increased crack resistance. Applied crack detection methods prove that the material mechanical effects yield to a retarded crack initiation.

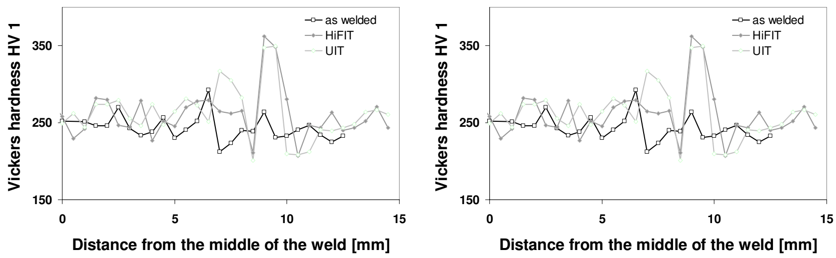

Figure 2 Vickers hardness (left) and residual stress profile (right)

Fatigue tests show that these effects lead to a significant increase of the fatigue strength and reduced slopes of the SN-curves.

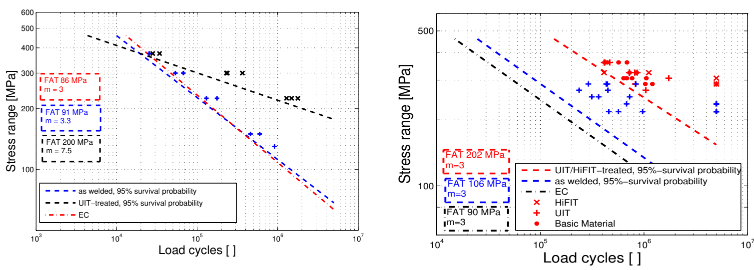

Figure 3. Experimentally derived SN-curves for butt welds S460TM and S690Q

Design methods which consider the positive effects of the improvement methods are developed. Generally the experimentally derived SN-curved can be considered in the nominal stress approach. Based on existing results the IIW recommendations propose improvement factors for improved welds which can be considered for all notch classes. This paper proves that the improvement factors given for common hammer peening are conservative. Secondly, it is shown that the change of the slope of the SN-curves of treated welds has to be considered using simple improvement factors.

Alternatively, local concepts can be adapted to describe the effects of post weld treatments for various details. In this paper a concept based on the notch stress method is presented. The change of the weld toe geometry is respected by simulating the shape of the measured weld toe. The material mechanical effects are also incorporated in the model. For the fatigue strength calculation the effect of the residual stresses is compared to mean stresses, taking into account possible residual stress relaxation under fatigue loading. Based on approaches of the Eurocode and the IIW recommendation the reduced influence of compressive stresses on crack propagation is considered.

As another simple method a local concept is presented, which considers the influence of the hardening and compressive residual stresses by applying reduction factors to the local fatigue strength. The concept has been developed for heat treated material but will be quantified in further fatigue tests for welded details treated by high frequent hammer peening methods. Respecting the residual stresses in the same way as mean stresses it can be seen that this approach is still conservative. The effect of the hardness also has to be considered. Here further experimental investigations have to be carried out in order to quantify the influence factor.

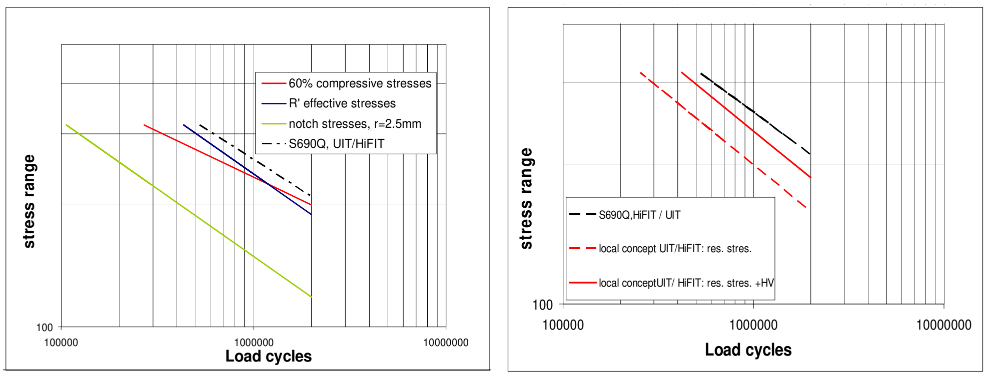

Figure 3. Experimentally derived SN-curves for butt welds S460TM (left) and S690Q (right)

The investigations show that the improvement factors given in the IIW recommendations for hammer peened joints which parallel shift the SN-curves to higher strength lead to conservative results in case the correct slope is considered. The notch stress approach leads to very conservative results in case only the geometric effect is considered. Including the residual stresses and weighting the minor influence of the compressive stresses on the fatigue like the EC and IIW recommendations propose for base material and details with negligible residual stresses lead to very realistic fatigue life estimation in case of adapted slope. A local concept allows considering the influence of the increase of the surface hardness as well as the residual stresses on the fatigue resistance. The influence of the surface hardness has to be analyzed more detailed. The investigations show that a realistic approach for the slope of the defined SN-curves is of major importance for reasonable fatigue life estimation.

Design of Steel Structures with Enhanced Fatigue life – Adoption of Ultrasonic Impact Treatment

Dipl. Ing. P. Gerster, Ing. R. F. A. de Ridder

Abstract

The latest stand in technology shows that fatigue strength of steels used for weld constructions is independent of its yield stress point. This is to be regarded as one of the main reasons for the yet delayed implementation of high strength steels in constructions under dynamic loading. Through the implementation of Post Weld Treatments, industry has a mean to enhance fatigue strength, particularly in these higher strength steels. Ultrasonic Impact Treatment (UIT), a innovative PWT technology, has entered a stage of general acceptance in the industry of maintenance and renewal. With UIT industry has been provided a technology to improve fatigue life [n] with a factor ≤ 8 or to increase the fatigue stress [MPa] with a factor ≤ 2.

The next step is the acknowledgement of UIT in the design and manufacturing of new structures. However due to the fact that applicable Codes & Standards like Eurocode 3 are still under development, UIT has not been generally accepted by the designer of new steel structures. Since 1998, UIT has been tested at many international R&D programmes at universities such as Lehigh, Stuttgart, Hannover and Braunschweig. The results are incorporated in S-N curves with various types of steel (S355, S460, S690), weld details and stress ratios (R). Certifying Authorities have given several Approvals. The available S-N curves offer a designer or engineer the position to choose between designing a weld detail using FAT Class 80 or to design a similar weld detail via UIT and obtaining FAT Class 125. The choice for UIT will offer benefits to the industry by a reduced capital and operational expenditure, due to a reduction in down-time, material savings and enhancement of fatigue life. This paper offers the designer the first basis for acceptance and approval of UIT as Post weld Treatment.

Fatigue assessment of welded joints considering residual stresses due to welding process and post weld treatment

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Abstract For welded joints under dynamic loads the fatigue resistance of the base material and the weld is very important to design steel constructions in fatigue limit state. Residual stresses due to the welding process in most cases reduce the fatigue resistance of welded constructions. But the fatigue strength can be enhanced by methods of post weld treatment. One of them is the Ultrasonic-Impact-Treatment, which introduces beneficial compressive stresses at the weld toe zones and reduces stress concentrations by improving the weld toe profile. The equipment comprises a handheld tool and an electronic control box (Fig. 1). The tool is easy to handle during application. It operates at the head movement with a mechanic frequency of 200 Hz overlain by an ultrasonic frequency of 27000 Hz.

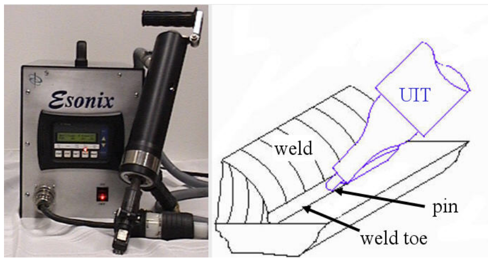

Figure 1. Ultrasonic Impact Treatment (UIT).

Numerical simulations were carried out for seam butt welds using an arc welding process followed by a process of needle peening. The symmetric half model, implemented in ANSYS®, consists of three zones the weld, the heat affected zone and the base material of the steel plate (Fig. 2). The dimensions of the steel plate fabricated from S355 J2G3 are 100 x 100 x 6 mm. Material properties are implemented depending on temperature. The notch at the weld toe has a variable radius to consider the actual weld geometry for as welded and treated conditions. The objective of numerical investigations was to analyse the influence of residual stresses at the fatigue life for welded steel plates with and without post weld treatment.

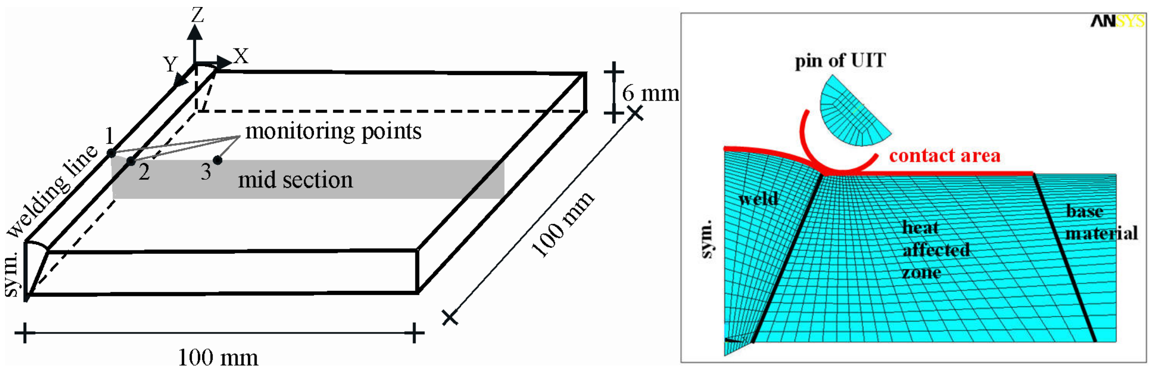

Figure 2. Geometry and FE-model of a steel-plate with a single butt weld.

With this FE-model two main effects are investigated. First the transient field of residual stresses due to welding and post weld treatment and second the change in geometry of weld profile. Both effects have a significant influence for the fatigue life of the welded joints. The simulation of the welding process consists of two of analyses. At first the transient field of temperature is calculated during arc welding process. After the transient thermal analysis the structural analysis is following to estimate the residual stresses. The simulation is carried out up to t = 2000 s to estimate the final residual stress state after the cooling period. In the next step the post weld treatment by UIT is considered using a contact algorithm. For the simulation only the top of the UIT-pin shown in Figure 2 was modelled. The pin is positioned in the mid section with an initial gap to the base plate. After restarting the transient structural analysis the pin moves in an angle of 60° to the weld toe and deformed this surface. Due to the treatment the transverse stress in the treated area changed from tensile residual stresses to compressive residual stresses near the yield stress. Because of the introduced compressive stresses which are one effect of UIT the fatigue strength increases significantly compared to as welded. Furthermore the weld geometry is rounded by the pin and the toe notch radius increases. The residual stress distributions transverse and longitudinal to the weld toe are compared for the as welded and treated conditions in mid section (Fig. 3). It can be noticed that the post weld treatment by UIT has a great influence on the local stress state at the weld toe which is often the position for crack initiation. The numerical results are suitable to estimate the fatigue strength under consideration of the changed residual stress state at the weld toe.

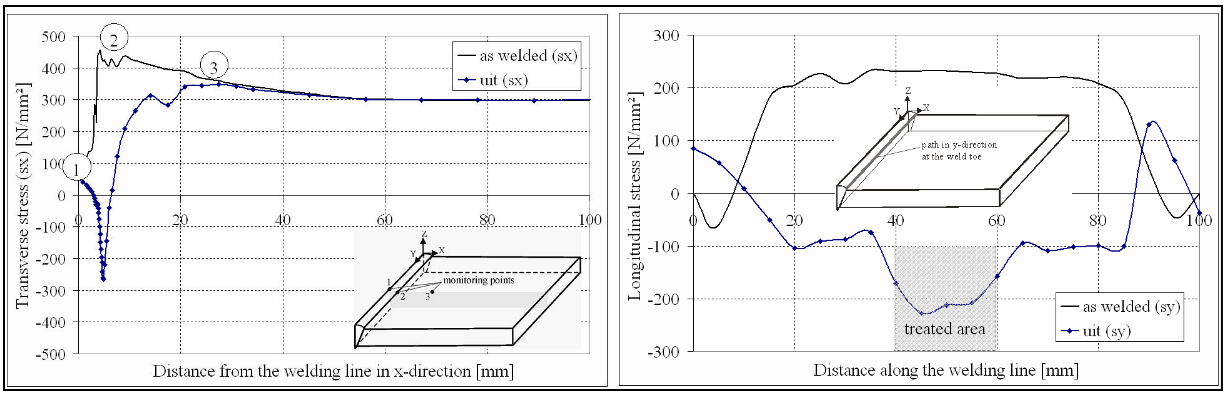

Figure 3. Comparison of residual stresses before (a) and after (b) post weld treatment.

The total fatigue life of such welded joints was estimated as the sum of crack initiation life and crack propagation life. The crack initiation life was calculated with notch strain approach using the version of SEEGER. The S-N curve was determined with the damage parameter P_{SWT} assuming the material properties of the base material. Elastic-plastic behaviour, residual stresses and the different elastic stress concentration factors for both conditions were taken into account. One result of the calculations is the predicted S-N curve for as welded condition which has the lowest fatigue strength because of the tensile residual stresses. In contrast to as welded condition the curve with the treated toe has higher fatigue strength. The post weld treatment introducing compressive stresses in the notch root are highly effective in this case. The analysis indicates that the influence of residual stresses at the weld toe is significant for the crack initiation life. Finally, the results are shown graphically as plots using the tool which is implemented in ANSYS® (Fig. 4). Thereupon it is extended at the consideration of residual stresses according to SEEGER'S attempt of residual stresses in thin surface layers and according to LAWRENCE characterization of residual stresses as mean stress. Besides, for getting adequate results there is a need for fine meshing especially at crack critical sites at the weld transition. That's why these plots can only be used for qualitative declarations and considerations at which locations the number of life cycles are critical and cracks may be initiated.

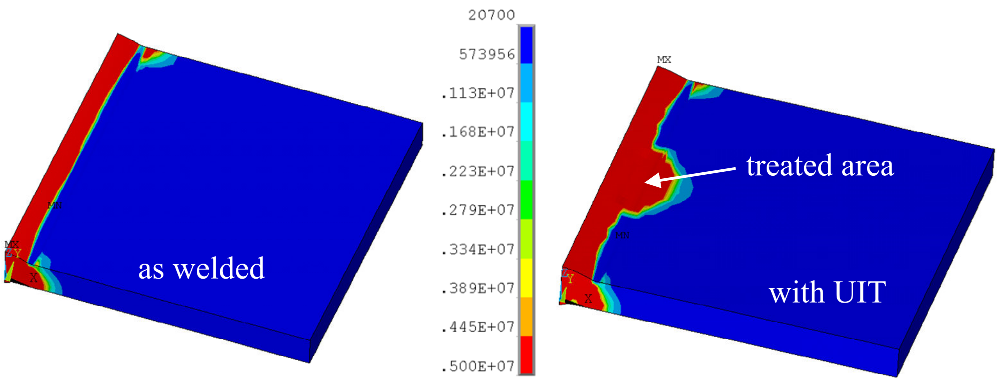

Figure 4. Number of cycles until crack initiation for as welded (a) and treated condition (b).

For the butt-welded plate as expected the critical location for crack initiation is the weld transition (Fig. 4a). Figure 4b shows the weld after treatment with UIT. To evaluate the effect of UIT the region of static pressing of bolt has to be regarded. It has to be mentioned that only the midsection of the weld toe line was treated. For the crack propagation equation after PARIS and FORMAN are chosen. To consider different ratio a/c in crack propagation the stress intensity factor according to NEWMAN has to be taken. That means that the notch effect of weld has to be considered additionally. The notch effect is taken into account about an extension of initial crack length until reinforcement of weld. Finally the total fatigue life was estimated as the sum of crack initiation life calculated with notch strain approach and crack propagation life calculated with crack propagation approach. The positive effect of post weld treatment by UIT can be seen for the fatigue resistance, because the stress level is higher and the slope flattens compared to the as-welded condition.

Notes :

Notes :

Workshop 2

Design procedures against thermal and thermomechanical fatigue damage

Procédures de conception vis-à-vis du dommage par fatigue thermique et thermomécanique

A simplified method to predict thermal fatigue in mixing tees of nuclear reactors

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NRG Petten, The Netherlands

Abstract The phenomenon thermal fatigue is investigated in a mixing tee. The mixing tee configuration is used in nuclear reactors where thermal fatigue is a safety related phenomenon. Turbulent mixing of hot and cold fluid flows causes temperature fluctuations in the pipe wall, which cause stress fluctuations. When the amplitude of these thermal stresses is large enough the wall can suffer from fatigue resulting in cracks in the wall. The influence of local temperature gradients on the pipe wall of the Fatherino model is determined by Computational Fluid Dynamics (CFD). More specifically, Large Eddy Simulation (LES) is used to predict the mixing flow. The results from the CFD calculation are transferred to a finite element code, where the stresses due to the temperature gradients are calculated. The results from the CFD model show fluctuating wall temperatures. The results are presented in a specific style for thermal fatigue namely the temperature differences, and not the absolute temperatures. These temperature differences are the source of the fluctuating stress and fatigue in the pipe wall. This alternative presentation shows that the fatigue stress is caused by moving temperature spots, which are convected by the main flow velocity. In order to simplify the calculation method, the three dimensional model is transferred into a one-dimensional model through several intermediate steps. This approach gives insight into the model simplifications and its influence on the results. It is shown that a one-dimensional simplified model can conservatively predict the fatigue behaviour of a three-dimensional model loaded by a moving temperature spot. For the coupling to the unsteady CFD model, it is shown that the treatment of the interface temperatures is extremely important. This method uses the information of the three-dimensional CFD results in a one-dimensional model and opens a new opportunity to predict thermal fatigue in mixing tees by a simplified method.

Propagation en fatigue d'une fissure semi-elliptique sous chargement thermomécanique à amplitude variable

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Résumé: On explique le faïençage thermique à grand nombre de cycles d'une structure, par l'arrêt dans l'épaisseur de la propagation des fissures. Cet arrêt est lié à la décroissance du facteur d'intensité des contraintes. Des études paramétriques 2D et 3D sont réalisées dans le cas d'un chargement à fréquence et à amplitude constante pour obtenir des informations sur le chargement à partir de la position d'arrêt des fissures. Ceci permet un encadrement de l'amplitude et de la fréquence du chargement.
Afin de généraliser cette analyse au cas des chargements complexes, une méthodologie pour modéliser la propagation d'une fissure semi-elliptique à grand nombre de cycle a été mis œuvre dans le code éléments finis (Code-Aster [1]). Deux techniques sont utilisées, la première repose sur le remaillage automatique de la structure complète, la deuxième sur la méthode XFEM où seul la fissure est redéfini par réactualisation des levels sets après chaque pas de propagation.

THERMAL FATIGUE APPEARS TO BE MORE DAMAGING THAN UNIAXIAL ISOTHERMAL FATIGUE FOR THE AUSTENTIC STAINLESS STEELS

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ABSTRACT: Thermal fatigue sometimes occurs in different types of nuclear reactor components. Present investigation deals with the primary cooling circuits of Pressurized Water Reactors (PWRs). For such components, materials are austenitic stainless steels. To estimate the crack initiation damage, uniaxial fatigue curves are used. They were deduced from strain control or stress control isothermal fatigue tests using normalised specimens.

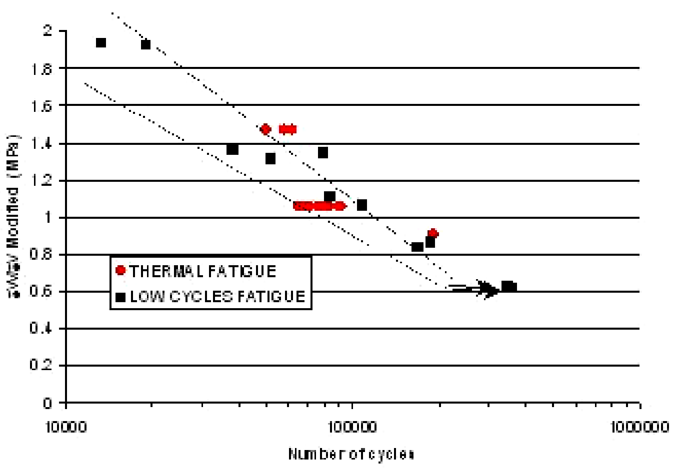
However, for in-service components, thermal loadings induce biaxial mechanical loadings. In that frame, the questioning of an eventual influence of the triaxiality factor on fatigue damage can be asked. To investigate differences between uniaxial fatigue damage and in service biaxial thermal fatigue damage, a campaign has been conducted on a specific thermal fatigue device (SPLASH). The specimen is continuously heated by Joule effect and cyclically cooled by a water spray.

To deduce the thermo-mechanical state of the specimen, two uncoupled computations are performed: a thermal analysis and a mechanical analysis with the previous computed temperature field as a given loading parameter. All the computations have been performed using the object-oriented finite element code cast3M.

All the analysed tests show clearly that initiation under thermal fatigue occurs before initiation under uniaxial isothermal fatigue: thermal fatigue is the most damaging case. Such difference is not due to difference on microscopic mechanisms for that temperature range. It results from a pure mechanical origin: a biaxial state corresponds to an increase of the hydrostatic stress.

In a last part, thermal fatigue experimental results are compared to existing multiaxial fatigue. Criteria based on a stress approach are not adapted, since significant a cyclic plasticity occurs close to the endurance limit even for high number of cycles. Strain and energy criteria are well adapted. In particular, the energetic criterion proposed by the "Ecole Polytechnique – Laboratoire de Mécanique des Solides" gives very well estimations for thermal fatigue initiation. Let us note that such criterion was also based on previous traction torsion tests performed by Itoh [1].

Additional thermal or biaxial mechanical tests are needed to propose a new approach including the multiaxial damaging.



Multiaxial fatigue: Criterion proposed by "Ecole Polytechnique – LMS" Comparison between TF and LCF tests

Experimental investigation on the fatigue life of 304L tubular welded joints

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In the nuclear energy industry, the use of components made of austenitic stainless steel is widely spread, because of its specific thermal properties. The assembly of these pressure vessels and piping by welding processes often requires surface mechanical treatments such as grinding or polishing before or after welding. The objective of these operations is to prepare surfaces for improving their state, because it is known that hardened surfaces and lower roughness ensure better fatigue resistance.

This study aims at having a better knowledge of the high cycle fatigue behaviour of 304L tubular welded structures with different surface finish, at ambient temperature. We focus on the influence of operations such as welding and grinding.

The experiments are performed on AISI 304L austenitic stainless steel half-rings. Some of these specific specimens, closer to the in-service geometry, are base metal rings (which stand as reference), the rest presents a longitudinal and symmetrical Y-weld joint, with or without grinding. By submitting such specimen to high cycle mechanical fatigue (10^6 cycles aimed) we intend to reproduce stress gradient that can be achieved by in service thermal cyclic loading.

This study confirms that presence of weld roots has a detrimental effect on austenitic stainless steel components fatigue damage. Manufacturing operation such as grinding improved the fatigue lifetime results with improving the surface geometry of the specimen. The objective is to compare the results to design curves used to assess nuclear components fatigue life, resulting from low cycle fatigue tests realized on cylindrical specimens.

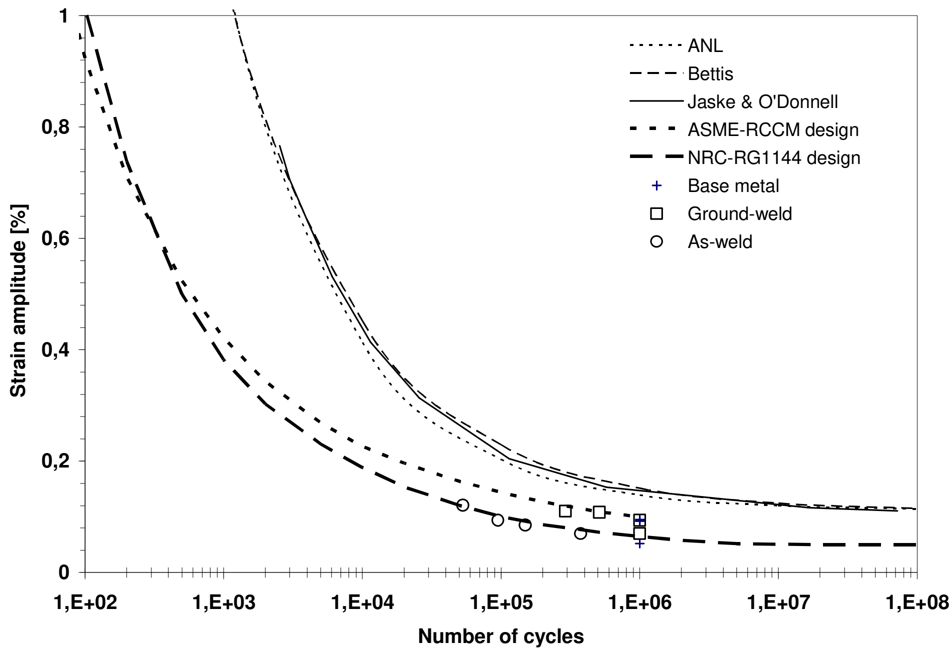

Figure: Comparison of fatigue tests results with S-N curves (R_σ=-1).

Thermal Fatigue of Austenitic Stainless Steel : Influence of Surface Conditions

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Some cases of cracking of 304L austenitic stainless steel components due to thermal fatigue were encountered in particular on the Residual heat removal circuits (RHR) of the pressurized water reactors (PWR). EDF has initiated a R&D program to understand and assess the risks of damage on nuclear plant mixing zones. The INTHERPOL test developed at EDF R&D is designed in order to perform pure thermal fatigue test on tubular specimen under mono-frequential thermal load. These tests are carried out under various loadings, surface finish qualities and welding in order to give an account of these parameters on crack initiation. The main topic of this study is the research of a fatigue criterion using a micro/macro modelling approach. The first part of work deals with material characterization (stainless steel 304L) emphasing the specificities of the surface roughness link with a strong hardening gradient. The first results of the characterization on the surface show a strong work-hardening gradient on a 250 microns layer. This gradient does not evolved after thermal cycling. Micro hardness measurements and TEM observations were intensively used to characterize this gradient. The second part is the macroscopic modelling of INTHERPOL tests in order to determine the components of the stress and strain tensors due to thermal cycling. The third part of work is thus to evaluate the effect of surface roughness and hardening gradient using a calculation on a finer scale. This simulation is based on the variation of dislocation density. A goal for the future is the determination of the fatigue criterion mainly based on polycrystalline modelling. Stocked energy or critical plane being available that allows making a sound choice for the criteria.

Identification of structural design curve using experimental thermal fatigue data

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The behavior of structures (e.g. nuclear power plant components) submitted to thermal fatigue is affected by numerous uncertainties, e.g. the random nature of material parameters, the statistical variability of the loading, the scatter observed in fatigue test data. Thus, it is interesting to introduce a global probabilistic framework as an alternative to current nuclear design codes, in order to assess the fatigue lifetime of a component. This requires to identify the probability density functions of all the random variables involved in the thermal fatigue model, especially the structural random number-of-cycles-to-failure $N^{stru}(S,\omega)$ at a given stress level S.

In order to identify the structural random number-of-cycles-to-failure $N^{stru}(S,\omega)$, the first challenge deals with the estimation of the specimen random number-of-cycles-to-failure $N^{spec}(S,\omega)$, using a statistical treatment of fatigue laboratory data. Several studies have been carried out to fit fatigue laboratory data sets by maximum likelihood estimation methods under different assumptions. On the other hand, fatigue life tests are performed in idealized conditions (e.g ambient temperature, standard specimens) in laboratory. In the existing nuclear design code, two specimens-to-structure passage factors, γ^N and γ^S, are introduced to relate the number-of-cycles-to-failure of actual reactor components starting from those of laboratory test specimens. The factors account for the effects of size, surface finish, and material and geometric singularities such as welds. The literature shows that these factors are not well known, leading to the introduction of random variables.

Experimental results obtained on the INTHERPOL facility are exploited in order to assess a "passage factor", which is a multiplicative factor γ^s to be applied to the stress level S in order to obtain the number-of-cycles-to failure of the mock up structure.

A general probabilistic inverse method is developed that makes use of the polynomial chaos representation of the passage factor random variable. Then the method is applied using 12 experimental points obtained on the INTHERPOL facility. It appears that the passage factor for the mock-up structure under consideration is about 1.26 and has little scatter. Note that these results should be used per se, since the number of INTHERPOL data points is low and the points are grouped in a specific region of the *S*-*N* domain.

As a post-processing, the PDF of the number-of-cycles-to-failure of the mock-up structure is derived. The associated 95%-confidence interval encompasses satisfactorily the INTHERPOL data points. Further application of the method is required when additional mock-up data points involving other experimental conditions (surface finish, shape of welds) are available.

Strain based approach to crack initiation and thermal fatigue of austenitic stainless steels

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Abstract

The fatigue criterion is generally described as a local relationship between criterion function and the number of cycles to failure of the specimen. Mathematical descriptions of such relation provide the basic tool for fatigue assessment. The most of standard lifetime curves for fatigue crack initiation, which are measured on strain-controlled mechanical tests of round polished bars with various diameters in isothermal conditions, are based on the phenomenological Manson-Coffin model and fatigue parameter is represented by amplitude of plastic deformation. It could be noted that original Manson-Coffin equation was derived for uniaxial loading conditions. In the case of local strain-based approach it is assumed, that critical region in the sense of stress-strain and fatigue behavior exists. If the state of stress in the critical region can be approximated by plane stress condition, the fatigue behavior of material can be described by results of a smooth and axially loaded laboratory specimen. In another cases this statement is not so clear, especially when multiaxial state of stress appears. In general multiaxial loading shortens fatigue life in comparison with uniaxial one. Typical example of multiaxial condition is cyclic temperature loading. Thus the possibility of description of components life under high-temperature thermal fatigue conditions based on uniaxial pure mechanical fatigue data has to be examined.

An experimental-numerical study was focused on the effect of the temperature difference of cycling on the life of austenitic stainless steel under high-temperature thermal fatigue conditions. Particularly initiation stage of thermal fatigue cracks in AISI 321 austenitic stainless steel subjected to repeated thermal shocks was investigated. Non-standard experimental set-up was developed in order to rapid crack initiation of tested specimen. Thin flat rotational discs with rather sharp notch in the center of rotation were exposed to temperature cycles in order to establish the number of cycles to crack initiation. The effect of the temperature difference of cycling was studied by varying ΔT from 150°C to 340°C while holding the lower temperature constant at 100°C. The initiation stage is interpreted as specifying the number of cycles required for the formation of an engineering crack 0.5 mm long.

As a result of our investigation of thermal fatigue of AISI 321 austenitic stainless steel we put forward an additional parameter into the Manson-Coffin fatigue law, which is suitable for describing of cyclic damage due to temperature changes together with plastic amplitude. Finally, very good agreement between fatigue life under thermal loading and fatigue life under isothermal uniaxial testing condition was observed.

Car manifold's fatigue life under thermo mechanical loadings

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Many industrial components undergo severe thermo mechanical loadings. Due to their complicated geometry or their important size, they are often made of several components welded together. These weldments are microstructurally and mechanically heterogeneous across the weld joint. Due to these discontinuities, weldments can be potential sites of the fatigue failure, inducing a significant lifetime reduction.

Several authors have investigated weldment's influence on low cycle fatigue lifetime, in isothermal conditions. It has been shown that the fatigue life is influenced on the one hand, by the geometry of the weld : back strip geometry, welding defects. On the other hand, it is also influenced by the interaction of the different cyclic plastic behaviour of the materials which compose the weldment. In particular, strain distribution in the weldment plays a key role in low cycle fatigue. If the present materials have close fatigue strength limit, the structure will always break in the zone where strain concentrates.

In the automotive industry, several components, like manifolds or cylinder blocks, are subjected to thermo mechanical loadings. In order to respect the specifications in terms of fatigue life, it is required to pass several times by the following steps: design, testing and correction. In order to reduce the number of iterations, engineers need accurate and less time consuming computational tools. Some work has been done to provide accurate models for manifold's lifetime estimation. Most of them have not taken into account the effect of weldments on fatigue life. The present work is an attempt to characterize the fatigue life of a ferritic tubular car manifold, considering the reduction factor lifetime due to weldments.

In order to get an accurate prediction of the manifold lifetime, it is important to numerically evaluate the mechanical response in the critical zones. Therefore, the behaviour of the base metal and welds that compose a stainless ferritic car manifold has been investigated. The base metal is a X2CrTiNb18 stainless steel. The filler metal is a X3CrNb17 stainless steel. From an industrial point of view, it is important to characterize the weld's behaviour in the simplest way. Then, an innovative experimental procedure, which allows evaluating an average but realistic behaviour of the weld, has been developed.

Then, the fatigue life of the welded zone has been investigated. A comprehensive campaign of isothermal fatigue life tests has been handled on welded and non welded specimens. The influence of behaviour mismatch on the lifetime reduction factor has been experimentally analysed as a function of temperature.

Two criteria have been identified for predicting the fatigue lifetime of non welded specimens. The first criterion is based on an energetic approach, which considers that the dissipated energy per cycle is a good damage indicator. The second criterion is based on continuum mechanics. A state variable D models the loss of resisting area due to micro cracks. The failure of the representative element volume occurs when D reaches its critical value. The damage evolution law chosen here has firstly been proposed by J. Lemaitre. Both criteria gives satisfactory lifetime prediction in the case of isothermal tests. Anisothermal validation tests are planed to compare their robustness in more realistic conditions. The application to the welded structure is presently under study.

Creep-fatigue-oxidation interactions in 9-12%Cr steels

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The martensitic steels of the 9-12%Cr family are used for many applications in the energy industry. The modified 9Cr-1Mo steel is a candidate for several components of the generation IV nuclear reactors. The repeated start- and stop-operations during service lead to loadings of creep-fatigue type, with very long holding periods (typically one month). As complete tests with such long holding periods cannot, of course, be carried out in laboratory, the actual in-service mechanical behaviour must be extrapolated from the results of short term mechanical tests. In order to make these extrapolations safer and more comprehensive, the present work is focussed on the understanding of the physical mechanisms responsible for damage and failure.

Numerous pure fatigue, relaxation-fatigue and creep-fatigue tests were carried out at 550°C in air and vacuum. The fatigue and creep-fatigue lifetimes measured in air are presented in figure 1. Plotting these lifetimes in terms of the total strain range applied $\Delta\varepsilon_{fat}$ (figure 1.a) highlights the fact that, the higher the creep strain applied, the shorter the lifetime. However when plotting these same data in terms of the (visco)plastic strain applied per cycle $\Delta\varepsilon_{vp}$, a usual Manson-Coffin law seems able to describe all results (both PF and CF lifetimes), at least in the range $0.1\% < \Delta\varepsilon_{vp} < 1\%$. This suggests that the effect of holding periods is comparable to a simple increase of the fatigue strain applied: no evidence of an additionnal damage mechanism can be found.

A more surprising result arises when the effect of tensile and compressive holding periods is compared. Figure 2 compares the fatigue lifetime measured for compressive and tensile holding periods. For low fatigue strain ranges ($\Delta\varepsilon_{fat} \leq 0.5\%$) and limited applied creep strain ($\varepsilon_{creep} \leq 0.2\%$) the fatigue lifetime of compressive CF tests is always shorter than half of the tensile CF lifetime. These results show that, under certain conditions (more specifically low strain ranges and "short" holding periods), compressive holding periods are more deleterious than tensile holding periods, whereas, for higher strain ranges, the difference between tensile and compressive holds is not significant.

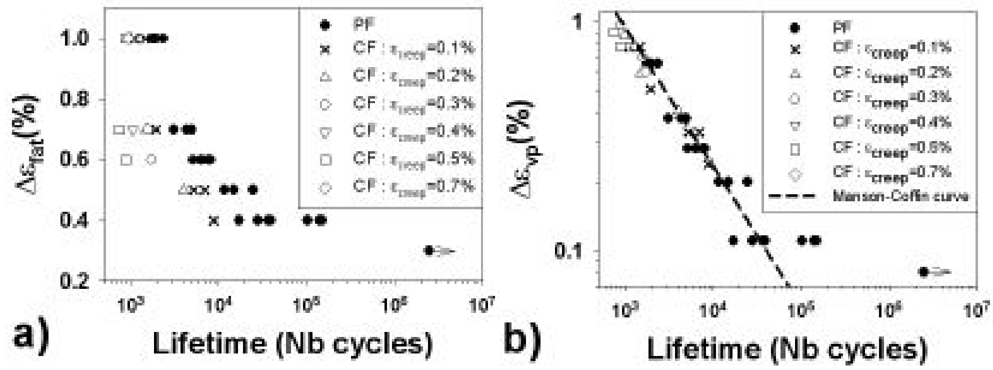

Figure 1. Pure fatigue and creep-fatigue (with tensile holding periods) lifetimes expressed in terms of a) the total strain range and b) the viscoplastic strain range applied (T=550°C, air).

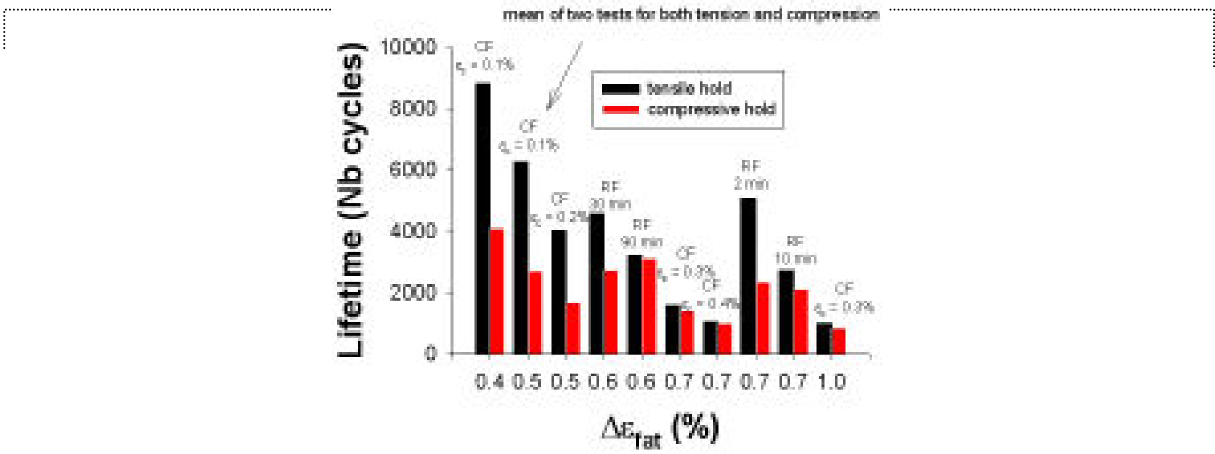

Figure 2. Comparison of the lifetimes resulting from tensile and compressive holding periods (T=550°C, air).

In order to investigate further the damage mechanisms responsible for the experimental lifetimes obtained, a series of detailed observations were carried out in optical microscopy and SEM. Finally, two main types of damage were observed, all the tested samples correspond to one of them. In all cases the damage consists in the propagation of transgranular cracks, no evidence of intergranular cavities (usually corresponding to creep damage) was found.

Crack initiation mechanisms.

Type 1: In this domain, no clear evidence of environmentally assisted crack initiation is found. Therefore, crack initiation may occur in a rather usual way, either on surface inclusions, on fatigue extrusions, or due to intergranular processes.

Type 2: Numerous evidences of an environmentally assisted crack initiation are found. The high strain amplitude leads to the cracking of the oxide layer on defect or porosity. These cracks of the oxide layer induce stress concentration at their tip in the material. Therefore, it is easier for these cracks to propagate inside the material from these high-stress regions, than for a new crack to initiate in the bulk material somewhere else. Experimental evidences (numerous cracks observed are suspected to initiate in the oxide layer) such as literature references [7,11] confirm that in this domain, cracks initiate in the oxide layer. The repeated crackings of the oxide layer lead to the multilayered and thick oxide morphology mentioned above. This mechanism is self-sustained, since the thicker the oxide is, the poorer its mechanical properties are.

Crack propagation mechanisms.

Type 1: Branched and narrow cracks are observed. Additionally a thin oxide layer covers the whole crack lips up to the crack tip. These observations suggest that the cracks may propagate preferentially along microstructurally "easy-propagation" paths, such as slip bands or highly misoriented boundaries. The thin oxide layer observed along the crack lips is sufficient to increase slip irreversibilty and to prevent crack closure. Such environmentally assisted crack propagation would therefore lead to a reduced fatigue lifetime compared to tests carried out in vacuum.

Type 2: Cracks are found to propagate straightly and to be filled with oxide. Moreover, evidence of internal oxidation was found at crack tips. The straight crack paths may thus come from the fact that the internal oxidation (due to oxide cracking as explained above) damages the microstructural boundaries ahead of the crack tip. Therefore, even though slip bands could still exist, they are no longer the easiest propagation paths. The cracks will propagate along the damaged grain or lath boundaries with no reason to deviate from a simple straight path. However, as the cracks are completely filled with oxide and widely opened, it is not clear, whether the propagation rate is increased or decreased. Indeed, in an extreme case, the crack could even be considered as healed if it is completely filled with oxide and if the applied strain is not high enough to crack it.

The longer lifetimes obtained in tests carried out in vacuum confirm the major influence of oxidation.

Notes :

Notes :

Workshop 3

Reliability approaches in fatigue design

Approches probabilistes en conception vis-à-vis de la fatigue

Reliability assessment of train screws subjected to fatigue, corrosion and human errors

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The reliability of railway equipment is of central interest in the choice of design methodologies and maintenance strategies, in order to ensure safe operation of the railway network of the SNCF. The screwed joints in the TGV trains are among the components which are highly subjected to fatigue. In addition to mechanical loading, the environmental effects (i.e. temperature, humidity, freezing…) lead to the corrosion in the thread. Moreover, during the maintenance operations, the human factor plays a very important role in the assurance of the screw integrity under fatigue; hence, the reliability assessment should take account for this factor in order to estimate the screw lifetime.

The herein study aims to establish a complete reliability-based methodology for the supervision of the equipment subjected to fatigue, in order to optimize their maintenance on the basis of cost and reliability balance. This methodology incorporates the life cycle of the equipment, including the deterioration modes, the human errors and the uncertainties in the material properties, the geometry and the loading, as well as the impact of maintenance operations.

The uncertainty analysis allows us to define the probabilistic distribution of the fatigue damage as a function of train operational time. Although the mean damage is very low, the distribution tail is largely extended to high damage levels, which strongly increase the failure probability. The representation of damage by classical distribution models, such as lognormal and Weibull is not appropriate to estimate the system reliability.

The corrosion in the thread induces a resisting moment during the tightening of new screws, and thus leads to a significant loss of prestressing force. In order to integrate this phenomenon in the reliability assessment, the Agence d'Essai Ferroviaire of the SNCF has performed several tests to measure the resisting moment as a function of corrosion levels.

The human factor is taken into account by considering different scenarios during the assembly procedure. The errors in the screw type, in the tightening moment and in the cleaning of assembled surfaces have a major influence on the screw integrity. The impact of these errors is amplified by the joint corrosion.

This work has shown that even with a large safety margin in the fatigue design of these screwed joints, there is a lack of robustness when operating conditions are considered. Although the high resistance to the applied load, the joint is still very sensitive to parameter variations: friction, tightening and prestressing. Increasing the deterministic design margins does not improve the safety, because of the dominant influence of the human and environmental factors.

- Gas-loaded accumulators – A guide to applying the guarantee factor method to standard EN 14359 -

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Abstract Within the context of works under European Standard EN 14359 relating to gas-loaded accumulators for fluid power applications, the manufacturers have to verify by testing the in-service fatigue reliability of their accumulators. The aim of this paper is to help manufacturers to apply this testing methodology by assessing the required industrial data and conditions. An application is developed with a focus on how to provide reasonable estimates, using theoretical and statistical analysis of a fatigue strength variation coefficient level extracted from experimental results. It is concluded that the method can be applied to accumulators with some restrictions.

1 INTRODUCTION

A gas-loaded accumulator is a part of hydraulic transmission system allowing to store energy by compression of a gas. Hence, it is like a thin shell with gas inside, under a pressure of several megapascals (MPa). Through recent requirements of customers, accumulators manufacturers have to demonstrate the level of fatigue reliability of their accumulators according to given operating pressure ranges.

To answer their customers, gas-loaded accumulator manufacturers (ETNA Industrie, Hydro Leduc, OLAER Industries) have asked the CETIM, UNITOP and I-Comete to assess the requirements of the guarantee factor reliability approach to demonstrate the level of fatigue reliability required, which is one of the two experimental methods proposed by the European Standard EN 14359 relating to gas-loaded accumulators. This method is described in paragraph 7.6.7 of the standard.

After a quick summary of the probabilistic background of the method, the requirements for applying this approach to an industrial mechanical component are introduced. In the last part, an example of application performed on an operating accumulator using theoretical, experimental and a statistical approach is shown.

2 GENERAL PRINCIPLE OF THE GUARANTEE FACTOR METHOD

This method allows the verification of the fatigue behaviour of accumulators, to withstand a large number of what are called "unlimited" cycles. Its principle is based on verifying the ratio between the characteristic strength of the accumulator and the characteristic stress according to its intended function.

This method includes a probabilistic analysis phase and an experimental phase:

- The probabilistic analysis phase corresponds to the Stress / Strength theory.
- The experimental phase validates the guarantee factor. The testing method proposed by the standard corresponds to the **no failure test method**.

3 REQUIREMENTS FOR APPLYING THE GUARANTEE FACTOR METHOD TO ACCUMULATORS

The requirement for applying the guarantee factor method to accumulators is the knowledge of the following data:

- **ΔPE**: mean of the in-service equivalent pressure range distribution (in-service profile) at 2.10^6 cycles
- **CVE**: coefficient of variation of the in-service equivalent pressure range distribution (in-service profile) at 2.10^6 cycles
- **CVM**: coefficient of variation of the fatigue strength distribution to the pressure range at 2.10^6 cycles
- **β**: reliability index=f(reliability target)
- **n**: number of items successful in terms of cycle objective (2.10^6 cycles).
- **a'** : probability factor=f(confidence level)

The main requirements linked to the use of this approach for the accumulator manufacturers are:

- A good knowledge of the fatigue failure modes of the component,
- The fatigue strength influence parameters have to be under manufacturing control in order to fit with a well-known distribution of the fatigue strength (normal or log-normal distribution) and a level of variation in relation with fatigue operating applications.
- A strong feedback of the operating pressure range distribution stood by accumulator until target lifetime.

4 CONCLUSION

The analysis of the guarantee factor reliability approach proposed by the European Standard EN 14359, relating to gas-loaded accumulators, to estimate the operating fatigue reliability of accumulators has allowed to classify this method as a probabilistic stress / strength approach. The experimental assessment of the mean fatigue strength is performed by a no failure methodology on a single level of pressure range at 2.10^6 cycles.

The fatigue tests performed have allowed to define the failure modes and the level of fatigue strength variation of a 15 items sample by the S,N curve approach. The estimation of the coefficient of variation of the production has been assessed by a 90% confidence interval established with theoretical approaches and MONTE CARLO statistical simulation in Excel.

The level of coefficient of variation in this example is estimated around 10% which is considered as an industrial standard limit for applications subjecting mechanical components to fatigue. Values higher than this experience-based limit have been found on some batches. This could reflect a lack of design/process control without which it is illusory to apply any statistical method to determine a reliability level.

APPLICATION IN THE INDUSTRY OF THE RELIABILITY APPROACH IN FATIGUE DESIGN; A CETIM MULTIPARTNERS PROJECT

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Extended summary

1 INTRODUCTION

CETIM opened in 2006 a multipartners project named DEFFI: Démarche Fiabiliste de conception en Fatigue pour l'Industrie or Reliability Approach in Fatigue Design for Industry. The project is built on actual components from industrial partners and has the ambition to develop methods and tools to analyse the fatigue failure risk for these different components following the Stress Strength Interference approach. The three main steps are presented:

- the creation of the statistical distribution of the in service loading severity. That is built from calculated or measured data on typical life situations
- the mastering of the fatigue resistance scatter of the products based on a capitalisation strategy of the quality of fabrication.
- the calculation of the failure risk from this information.

This pragmatic approach calls some analysis tools and interpretation in fatigue of the handled information. These tools constitute the bases of a software platform which is developed within the project.
Industrial partners are Cnes, Snecma, Volvo, Mecalac, Pomagalski and SNCF.

2 TARGET OF THE PROJECT

Taking into account the context and the stakes described previously the "mission" of the project, in other words the direction of the action and its framework, is synthesized in a sentence:
To introduces into the mechanical engineering industry the methods of reliability in fatigue design and validation for reliable structures and mechanical components. The topic being relatively vast, the perimeter of the project and its limits were defined in the following way,

Included fields:

- tools of identification and capitalization of the loadings and their handling for a probabilistic use.
- development of a coherent experimental strategy in the global approach (loading analyses, structural calculation, probabilistic approach).
- quantitative evaluation of the parameters allowing to validate the hypothesis on which is based the probabilistic approach.

Excluded fields:

- new developments in static and dynamic structural analysis.
- development of new laws on the behaviour and the damage of materials.

3 STATE OF THE PROJECT

3.1 Organisation of the activities

The project has a cross organisation with in one axis the generic scientific activity and in the other axis the application to the different industrial cases.
The software platform develops the necessary tools for the description of the Stress (the loading and its variability), for the description of the Strength (the fabrication scatter linked to a material process couple), and for the probabilistic analysis from this information. All these tools are gathered in a software platform.

The application to each industrial case includes the organisation of the in service measurement of loads, the capitalisation of the information on the fatigue resistance of the product linked to the fabrication quality, and the calculation of the failure risk. All this information gathered and exploited separately for each case in a Justification and Validation File. This document will be the memory of the project through its application to each industrial case. This represents therefore the know-how acquired in each company.
The entire project documentation is available for partners on a dedicated internet place with confidential areas for each industrial case.

3.2 Software Platform

The software platform is organized around the three main step of the Stress-Strength Interference approach: tools to analyse the variability of the loading in service: the **Stress**, tools to analyse the scatter of the fatigue strength of the components: the **Strength**, tools to analyse the risk of failure and the **reliability** with regards to the fatigue damage. Schematic organisation of the software platform is given Fig 1. Ecole Nationale d'Arts et Métiers (ENSAM-Angers) is involved for all fatigue developments, Institut Français de Mécanique Avancée (IFMA) and Phiméca are involved in statistical and probabilistic developments

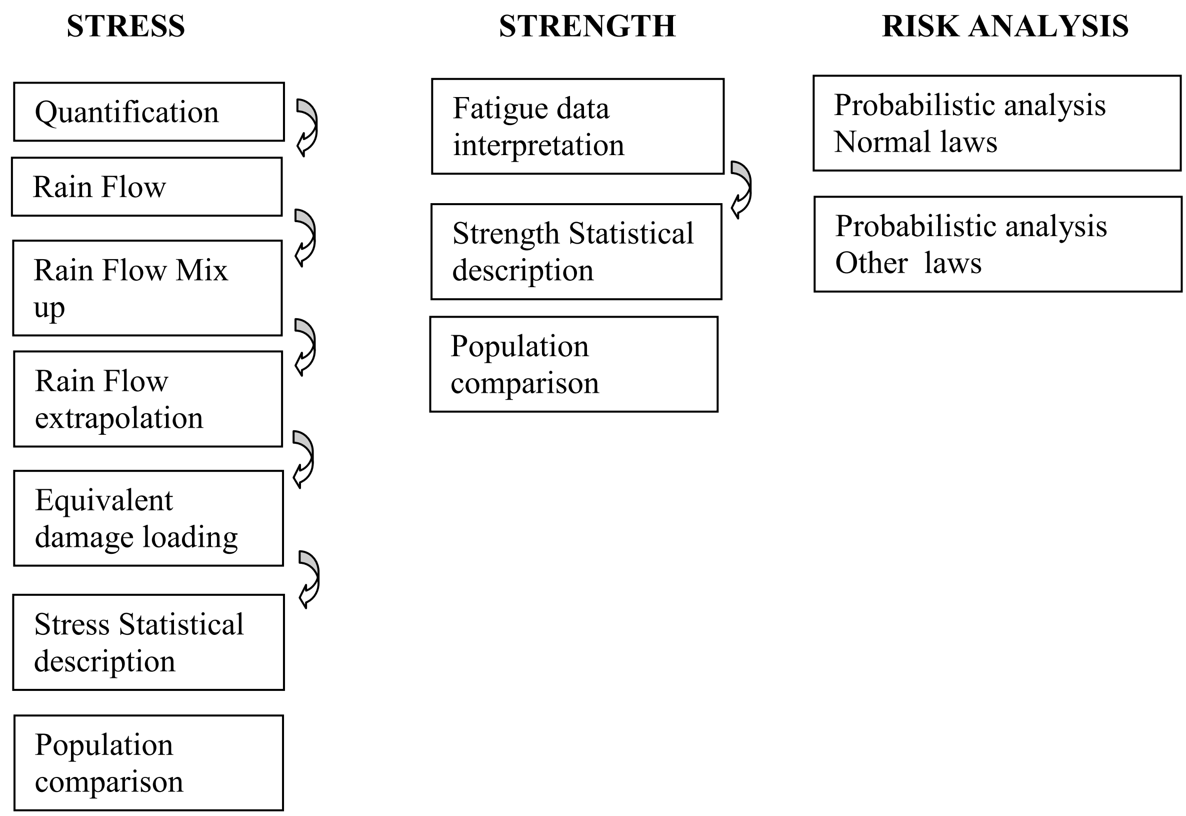

Figure 1 - Tools in the software platform

3.3 Application to industrial cases

Five different cases of application have been decided by the industrial partners:

- a bogie of a TGV
- a seat of cable transportation
- a fleche and an arm of earth moving machines
- an element of the Vulcain engine for Ariane 5 launcher

For each application the project uses the platform software to describe the Stress and the Strength, and to perform the risk analysis.
The software platform developed in the project will create the condition of success in the application of the Stress-Strength Interference method in the mechanical industry.

Calibration des coefficients partiels pour le dimensionnement des structures en fatigue

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De plus en plus de concepteurs s'intéressent à l'évaluation de la fiabilité des structures qu'ils conçoivent et dimensionnent. Quelle est la probabilité de défaillance des structures dimensionnées ? Quelle est la marge de sécurité associée ? Comment dimensionner au plus juste sans pénaliser la fiabilité de la structure ? Quelles sont les variables d'intérêt dont les fluctuations ont des conséquences très importantes sur la fiabilité de la structure et au contraire quelles sont celles dont les fluctuations ont peu d'importance ? Beaucoup de questions soulevant le problème de la robustesse de la conception sont aujourd'hui posées. Des éléments de réponse à ces questions peuvent être apportés grâce aux approches probabilistes dont les développements scientifiques en amont pénètrent petit à petit la recherche industrielle dans différents domaines (construction automobile, construction navale, génie civil,...).

Traditionnellement, la justification du dimensionnement s'appuie sur un ensemble de connaissances issues de la science et de l'expérience. Cet ensemble est codifié dans des méthodes et des règles faisant intervenir une définition des variables de conception ; un modèle de connaissance du processus physique et/ou mécanique et en général, des marges estimées entre le besoin et la ressource. Si cet ensemble de connaissances conduit à des solutions très généralement satisfaisantes, il ne permet pas au concepteur de disposer d'une mesure chiffrée de la défaillance et conduit en général à des structures très hétérogènes en terme de fiabilité.

Cet article est basé sur l'application des méthodes probabilistes dans le contexte particulier des structures mécaniques dont la défaillance peut se produire en fatigue (80% des structures mécaniques actuellement en service). Il constitue une première phase de réflexion pour répondre aux questions posées par les industriels. Après avoir rappelé quelques généralités sur les méthodes de calcul de fiabilité et exposé la procédure de calibration des coefficients partiels, ce papier présente la méthode de l'équivalent fatigue [1] mise en œuvre pour la modélisation d'une séquence de chargement dans le but d'un calcul de fiabilité. L'application de ces méthodes à une structure dont le modèle mécanique est de type éléments finis utilisant le critère de fatigue de Dang Van est ensuite exposée (voir figure 1).

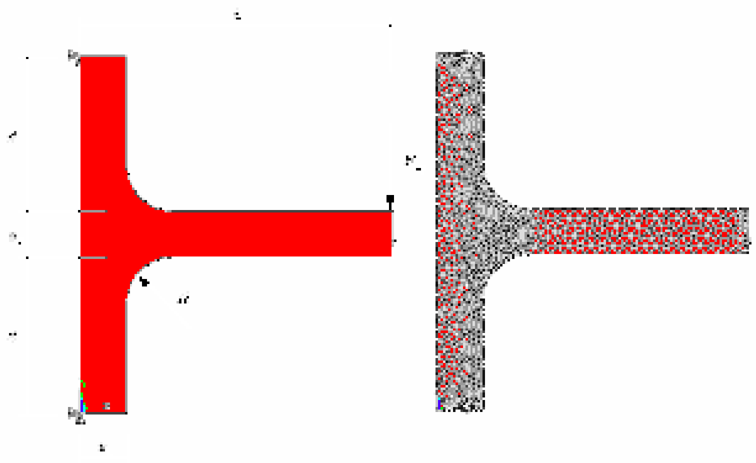

Figure 1. Structure sollicitée en fatigue.

[1] JJ. Thomas. Fatigue modeling for automotive applications. Society of automotive Engineers, 2002.

A probabilistic approach for the fatigue life prediction of structures

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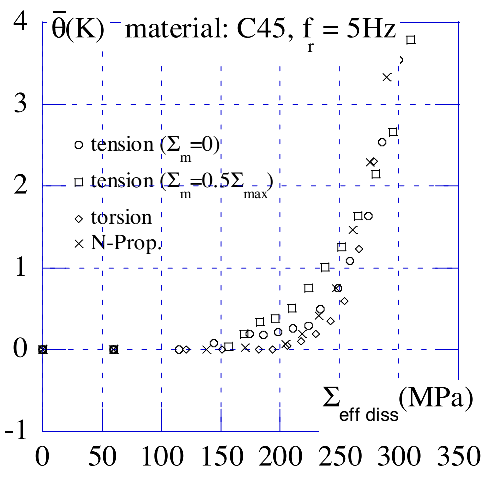
The goal of this study is to predict quickly the fatigue limit of a structure under multiaxial loadings thanks to self-heating tests results.

The self-heating test (or main fast estimation method), is based on the idea that the temperature of the specimen under cyclic loading is linked to it's fatigue limit. One measures the change of the specimen temperature under uniaxial cyclic loadings with thermocouples or thermography and then plots the steady-state temperature as a function of the stress amplitude applied to the specimen (see figure). For some materials such as steel or cast iron, a first part of the curve shows nearly no change in temperature, whereas in the second part the temperature increases significantly with the stress amplitude. A correlation between the mean fatigue limit and the stress level leading to the temperature increase has been empirically proposed. The assumption of a dissipation induced by microplasticity explains this correlation. A probabilistic approach based on a Poisson point process controlling microplasticity distributions even relates the thermal results to the scatter of fatigue results (i.e., microplasticity leads to microcrack inception, and thus to failure).

This approach is here extended to heterogeneous proportional and non-proportional loadings by use of an effective dissipative stress. The model is then applied to a small structure (a tubular tension-torsion specimens made of C45 (AISI 1045) steel). It is able to predict fatigue limits for different loadings after identification of the parameters of the model on self-heating results and a fatigue limit in tension. Predictions of fatigue limit and experimental results are in good agreement (see table).



Steady-state temperature for different loading paths: tension with Σ_m=0, tension with $\Sigma_m=0.5\times\Sigma_{max}$, torsion and non-proportional (ϕ=48°, $\delta=\pi/2$) as functions of the effective dissipated stress amplitude.

Error of prediction for different loading path

Loading	Prop. (ϕ=90°)	Prop. (ϕ=45°)	N-Prop. (ϕ=45°, $\delta=\pi/2$)
$REP=\dfrac{\bar{\Sigma}_\infty^{exp}-\bar{\Sigma}_\infty^{pre}}{\bar{\Sigma}_\infty^{exp}}$	10%	7%	-5%

Notes :

Notes :

Workshop 4

Fatigue life assessment under multiaxial loading

Evaluation de la fatigue sous chargement multiaxial

Comparison of Some Selected Multiaxial Fatigue Assessment Criteria

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Multiaxial fatigue life assessment is a present problem which is still under development and verification. Many propositions can be found in the literature [1-5], however the lack of comparisons with different experimental results can be noted. In this paper, experimental data of constant amplitude tests of notched specimens obtained by Simbürger [6] as well as by Atzori et. al. [7] will be taken as basis for an evaluation by five fatigue assessment criterions. The hypotheses were Dang Van [1], Equivalent Effective Shear [2], two Energy Criterions [3, 4] and Gough-Pollard [5]. The multiaxial loading state was received through the combination of bending and torsion in in-phase and out-of-phase cases with constant local ratio $\tau_{xya} / \sigma_{xa} = 0.58$ and 0.53 respectively. Using selected fatigue assessment criterions computational Woehler curves was calculated and compared with those obtained experimentally. From the obtained results it was concluded, that best results were obtained by a plane oriented integral hypothesis.

Referees

[1] Dang Van K., Cailletaud G., Flavenot J.F., Le Douaron A., and Lieurade H.P.: Criterion for high cycle fatigue failure under multiaxial loading, Biaxial and Multiaxial Fatigue, EGF 3 (Edited by M.W. Braun and K.J. Miller), 1989, Mechanical Engineering Publications, London, pp. 459-478

[2] Sonsino C.M.: Multiaxial fatigue of welded joints under in-phase and out-of-phase local strains and stresses, International Journal of Fatigue, Vol. 17, No. 1, 1995, pp. 55-70

[3] Socie D.F.: Multiaxial fatigue damage models, Journal of Engineering and Materials Technology, 1986, Vol. 109, pp. 292-298

[4] Łagoda T., Ogonowski P.: Criteria of multiaxial random fatigue based on stress, strain and energy parameters of damage in the critical plane, Mat.-wiss. u. Werkstofftech., Vol. 36, No. 9, 2005, pp. 429-437

[5] Gough H.J., Pollard H.V.: The strength of metals under combined alternating stresses, Proc. Of the Inst. of Mech. Engs., 131, 1935, pp. 1-101

[6] Simbürger A.: Fatigue Behaviour of Ductile Materials under Multiaxial out of Phase Stresses with Constant and Changing Directions of Principal Stresses, Laboratorium für Betriebsfestigkeit, Report Nr. FB-121 (1975), ps. 247, in German

[7] Atzori B., Berto F., Lazzarin P., Quaresimin M.: Multi-axial fatigue behaviour of a severely notched carbon steel, International Journal of Fatigue, Vol. 28, 2006, pp. 485-493

Fatigue Assessment of a Rear Axle for Light Trucks

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ABSTRACT

Welded components require careful design and realization due to the fact that welds can be their most critical points. Different methods are available in literature for life prediction and design of welds, among them it is possible to recall: Hot Spot [1,2], Local Stress [3,4] and Fracture Mechanics [3,4]. The critical situation is even more delicate considering those components subjected to fatigue loads, such as in the automotive field, because the application of the predicting methods is based on the availability of reliable and well-describing service loads and on fatigue strength curves possibly obtained by full-scale tests.

In the first part of the present paper, we will address the fatigue assessment of welded components, in particular the axle beam of a rear axle for light trucks (Fig. 1a). The analysis started with in-service measurements of actual loads. In particular, load spectra measurements were performed on urban, extra-urban, high-way and off-road conditions (Fig. 1b). The load spectra will be used in order to derive an equivalent constant amplitude load to be applied at the bench during full-scale tests of the components. Then, by means of finite element analyses (Fig. 1c), the stresses in the component will be obtained and post-processed by means of two different techniques for the assessment of welded joints: "Hot Spot" and "Local Stress" methods. The results will be finally compared with full-scale tests (Fig. 1d).

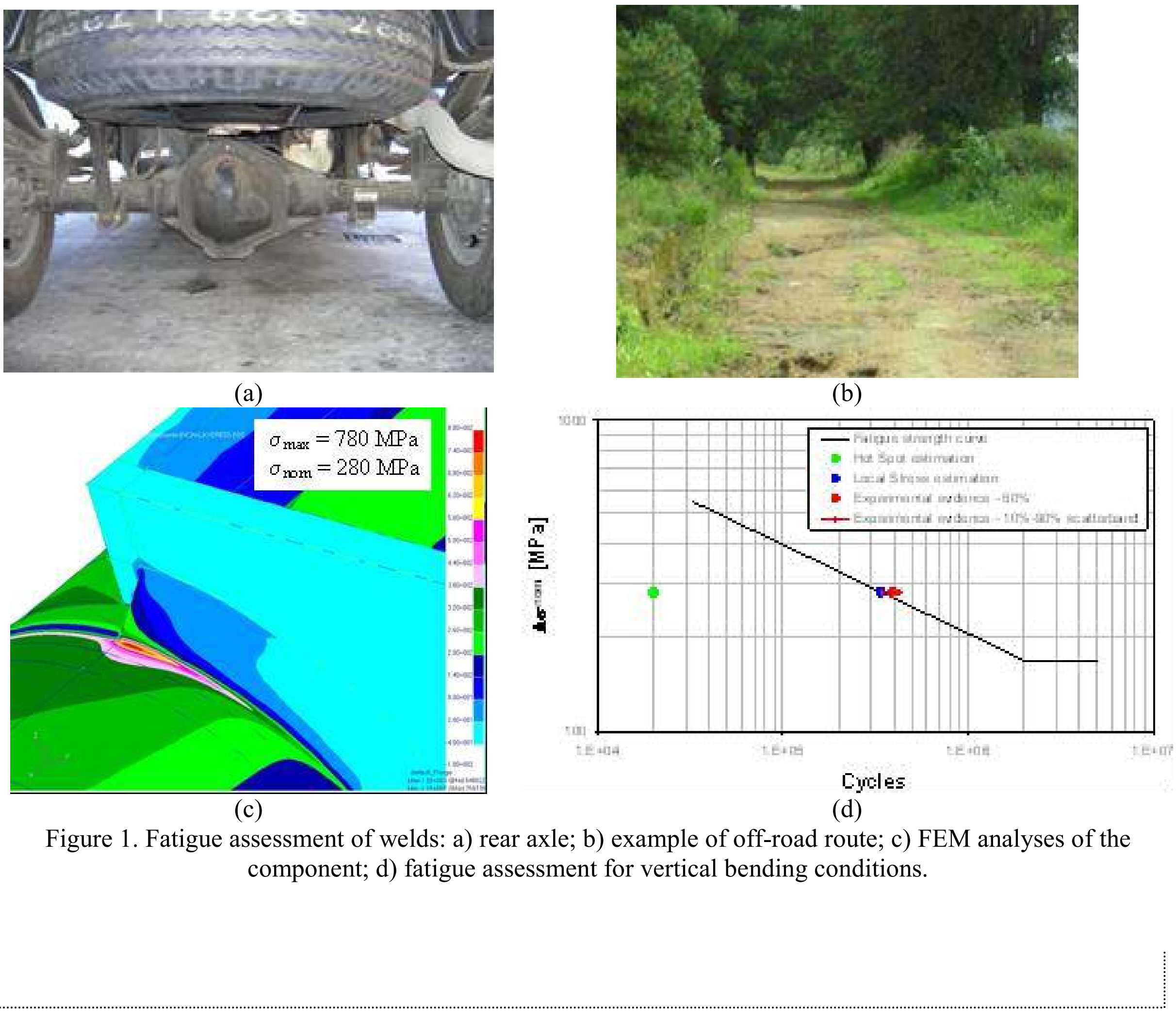
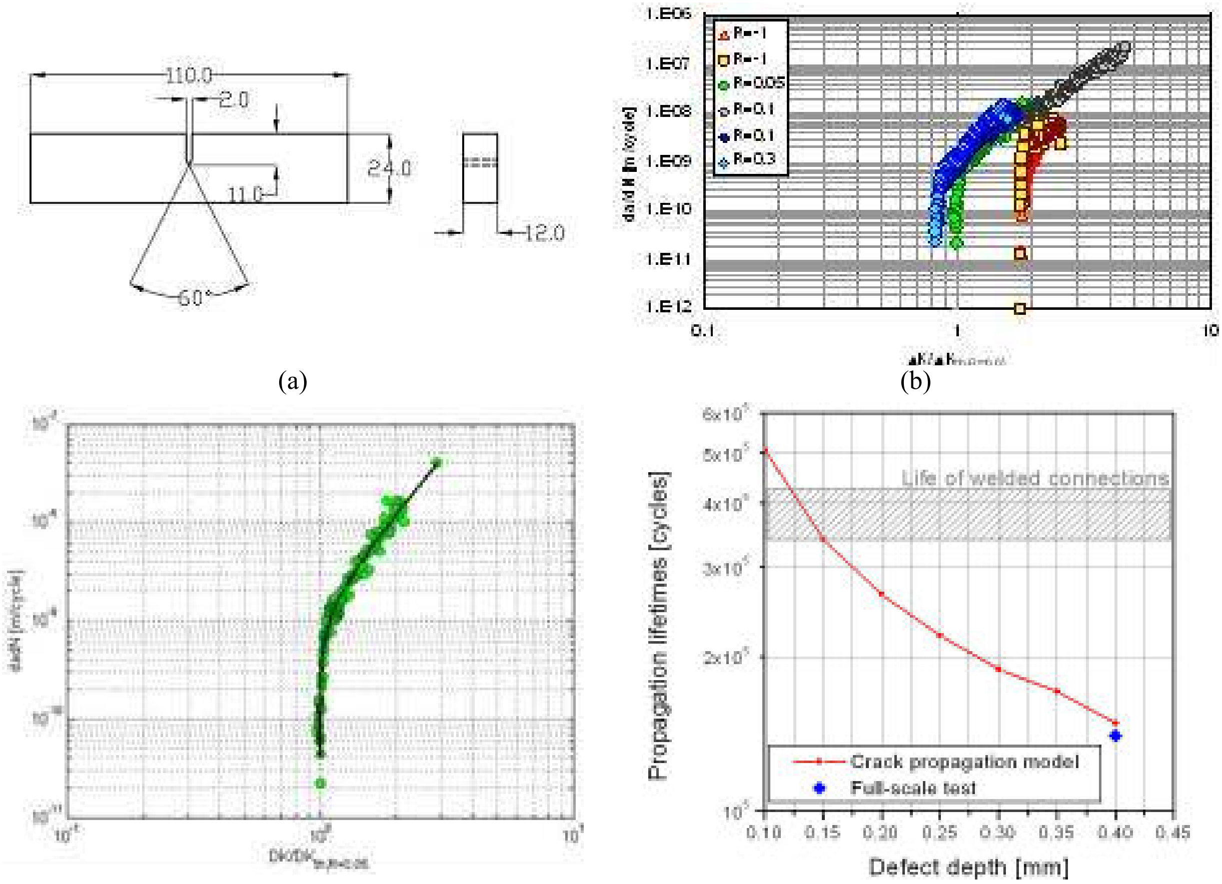


Figure 1. Fatigue assessment of welds: a) rear axle; b) example of off-road route; c) FEM analyses of the component; d) fatigue assessment for vertical bending conditions.

In the second part of the paper, we will consider the possible presence of inhomogeneities onto the rear axle body due to the application of acceptability criteria or to the probability of detection during Ultrasonic Non Destructive Testing. To this aim, a fitness-for-purpose analysis [5] has been carried out based onto fracture mechanics experiments (Fig. 2a and b) and the application of a crack propagation algorithm (Fig. 2c). Prediction were then validated by full-scale tests carried out on rear axles containing suitable artificial defects (Fig. 2d).



(a) (b)

(c) (d)

Figure 2. Fitness-for-purpose analysis of rear axles: a) SE(B) specimen; b) crack propagation curves for 20MnV5 steel; c) simple crack propagation model; d) life estimates and experimental full-scale result.

1 REFERENCES

1. E. Niemi, Stress Determination for Fatigue Analysis of Welded Components, IIW-Doc. IIS/IIW-1221-93, International Institute of Welding, 1995.
2. S.J. Maddox, Hot-Spot Stress Design Curves for Fatigue Assessment of Welded Structures, IIW-Doc. XIII-1900a-00, International Institute of Welding, 2000.
3. D. Radaj, Design and Analysis of Fatigue Resistant Welded Structures, Woodhead Publishing Ltd, 1990.
4. D. Radaj, C.M. Sonsino, Fatigue Assessment of Welded Joints by Local Approaches, Woodhead Publishing Ltd, 1998.
5. European Fitness-for-service Network, FITNET FFS Procedure, Final Draft MK7, 2006.

Stress gradient effect in HCF for notched components taking into account cyclic plasticity

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Fatigue crack initiation on components is usually arising around notches where gradients and high stress-strain levels are encountered. Two major difficulties can be identified when dealing with fatigue strength assessment in such cases: to compute the cyclic stress strain state at the notch where macroscopic plastic strains take place and to take into account the stress/strain distribution (gradients, "supporting effect").

This paper is devoted to the fatigue strength assessment of notched specimens (Kt=2 and 3) made of a 42CrMo4 quenched and tempered steel under tension and rotating bending with and without mean stress. To take into account the stress-strain gradient effect the non-local energy based multiaxial fatigue criterion proposed by [1-5] is used. The driving force for damage initiation and growth, up to fatigue crack initiation at the macroscale considered here is the strain work density given to each elementary volume of material per loading cycle, *Wg* given by Eq (1), where <a> = a if a > 0 and <a> = 0 if a ≤ 0, (.) denotes the time derivative.

$$Wg(M) = \sum_{i,j} \int_T \left\langle \sigma_{ij}(M,t)\dot{\varepsilon}_{ij}(M,t) \right\rangle dt \tag{1}$$

$$V^*(Ci) = \{\text{points } M(x,y,z) \text{ around } Ci \text{ so that } Wgeq(M) \geq Wg^*\} \tag{2}$$

$$\varpi_g(C_i) = \frac{1}{V^*(C_i)} \iiint_{V^*} \left\langle W_{geq}(M) - W_g^{\ *} \right\rangle dv \tag{3}$$

The volume influencing fatigue crack initiation V* is then defined by (2) around each critical point Ci (where *Wg* reaches a local maximum). The influence of the stress triaxiality on fatigue crack initiation is considered by computing the strain work density given to the material within the volume V* which is equivalent to an uniaxial stress state, $Wg_{eq}(M)$. Over V*, the damaging parameter is the mean value of the strain work density given to the material exceeding the threshold *Wg** (3). Finally, to prevent fatigue crack initiation at the critical point, the non-local multiaxial fatigue criterion is: $\varpi_{g\,eq}(C_i) \leq \varpi^D_{g,uniax}$ where the threshold damage parameter at the fatigue limit $\varpi^D_{g,uniax}$ is identified from two fully reversed fatigue limits on smooth specimens.

For each loading type, the stabilized elastic-plastic stress strain fields were computed on the notched specimens using FEA. The material constitutive behaviour was considered as elastic-plastic using linear isotropic elasticity and non linear kinematic hardening model (Armstrong Frederick model) assuming the material follows the Von Mises plastic flaw criterion. Material parameters were identified from a set of stabilized (half life) stress-strain hysteresis loops (low-cycle fatigue tests) obtained on smooth specimens under strain control fully reversed tension.

Table 1 shows the different stabilized stress-strain states computed at the notch root. For the different geometries and test conditions, elastic shake-down was reached except for two loading cases with the highest Kt geometry which leads to plastic shake-down (accommodation). In this paper, the proposed formulation does not consider the plastic strain work density in the damaging parameter (HCF regime). Thus in case of plastic shake-down only the elastic part of the stress strain history will be taken into account for fatigue strength assessment. Nevertheless, even when elastic shake-down occurs, it has to be pointed out that, due to cyclic plasticity at the notch root, the stabilized local stresses and strains computed using an elastic-plastic modeling are very different from the elastic stresses and strains. Simulated fatigue limits using the above proposed volumetric method are indicated in Table 2 where (Cs) is the usual safety factor and REP is the Relative Error of Prediction.

Table 1 : Comparison of REP, Cs and V* half size for purely elastic and elastic-plastic computations

		Test	*Test*	*Simulation elasticity*			*Simulation elastic-plastic*			
Loading	*Kt*	*Smoy (MPa)*	*Samp (MPa)*	*Cs*	*REP (%)*	*V*/2 (mm^3)*	*Cs*	*REP (%)*	*V*/2 (mm^3)*	*Stabilized state*
Tension	1	0	508	Ref.	Ref.	--	Ref.	Ref.	--	---
Tension°	1	400	467.5	1.64	26	213	1.44	16.5	322	elastic shake-down
Tension	2	500	252	2.15	68	1.2	1.08	9.5	11.4	elastic shake-down
Tension	3	0	220	1.45	16	0.16	1.23	9.5	0.335	plastic shake-down
Tension	3	500	165	2.34	80	0.17	1.32	21	3.050	elastic shake-down
Rot. bending	1	0	540	Ref.	Ref.	--	Ref.	Ref.	--	---
Rot bending	2	0	267	0.87	-4.5	0.22	0.71	-4.5	0.07	Elasticity
Rot bending	3	0	180	1.16	5.6	0.022	1.01	~ 0	0.02	plastic shake-down
Torsion	1	0	320	Ref.	Ref.	--	Ref.	Ref.	--	---

° in such case, all the cross section is included in V*.

The results obtained for an elastic-plastic behaviour are clearly better than for a simple purely elastic approach independently of the stabilized state. This confirms that a purely elastic approach can not capture the stress-strain distribution at the notch even if a non-local fatigue life criterion is used (the averaging process over a volume is not sufficient to overcome the elastic over stress at the notch). Most of the computed fatigue limits are in good agreement with the experimental results having REP values ranging from 0 to 21%. The highest REP values (21%) is obtained for the Kt=3 specimen which is found to be the specimen having the highest computed plastic strain amplitude at the notch. Some limitation of the constitutive model used in this study could partially explain this result. Futhermore, simulations lead to fatigue strength assessments lower than the experimental values (safety side) as shown by the positive REP values in Table 1.

The best quality of simulations with a cyclic elastic-plastic material behaviour shows that assessment of such V* volume is not realistic in elasticity. Furthermore, the size of V* notably varies with the geometry and load type of specimens. This observation which results of the proposed criterion (using a threshold energy Wg*) to define the critical volume V* could be discussed in relation with the real mechanism of fatigue crack initiation. As proposed by other authors [6] in the past, the representative volume of fatigue damage process might be constant for a defined micostructure. Other experiments should be done to clarify this important point of non-local approach in fatigue.

It has been shown in this paper that elastic-plastic finite element computations are needed for fatigue strength assessment of notched components. Even with a volumetric approach to consider the gradient effect ("supporting effect"), elastic-plastic cyclic calculations have to be performed to evaluate the shake-down state. However, the cyclic plastic constitutive model identified from uniaxial test on smooth specimens may not be representative of the real material behaviour at the notch root (hydrostatic stress, gradient,…). Further experimental work is in progress in order to identify the local stress-strain behaviour for highly notched specimens and to better identify cyclic-plastic constitutive behaviour in such cases.

1. A. Banvillet, T. Palin-Luc and S. Lasserre, *Int. J. Fatigue,* 25 (8), 2003, 755-769.
2. J. Bénabes, N. Saintier, T. Palin-Luc, J.-L.Charles, F. Cocheteux: An energy based multiaxial fatigue life calculation method taking into account the stress-strain gradient effect, Proc. Fatigue 2006, Atlanta, on CD Rom, ref FT572, 10 p.
3. T. Palin-Luc and N. Saintier, *MP Materialprüfung Materiasl Testing*, 49 (7-8), 2007, 370-377.
4. T. Palin-Luc and S. Lasserre, *Eur. J. Mech. A/ Solids,* 17 (2), 1998, 237-251.
5. J. Bénabès, Approche énergétique non locale du calcul de durée de vie de structures en fatigue multiaxiale sous chargements d'amplitude variable. Application à une roue de train ferroviaire, PhD thesis, ENSAM, 2006.
6. J.F. Flavenot and N.Skalli, A critical depth criterion for the evaluation of long-life fatigue strength under multiaxial loading,Biaxial and Multiaxial Fatigue, EGF3 (edited by M.W.Brown and K. Miller) 1989, Mechanichal Engineering publications, London, 355-365.

An Evaluation of Simplified Methods to Compute the Mechanical Steady State

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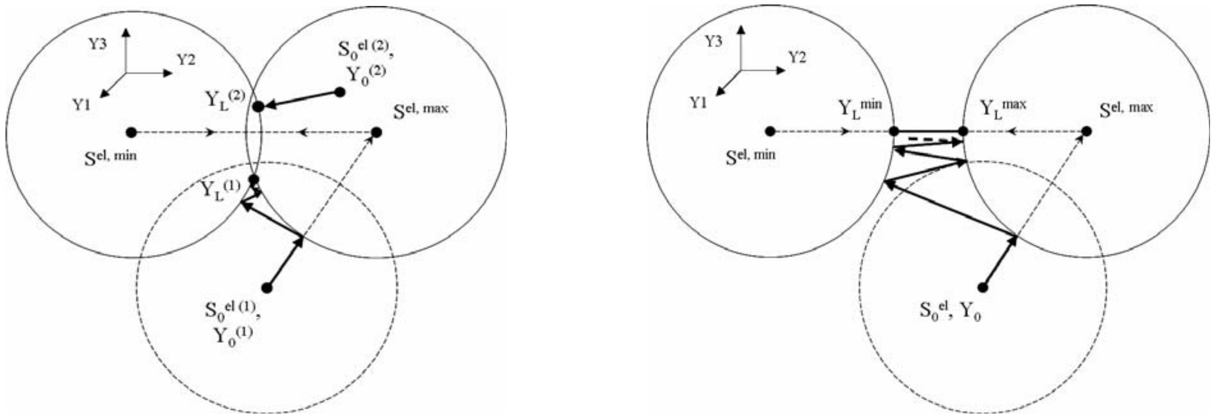
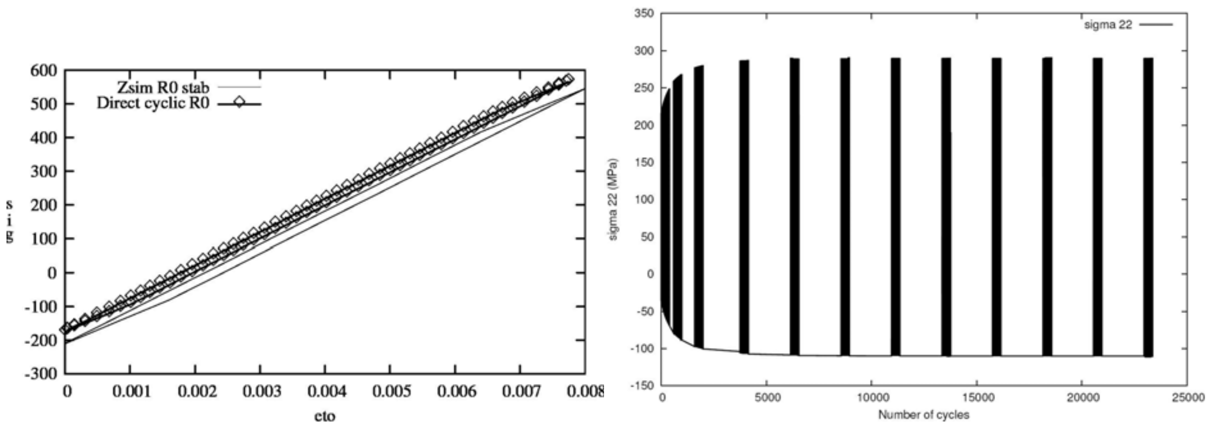
Numeric simulation has become essential in mechanical industries to validate structures at the design level. It is often difficult to find a good compromise between the simulation time and its accuracy. Indeed, high reliability in fatigue prediction requires non-linear behaviour rules, a fine meshing that means a high number of degrees of freedom (dof)… Moreover, real structures are often subjected to complex loading. That is why computations to validate components are often very time consuming. To reduce significantly the computation time, simplified methods to reach the steady state of the structure were developed among the last decades. In this paper three methods will be studied: Zarka's method, cycles skip, the direct cyclic method.



(a) (b)

Figure 1: Zarka's method : determination of the steady state of Y parameter in case of
(a) elastic and (b) plastic shakedown



(a) (b)

Figure 2 : (a) Shift in mean stress between incremental and direct cycle method steady states
(b) cycles computed by cycle skip method

The purpose of this paper was to evaluate three simplified methods used to reach the steady state: Zarka's, direct cyclic, and cycles skip methods. From the calculations performed it would not be appropriated to compare one method to each other because they have not the same features and thus, one has to use them according to the application. For example, even if Zarka's method is faster than the cycles skip one, it cannot be used with a non-linear kinematic hardening. In this case, only small strain amplitude cycles give rather good results, because the slope at the working point of the hardening curve has to be extrapolated. However, for a small kinematic hardening, cycle skip method is more time consuming, so that using a linear kinematic hardening may be a good compromise to reach a first approximation. Regarding the direct cycle method, one could say that it is faster than cycles skip one. Indeed, it needs no incremental computation; however, a shift is observed in stresses when strain is imposed. That means that this method should not be used with stress or strain criteria. No error is observed on the energy; that is why this method is particularly recommended with use of energy fatigue criteria, based on critical plane or on dissipation.

Damage in high cycle fatigue
- From isotropic accumulation to spatial discrete distribution of damage -

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The effect of cyclic loading on metallic components concerns a high number of industrial applications but is difficult to analyse because of the data scatter observed in service. Moreover, this damage mode is very sensitive to the stress state, the mean level and the loading path. The loading history subjected to a structure is then essential to estimate the life potential available for the user.

This study aims at the estimation of the fatigue damage accumulated during the application of different successive block loadings. For each of them, the residual fatigue strength expressed as the remaining fatigue life is given. The fields of the limited and unlimited endurance are explored (lifetimes between 10^5 and 10^6 cycles). The predictions of the suggested modelling are compared to the observations of the initiation and growth of the damage related to various stress paths.

The physical characterization of the mesocrack activity is the first goal of this work. Some SEM observations are hence carried out both for simple and complex loadings. The damage interaction mechanisms between cracks is more especially investigated, these cracks being initiated or propagated by the application of different loading conditions.

The second goal is the development of a model built in the framework of damage mechanics and able to describe the grain degradation due to the initiation crack phase. This approach uses a strong coupling between damage and the cyclic plastic behaviour of the crystal at the mesoscopic scale. Theses models are inspired by well-known approaches trying to get the local cyclic behaviour of grains in polycrystalline aggregates (Dang Van, Papadopoulos, Morel). It is used a thermodynamic framework to guide construction and writing of theses models.

Whatever the loading mode applied, it is possible to get the residual lifetime by knowing the damage value reached. The extension of the lifetime can be imagined by perfectly handling the damage interaction laws between loading modes, and a coupling with a probabilistic approach can allow to estimate the strength potential with respect to the damage.

Rainflow Damage for bi-modal Power Spectra

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Rainflow counting is the generally accepted and recommended procedure for estimation of fatigue damage of structures submitted to random loading. In a number of ship and offshore engineering applications the loading power density spectrum is the combination of several loads pertaining to various frequency ranges (e.g. combination of a low-frequency natural response of the mooring with the higher frequency wave-induced one). Most of the time, those components are narrow-band and the fatigue damage for each of them can be individually estimated with a reasonable degree of conservatism and at low computational cost. However, the classical methods to compute the fatigue damage of the resulting wide bandwidth spectra, using either narrow-band approximation or the Monte-Carlo simulation, are often too conservative or time consuming.

The need appears thus to compute global damage for everyone or a large proportion of the combinations of components that can possibly occur during the whole life of ther investigated structure. Simplified formulas that enable to compute global damage from the properties of the individual spectral components are thus of great interest, since going through full computations for millions of loading cases is quite unpractical.

We propose in this paper the derivation of formulas for combining recursively narrow-band low-frequency components to a higher frequency one with reasonable conservatism. The main advantages of this method are that on one hand as many narrow-band low-frequency components as wanted can be recursively added, and on the other hand that since p.d.f's of the ranges are considered, the method can deal with two-slope S-N curves and endurance thresholds.

Assuming that the global signal is the sum of a narrow-band low-frequency signal l(t) and of a high frequency one h(t); those formulas use a partitioning of the rainflow ranges into two separate subsets A and B. Let us split the time into the consecutive intervals over which l(t) crosses zero with a positive slope. The turning points belonging to subset B are the highest maxima and the lowest minima in such intervals. The remaining turning points constitute subset A.

Using the mathematical definition of rainflow given by Rychlik (1987), it is easy to prove that B is a ``stable'' subset in the rainflow count, i.e. that any turning point in B is associated by the counting procedure over the full signal to another turning point also belonging to B. As a consequence, subset A is also rainflow-stable.

The number of turning points in B is given by the frequency of the low-frequency component, and that of the remaining ones in A by substracting it from the total number of cycles in the global signal. Distributions for the ranges amplitudes in each subset A and B can be estimated from the ranges corresponding to the high frequency component for A and from the properties of Gaussian processes for B. Those estimates imply only the damages corresponding to the high- and low-frequency components, their ratios of frequencies and standard deviations and the irregularity factor of the global signal (or that of the high-frequency one). Then, the sum of the damages associated to both subsets can give a reasonably conservative estimate of the total fatigue damage.

We propose two formulas for the distribution of ranges associated to the B turning points, one using the maximum of a number of consecutive Rice-distributed turning points assumed independent, and the other taking the upper fractile of that Rice distribution in order to ensure conservatism at all times. The distribution of ranges associated to turning points in A can be estimated via uniform scaling of the ranges of the high-frequency component. Again, two scaling ratios are proposed, one on a ``best effort'' basis, the other chosen so as to provide conservative results.

In the case of Miner type damage, total damage can thus be computed as a weighted combination of the high- and low-frequency components damages, with weight coefficients calculated from the above formulas.

The formulas are evaluated on applications consisting of two wave systems, a swell and a wind sea and of those two systems with a superimposed mooring response at a lower frequency. They show various levels of conservatism, in accordance with the expectations that follow from their construction.

On those examples, the conservatism is lower than the one resulting from the narrow-band approximation, and also than other formulas of a more empirical nature such as the Dual Narrow Band estimation (Det Norske Veritas) or the Jiao-Moan Combined Narrow Band formula.

Further, the formulas rely on a controlled use of the theoretical properties of rainflow counts rather than on experimental validation, and their use of defined statistical distributions for turning points of Gaussian processes allows for easy extension to two-slope S-N curves or to endurance thresholds.

Notes :

Notes :

Session Poster

Influence of residual damage on static mechanical properties of 6082 aluminium alloy

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Abstract

This investigation has been carried out in order to study the influence of the residual fatigue damage on the mechanical tensile and fracture toughness properties of a 6082-T6 aluminum alloy during high cycle fatigue. The results obtained show that, under the present experimental conditions, the tensile mechanical properties do not change with the amount of residual fatigue damage. The mechanical properties remain unchanged because in high cycle fatigue, the amplitude of plastic strain is smaller than low cycle fatigue where many works have showed that static mechanical properties change with increasing of numbers of cycle. However, the evolution of fracture toughness properties as the CODc and J_{1C} present a decreasing between 10 and 40% with fatigue damage to maximal stress applied of 275 and 200 MPa respectively. This decrease of the toughness parameters could be attributed to microcracks evolution during high cycle fatigue

Keywords: *6082-T6 aluminum alloy, fatigue damage, tensile properties, toughness parameters, lifetime.*

Fatigue life analyses and damage behaviour of brass alloy: effects of cyclic torsional overstrain and prestraining

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Many sanitary structures are subjected to random loading in service due to internal pressure variation and impact reaction caused by fluid shock. In this case, the fatigue life will be affected by load sequence (cyclic overstrain and prestraining) [1-3]. Neglecting the effect of cycle interaction in fatigue calculations under variable amplitude loading can lead to completely invalid life predictions. Furthermore, the knowledge of the cumulative fatigue behaviour is required for a better design of the new generation of sanitary installations.
The present paper picks up this problem by means of an experimental investigation of constant and variable sequence of amplitude strain-controlled fatigue testing. Variable amplitude tests included experiments with a single overstrain (SOS), periodic overstrain (POS) and prestraining (PS). Microscopic observations of fracture surfaces were made to understand the damage process of specimen.
Under (SOS) sequence a reduction in fatigue life of the as-received material was registered. It was about 8% compared with the conditions under constant-amplitude loading. The fracture topography of sample under a cyclic torsional test was characterised by the formation and propagation of shear cracking parallel to the direction of loading axial. However, the new features on the fracture surface under (SOS) conditions was firstly the temper colors produced by oxidation reaction and secondly the fractured asperities transferred from the mating surface, characteristic of a ductile torsional overload failure. Application of (POS) tests produced a fatigue reduction. In fact, the fatigue lives of specimens were only 70% of those without overstraining. When periodic overstrain is increased, this percentage was gone up to 90%.This life reduction was often attributed to the surface damage caused by the large overstrain cycles [4].The damage process was then accelerated by the lower-level cycles. It has also been stated that damage acceleration caused by overstraining was more pronounced in crack initiation, and to a lesser extent in crack propagation. In the case of (PS), the fatigue life was increased by about 20%. We noted also that the prestrained material produced a considerable tensile mean stress (about 30 MPa), which decreased slightly during testing. It is interesting to note in this case that the stress amplitude was observed to stabilize, although the mean stress did not. (PS) tests demonstrated a tendency towards a semi brittle fracture caused by a crack which propagated rapidly in the last service through the material.

References

[1] R. Jurcevic, D.L. DuQuesnay, T.H. Topper and M.A. Pompetzki. Fatigue damage accumulation in 20241T351 aluminium subjected to periodic reversed overloads. International Journal of fatigue, 12, p. 259-266. 1990.
[2] X.P. Huang, J.B. Zhang, W.C. Cui, J.X. Leng. Fatigue crack growth with overload under spectrum loading. Theoretical and Applied Fracture Mechanics, 44, p.105-115. 2005.
[3] Mohamed Kchaou, Ridha Mnif and Riadh Elleuch. Failure diagnostic of brass alloy under cyclic loading. Second congress Machine Design and Modelling CMSM'2007, Tunisia, 19-21 march. 2007.
[4] A.A. Johnson and J.A. Von Fraunhofer. Fractographic observations on a splined shaft which failed by high strain rate torsional overload. Surface and Coatings Technology, 29, p. 153-156. 1986.

Dynamic Tensile Behavior of Materials with Previous Fatigue Damage

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Summary.- In different engineering applications such as automobile and train crashes, the high speed impact of debris as well as the high speed manufacturing processes, makes it necessary to have deep understanding of the dynamic behavior of materials and components. There are different experimental techniques to determine the constitutive material behavior and several constitutive models have been proposed to predict the dynamic response of engineering structures. However, in all cases, initial damage free material is assumed and the structures are without fatigue damage when tested. The dynamic response of fatigue damaged steel and aluminum specimens subjected to impact loading is investigated in this work. Samples subjected to previous high cycle fatigue are considered. Results show that previous fatigue damage affects the quasi-static behavior of steel more significantly than that of aluminum. Dynamic yield stress of 6061-T6 aluminum samples is more sensitive to fatigue damage than to strain rate. Previous fatigue damage has a detrimental effect on ductility of 4140T steel, mainly on the dynamic tests.

A Modified Neuber Method Avoiding Artefacts Under Random Loads

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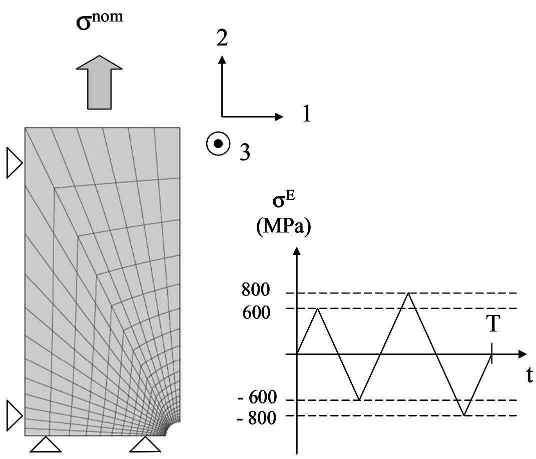
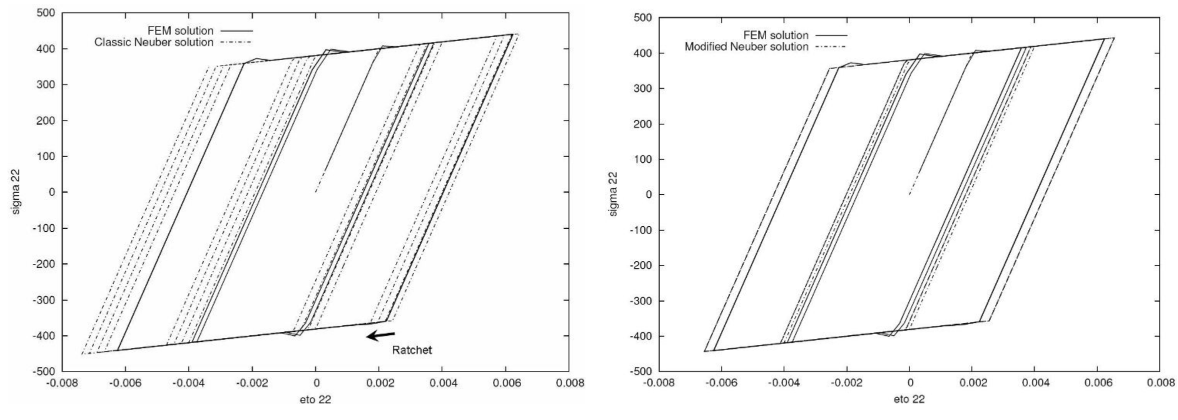
Many engineering components subjected to cyclic loading contain notches like grooves, holes, keyways, welds, etc. When such a component is loaded, a stress concentration appears at the notch root. Fatigue can then be reduced since, even if the component remains globally elastic, a plastic zone develops at the notch root, and an early crack initiation can be observed. In order to predict fatigue life of such components, engineers have to compute the local stresses and strains. Such type of calculation may be quite long, especially when non-linear constitutive equations are used. Simplified methods are then applied, as an alternative to FEM computation. Although many solutions have been investigated, like Molski-Glinka, Glinka, Ellyin and Kujawski… Neuber's rule remains the most currently used for industrial applications. In the case of uniaxial constant amplitude loadings, it appears to be a good approximation; however, a ratchetting phenomenon may appear when the method is applied to variable-amplitude loadings. In this paper, a modification to Neuber's rule is then proposed, and tested for several loadings spectra.



(a) (b)

Figure 1: (a) Mesh and boundary conditions applied to the specimen ; (b) Loading history, $\sigma^e = K_t\, \sigma^{nom}$



(a) (b)

Figure 2: Ratchetting response under the loading defined in Figure 1 (a) Initial algorithm (b) Modified algorithm

Local stress and strain history was determined following classical Neuber method at the notch root of a notched component under variable-amplitude loading. The elastoplastic solution was compared to a solution reached by FEM computation. A ratchetting effect that did not appear by using FEM, was observed by using Neuber's rule. Considering that this ratchet was due to asymmetric cycles, a modified Neuber method was proposed. Like the classical one, this new algorithm can only be applied to uniaxial stress states. It is also based on Neuber equivalence rule, but a change of origin at certain moments of the history makes it possible to avoid the shift due to asymmetric cycles. This new algorithm was tested successfully under several complex load spectra, for linear and non-linear kinematic hardening rules.

EFFECT OF INITIAL NOTCH SIZE ON FATIGUE CORROSION OF AN AISI 316 L STAINLESS STEEL

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In order to study the dynamic behaviour of austenitic stainless steel (316L) implants into physiological medium, simulation of fatigue corrosion of pre-notched specimens were carried out. Input notch data were taken from stable pits obtained from preliminary polarization tests. Calculations were made using effective mechanical and electrochemical conditions observed on human body implants. Two fatigue models have been applied. Hoeppner model is only a mechanical one, whereas Lindley model adds chemical effect.

Numerical results indicates the number of cycles leading to critical size of pits-to-crack transition and then to failure. Furthermore, the effect of the initial notch size on fatigue behaviour of the stainless steel is highlighted.

Both models indicate that decreasing initial notch size raises the number of cycles to failure. Adding chemical action to mechanical one accelerates the damage, in general. However, at higher sizes, one can observe a slowing down of the chemical effect. The prediction of lifetime needs thus to include the effect of other parameters, such as stress frequency, in order to comparate it with real implant lifetime.

Key words : banding, corrosion fatigue, austenic stainless steel, pits, crack..

Contact-Fatigue Life of High Precision Machined Surfaces

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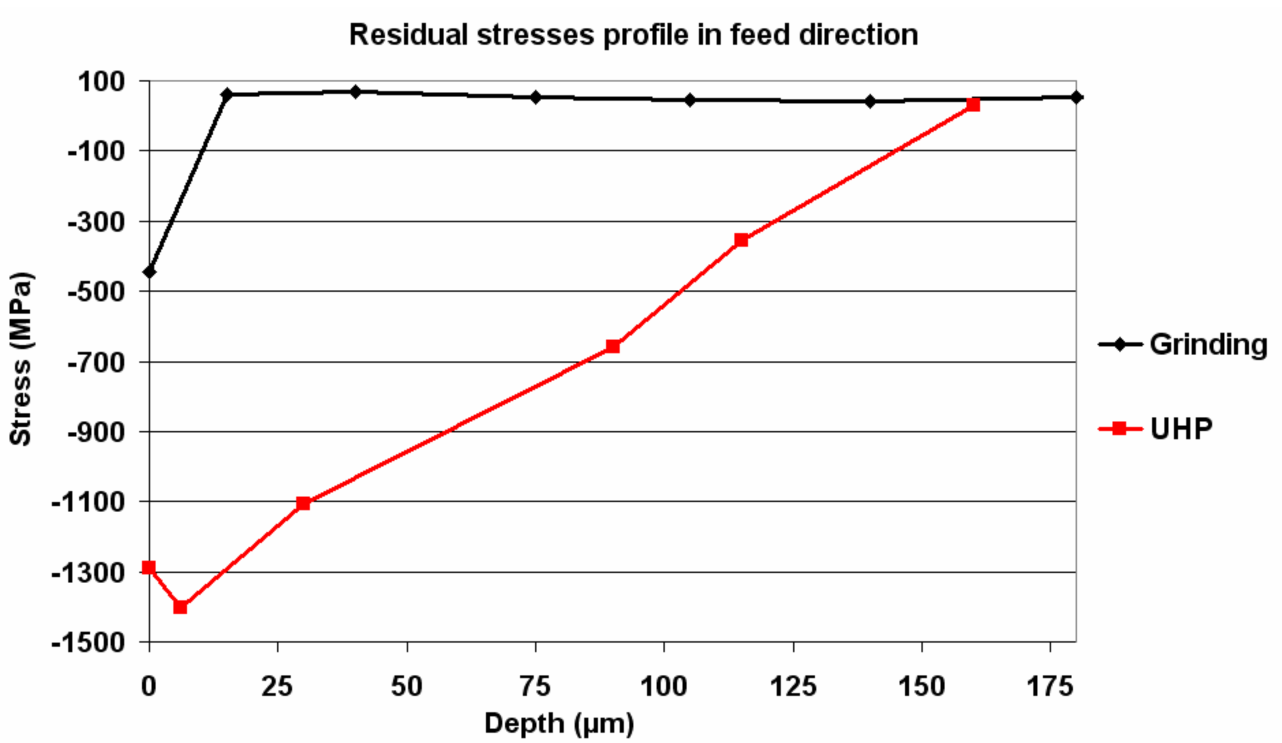
Geometrical precision of industrial parts (shape and sizes) and the quality of their surfaces depend on the process used to achieve them. One or more manufacturing processes, such as machining, can reach these objectives. However, some requirements on surface quality, as a function of part functionalities, lead to use a "super finishing" process. Performance level of these functionalities, such as fatigue life, depends on surface integrity which must be characterised morphologically (shape, roughness, etc.) and structurally (metallurgical phases, residual stresses, etc.).

For revolution parts, high precision turning (HPT) allows to reach very low dimensional and geometric margins imposed by mechanical industry and also low roughness. The main objective of this super finishing process is to avoid successive operations, therefore to manufacture a part using only one machine.

On a hard steel such as AISI 52100 (100Cr6, bearing steel), this process with a cutting tool makes leads to reach a roughness (< 0.2 µm) which is comparable with those obtained after grinding. Furthermore, residual compressive stresses appear from surface to a depth of 150 µm.

In a first step, roller surfaces were machined with different cutting tools and different cutting parameters on a high precision lathe. In a second step, they were tested in contact-fatigue. Finally, results of structural evolutions and topographical observations were carried out. All these results were compared to other roller surfaces obtained by grinding.

Accurate techniques of analysis were used, such as interferometric microscopy, X-Ray diffraction and EDXD, on roller surfaces before and after contact-fatigue running-in.



Tenue en service des pièces découpées

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Aujourd'hui, différents procédés de découpes sont utilisés pour obtenir des pièces planes à partir de tôles. Ces procédés conditionnent fortement l'aspect des bords découpés ainsi que les propriétés mécaniques des pièces obtenues. Aussi, les travaux que nous nous proposons de réaliser portent sur l'étude de l'influence de ces différents procédés sur la tenue en service des pièces découpées.

Pour cela nous avons retenu 3 procédés de découpe (découpe classique, découpe fine et découpe adiabatique) ainsi qu'un procédé de référence qui est le fraisage. Nous avons aussi défini la forme de l'éprouvette plate qui sera utilisée pour valider les modèles proposés.

Dans un premier temps, nous tacherons de modéliser les procédés de découpe avec un modèle unique afin d'évaluer les contraintes résiduelles sur le bord découpé, les moyens actuels de mesure ne nous permettant pas d'en effectuer un relevé.

Par la suite, nous tacherons de modéliser la géométrie et la microgéométrie de la surface afin d'évaluer l'influence de la rugosité et de la géométrie du bord découpé sur la tenue en service, en utilisant un critère de Dang Van implémenté dans Abaqus, dans le cadre de la simulation de l'essai de fatigue.

Afin de vérifier la pertinence du modèle développé, nous réaliserons en parallèle des essais de fatigue en traction ondulée (R=0,1) sur les éprouvettes découpées et sur les éprouvettes fraisées (procédé de référence qui n'induira pas de contraintes résiduelles au niveau du bord de l'éprouvette).

Cyclic Behavior of Extruded Magnesium

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Magnesium alloys are increasingly used for lightweight structural components in automotive industry. Vibrations in moving vehicle lead to cyclic loading of the components and necessitate focusing on fatigue behavior of magnesium alloys. Although cast alloys are more generally used, cast defects tend to limit ductility. Wrought alloys offer better mechanical properties but the strong crystallographic texture inherited from the deformation process leads to strong anisotropic properties. More particularly in terms of cyclic loading, hysteresis loops are asymmetric under strain-controlled tests and compressive ratcheting is observed under symmetric stress-controlled tests.

MATERIAL AND MECHANICAL RESULTS

The purpose of the present study is to better understand the cyclic behavior of such a metal submitted to small cyclic symmetric plastic strains ($\Delta\varepsilon p/2 = \pm.1\%$ and $\pm.4\%$). The material used in this work is a commercially pure magnesium, that was hot rolled, hot extruded and finally recristallized. The microstructure consists of equiaxed grains of about 60 µm. Rolling or extrusion operations generate a strong basal texture with the c-axis lying normal to the sheet. Cyclic cylindrical specimens with a 5 mm diameter and a 12 mm gauge length were taken from the rod in the direction of extrusion. Monotonic tensile and compressive tests were conducted to a plastic deformation of .1%. Cyclic tests were conducted under symmetric constant applied plastic strain amplitudes $\Delta\varepsilon p/2 = .1\%$ and .4% until fracture. Consistent with reports in literature, a large asymmetry of hardening evolution is evidenced. A high strengthening rate develops in compression just after yielding, following by a saturation of the stress for plastic strains higher than .01%. During tensile loading, the strengthening rate is high and evolves linearly with plastic strain. As expected, the hysteresis loops are strongly asymmetric. Moreover, the compressive stress tends to reach a plateau (about 67 MPa) whatever the applied plastic strain and reverse loading after compression leads to inflected tension portion and convex loop, see next figure.

OPTICAL AND TEM OBSERVATIONS

The following table sums up the mechanical tests: maximal positive and negative stresses Σ+ et Σ- (reached at saturation for cyclic tests) as well as the microstructural observations (Optical Microscopy and Transmission Electronic Microscopy).

Tests	Σ+	Σ-	Σ+/Σ-	Twin fraction	TEM observations
Tension (εp = .1%)	80			.8%	Slip (basal <a>, prismatic <a>, pyramidal <a>, pyramidal <c+a>) – (10-12) twinning
Compression (εp = .1%)		40		1.4% [4]	Slip basal <a>, (10-12) twinning
Cyclic loading ($\Delta\varepsilon p/2$ = .1%)	110	67	1.64	7%	Slip and (10-12) twinning Slip or twinning in twins
Cyclic loading ($\Delta\varepsilon p/2$ = .4%)	140	67	2.09	25%	Slip and (10-12) twinning Slip in twins

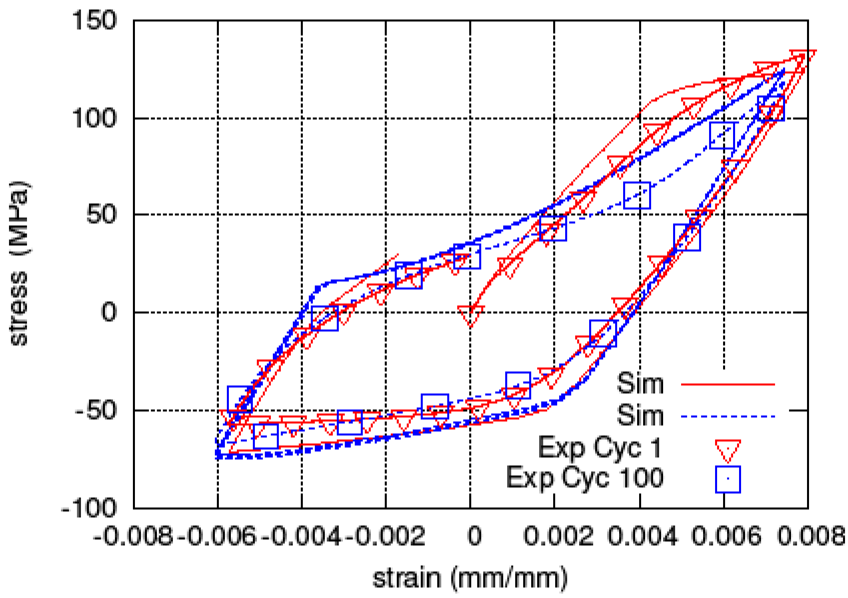
The critical resolved shear stress (CRSS) of basal slip on the (0001) plane with <11-20> Burgers vector is so low (around 1MPa) that it is activated even if grains are not well oriented (Schmid factors equal to .17 are obtained). The asymmetry between monotonic and compressive tests mainly results from the activation of different deformation modes. Due to the "polar" nature of twinning, the activation of the (10-12) twinning is associated with a contraction parallel to the c direction and with an extension in a direction lying in the basal plane in HCP materials such as magnesium. In others words, since specimens are taken in the direction of extrusion, twinning can be operative only under compression in this study. The CRSS for twin nucleation is higher than for basal slip activation but once twinning activates, deformation proceeds under weak hardening and a kind of stress plateau is observed whatever the applied strain. Hardening in tension is due to hard slip systems activation: <a> prismatic and pyramidal and <c+a> pyramidal dislocations.

NUMERICAL MODELLING

Based on microscopic observations, a crystal-plasticity-based constitutive model has been developed. The experimental measured texture is discretized into a finite number (343) of grain orientations defined by three Euler angles. In the multi-scale model the localization steps are successively: the macroscopic level → grain (g) → slip (s) or twin (t) system. Typical localization laws are used.

Twinning develops if the resolved shear on a twin system $\tau^t = \underline{\underline{\sigma}}^g : \underline{\underline{m}}^t$ is larger than a threshold. Twinning rate $\dot{\xi}^{gt}$ is written as a function of the plastic strain rate: $\dot{\xi}^{gt} = k(\xi_{max} - \xi^g)(\xi_{max} - \xi^{gt})\left\|\dot{\underline{\underline{\varepsilon}}}^g\right\|$. First results show that the model correctly takes into account the difference between tension and compression but cyclic tests are not so well captured since the curvature sign change of the loop after unloading is not actually caught.

To really answer for the particular convex curvature after unloading an untwining process has to be introduced in the model as follows: $\dot{\xi}^{gt} = -k_d \xi^{gt}\left\|\dot{\underline{\underline{\varepsilon}}}\right\|$. Such a process has been experimentally observed in recent literature. Next figure shows that our numerical results validate the experimental observations: twins create during compressive loading tend to vanish during reverse loading and all the strain caused by twinning during compressive pre-deformation is regained by untwining during tensile loading. It is worth noting that after few cycles, the modeled twin fraction tends to saturate to a value of 30%, a very close value to the experimental one (about 25%) for the Δεp/2 = .4% test (10% instead of 7% for the Δεp/2 = .1% test).



Modeling of cyclic behavior – Δεp/2 = .4%

Compatibility and cyclic properties of linear flow splitted steel

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In this paper, the work is presented which is a part of research activities of the Collaborative Research Centre (CRC) 666, where the technology for integral sheet metal design with higher order bifurcations is elaborated [1]. The results from constant amplitude fatigue tests are presented for steel in basic state and for the material state after new technique of linear flow splitting under room temperature, where a large plastic deformation occurs. Since manufactured products with the method of linear flow splitting will be part of cyclic loaded structures it is important to outline the fatigue characteristics of used material before and after splitting technology exactly. It is observed, that the investigated steel has better fatigue resistance after linear flow splitting. For the estimation of fatigue parameters of material with high plastic deformation a new method [2] is used, witch is taking mathematical connections into consideration between Ramberg-Osgood and Manson-Coffin-Basquin equations. In order to evaluate the 6 basic fatigue material parameters of these equations the presented method uses the projection of a 3D line (ε_{ap}-σ_a-N_f). Compared with traditional methods for determining fatigue parameters [3] similar fitting curves were received, however the new method assures the so called compatibility between stress-strain and strain-life curves.

References

[1] http://www.sfb666.tu-darmstadt.de

[2] NIESŁONY A., KAUFMANN H., EL DSOKI Ch.: New method for evaluation the Manson-Coffin and Ramberg-Osgood curve with respect to compatibility, In press

[3] ASTM Standard E606-92: Standard practice for strain-controlled fatigue testing, In: Annual book of ASTM standards, Vol. 03.01. ASTM; 1997, p. 523-37

Effect of retained austenite on high cycle fatigue behaviour of carburized 14NiCr11 steel

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ABSTRACT

Two vacuum carburizing treatments were applied to ductile steel 14NiCr11 to obtain equivalent hardened layers with retained austenite contents of 25% and 41%. The properties of the carburized surfaces were examined and characterized before fatigue tests and during cyclic loading. Transformation of retained austenite into martensite during loading, was evaluated by dispersive X-ray diffraction method. The effects of this transformation on the residual stresses have been measured by X ray diffraction in martensite and in retained austenite structures. It was shown that the cyclic retained austenite transformation caused a redistribution of the compressive residual stresses and an increased surface hardness that stabilized after a small number of cycles. The dependence of fatigue behaviour on surface properties was determined, and a relationship between the stabilized state and the fatigue limit is suggested. A phenomenological approach is proposed to correlate the influence of surface hardening and the stabilized residual stresses on fatigue limit of carburized specimens. The Crossland, Dang Van and Findley-Matake, multiaxial high cycle fatigue criteria were used in this approach and results have shown a good agreement with experimental data.

Key words: fatigue, carburizing, retained austenite, residual stress, multiaxial fatigue criteria

Fatigue growth modeling of elliptical and semi-elliptical cracks with a hybrid approach

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In this work, an approach based on the hybridization of weight functions is developed for modeling the elliptical and semi-elliptical cracks subjected to cyclic (fatigue) loadings in mode I. It consists in a prolongation of the domain of validity of the hybrid method, which was already the subject of a validation in the case of static loadings. The development of such approach is justified by enhance the efficiency of the numerical computation of Stress Intensity Factor (SIF).

The hybridization consists in dividing the elliptical crack into two zones, then using the appropriate weight function in the area where it is more efficient. The assignment of the weight functions is made so as to reduce the singularities effect in the weight function expressions in vicinity of the crack front. The proportion between zones is determined by optimizing two crack parameters (axis ratio and curvature radius). In order to extend the hybrid method to the semi-elliptical cracks modeling, the technique of hybridization is coupled with the PWFM (Point Weight Function Method) such that the free edge effect can be taken into account.

The application of this hybrid technique at the fatigue problems to the prediction of the fatigue crack growth of elliptical and semi-elliptical cracks in various structures is considered. The prediction consists in determining of the modification of the crack shape and the fatigue life (the number of cycles) of the structures. This prediction is carried out using mainly the law of Paris and also that of Sih giving the crack growth rate versus the SIF range. Several problems (elliptic crack in an infinite medium, semi-elliptical cracks in a plate, semi-elliptical cracks in a tube, ...) are treated in order to show the effectiveness of such an approach. Through these examples, different materials are used, from the most ductile to the most brittle. The results obtained with the present hybrid approach are in their majority in agreement with the experimental and numerical results available in the literature with an improved numerical efficiency.

Modeling of Defect Front Evolution During its Propagation in Fatigue

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Abstract

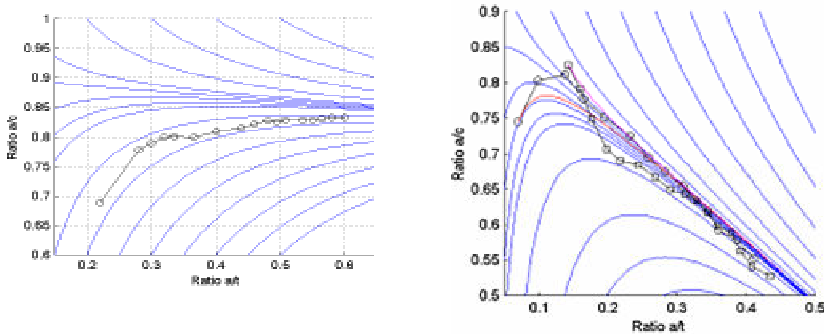
The life time of structures and the installations at high security, we obliged to preview the evolution of cracks that’s exist or being developed during the service field. This could be doable by theory prediction, by numeric simulation or by mechanical tests. One of cracks forms which are nearest to present on the mechanical structures, are on a helical shape, it means, semi-elliptic. The prediction of the evolution in the shape of himself type of defect during its propagation in fatigue, present a particular complexity by the fact of its geometry and by the difficulty in the choice of a law of fissuration of fatigue in three dimensions that takes to its account the mechanical parameters majority (bound to the material) and geometric (bound to the defect).

Since loan of a half century several researchers tried to foresee the evolution of surface cracks during their propagation in fatigue, especially those of semi-elliptic shape. The quasi-totality of these works was about shortcomings contained in plates and in tubes charged cyclically in flexion three and four points [1 to 9] or in plates charged in traction [10 to 21]. In spite of the number and the recorded work quality, the problem always remains posed. What to make for example, in the case of a semi-elliptic defect propagating itself in a partition of a thick tube under internal pressure?

A synthesis of results brought back by the literature relative to plates under a loading of flexion or traction and cylinders solicited in flexion and under internal pressure [22 to 26] already give us a suspicion’s answer on counts:

- to the change in the defect’s shape during its propagation [22 and 23],
- to the type of criteria to the of the approach used for the spoliation of test results [23, 27 and 28].
- to degrees of such or such empiric relation validity established in the goal to foresee the evolution in the shape of this type of shortcoming during their propagation in fatigue [23].

In this paper, we intends from a numeric simulation based on the method of finite elements, in addition of test results, leads on the thick plates in flexion three points and on the thick tubes under internal pressure to review the problem.



case of a tube under internal pressure case of a plate in flexion

Figure 8. Drawn of model proposed for the prediction of the shape evolution of semi-elliptic cracks.

Modelling of fatigue crack propagation after a overload-underload sequence

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There are many calculating models of crack propagation under spectrum loading, such as Wheeler model, Huang et al. who were using different approachs trying to explain fatigue crack growth. The problem of predicting crack growth rates case cannot be solved without an accurate knowledge of load-time history occurring in service.

Decoopman has developed a phenomenological model which describes quite well fatigue crack propagation after an overload cycle on 12NC6 steel in fatigue. This model describes how the crack growth rate evolves during the delay induced by the overload.

Nevertheless, it is limited to overload cycles. But, many authors (Schijve, Makabe) have shown that an underload cycle occurring after an overload cycle reduces the delay.

This study proposes to implement the underload effect in order to decrease the conservative results expected from this model. Decoopman's model proposes a delay weighting factor after an overload cycle. In order to take into account of an underload cycle, we suggest an acceleration coefficient to correct the model. The main advantage of this model is that the delay weighting factor and the acceleration coefficient are only dependent on yield stress y, the crack length a, and the various plastic zone sizes. Many experimental results have been compared to simulated results. This comparison shows a good agreement.

Energy approach of thresholds stresses in multi-axial fatigue under dissymmetrical loading

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Abstract: Several concepts were proposed in the literature to improve the forecasts of the stress: the gradient stress or the layer criticizes for example. However, according to authors none of these concepts explains the differences of the limits of endurance observed in traction, rotational bending and cross-bending. This is why, according to authors, it is important to reason on a cycle of loading. The global energy approach suggested in some papers are based on the concept influence volume around the "critical point" requested by the threshold stress and uses like parameter the voluminal density of the deformation energy provided by cycle of each element of volume.

The procedure of calculation of the deformation energy distinguish two levels: the level with an elementary test of rupture, where one reasons on a symmetrical load, and the level of the combined loads, where we propose an analytical study of the surface average energy variation expressed according to the thresholds stress of the part.

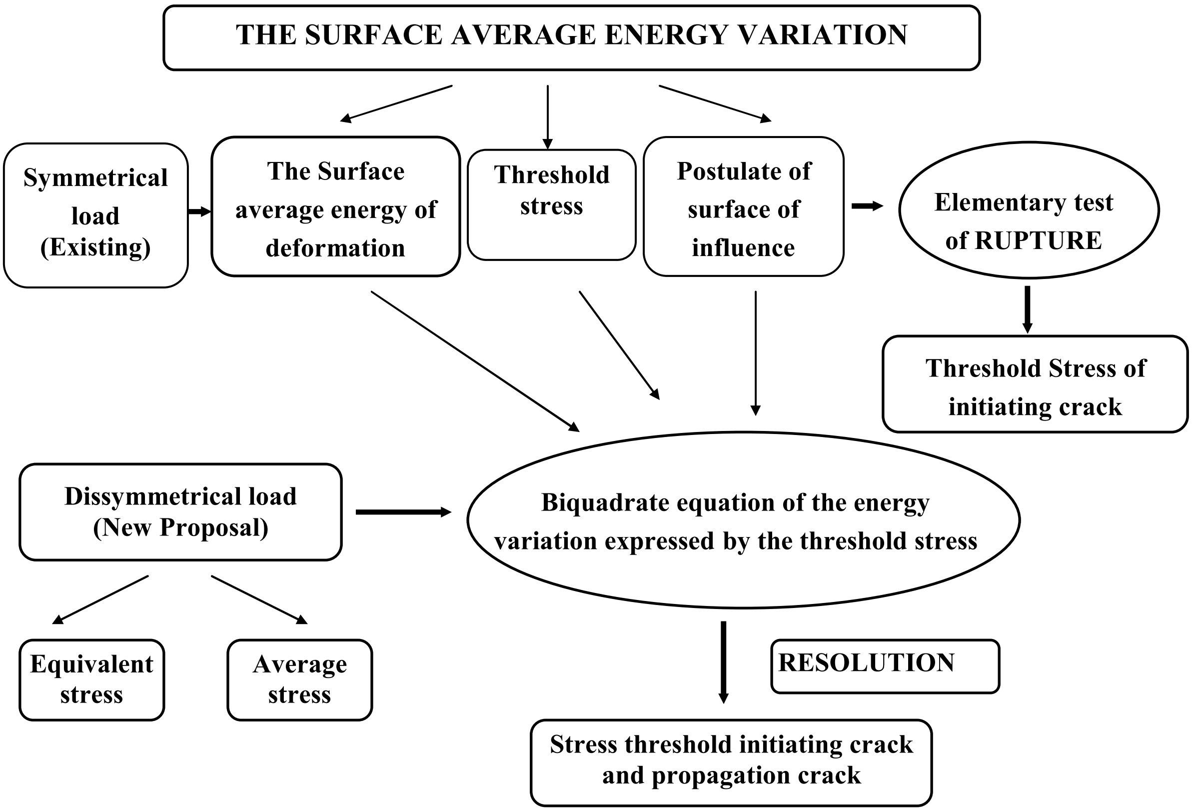

Fig 1.1: Synoptic general of the fatigue behaviour

In this context, we propose an analytical study based on the analysis of the total energy variation. Thus, the analysis of the biquadrate equation enables us to evaluate successively two stresses thresholds responsible for the initiating crack and the propagation of the maximum density of the microscopic cracks leading the test-tubes to the of cylindrical section.

This paper has the advantage of distinguishing the value at the initiating crack from the value at the propagation crack. Although the tests relate to same material, we note dispersion on the threshold stresses. Moreover, we note that the average stress delays the initiating of the microscopic cracks.

Degradation Assessment of Fatigue by X-Ray Diffraction Technique

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ABSTRACT

In many industrial applications materials are subjected to degradation of mechanical properties as a result of real service conditions. The assessment of the remnant lifetime of components and structures is commonly based on correlated procedures including numerous destructive, non-destructive and mathematical techniques that should guarantee reasonably precise assessment of the current damage extent.

Fatigue, the form of failure that occurs in structures subjected to cyclic loading, is the single largest cause of failure of structural components, estimated to compromise approximately 90% of all metallic failures.

The assessment of the component remaining lifetime by X-ray diffraction technique is based on the fact that mechanical properties of the most materials depend strongly on crystallite size and orientation of structural components. The original crystalline grains can decay into a number of fragments as a consequence of mechanical or thermal loads or phase transitions and frequently this fragmentation is not apparent by a microscope. X-ray diffraction method however, detects the real structure, because it characterises the crystallographic structure of the particles. Therefore, the X-ray diffraction can become a powerful tool during the remnant lifetime assessment of in-service degraded components and structrures, base metals and weldments.

There are two ways, in which the real structure can be studied by XRD. In the case of fine crystallites the diffraction lines are continuous with homogeneous azimuthal intensity distribution. In the case of coarse crystallites greater than 10 μm however, the diffraction lines become spotty and the information on the size, shape, orientation and various structural defects of crystallites can be derived from the distribution of diffraction intensity throughout the corresponding spots (azimutal or lateral diffraction line profile) by so called grain-by-grain (GBG) method.

For achieving an assessment of the material properties from the two-dimensional X-ray diffraction patterns an evaluation procedure has been developed taking into account particular features like the statistic and crystallographic underground separation as well as the isolation of the coarse grain figures in the measured patterns.

However, real structure investigation by GBG method requires special detection techniques. While conventional powder diffraction uses zero or one dimensional detectors, measuring the azimuthal diffraction line profile requires two dimensional detectors (global area detectors). Such detectors record X-ray diffraction patterns efficiently with exposure times in the range of ten seconds. This opens the door for the field or on site XRD for real structure investigation of critical components using modern digital technologies.

A mild carbon steel was used for this investigation (0.1%C, 0.4%Mn, 0.2%Si). Test specimens were fatigue loaded with 2000, 4000, 6000, 8000, 10000, 12000, 14000, 16000, 18000, 20000 and 22000 cycles at constant strain of 0.25% in tension without fracture. Azimuthal profiles (χ-scans) of the ferrite (211) diffraction line of some of these samples were measured. For each χ-scan, the total area P_1 of all solitary peaks corresponding to mosaic blocks greater than 10 μm as well as the area P_2 under the curve of the continuous background made up from overlapping reflections of the mosaic blocks smaller than 10 μm

was determined. Then, the proportion of the large mosaic blocks quantified in terms of the value of $y = \log_{10}[100.P_1/(P_1 + P_2)]$ was displayed as a function of the number of cycles n in

From this plot it is apparent that cyclic stress results in alternating dispersal and repeated assembly of dislocations. This leads to a rotating disintegration and growth of mosaic blocks, the boundaries of which are formed by the piled up dislocations. The size of the structural cells (mosaic blocks) peaked after 6000, 10000 and 22000 cycles, these summits being interlaced by valleys after 8000 and 16000 cycles.

CONCLUSIONS

The results of X-ray diffraction investigation of steel and Al-alloy fatigue loaded test specimens proved that the X-ray diffraction technique can efficiently qualitatively and quantitatively describe the changes that occured within the microstructure of test samples. This technique thus can be used for description of material degradation in service and asessment of the remnant life of components and structures.

The experimental data presented in this paper reveal the possibility of cyclic material response during harmonic fatigue loading. The idea of a monotonic damage function need not be generally valid, especially in the early stages of fatigue process before an extensive cracks are initiated. This fact can thus complicate the remaining lifetime evaluation because of the non-unique correlation between diffraction patterns (in this case, or another experimental technique) and the extent of material damage.

Acknowledgement
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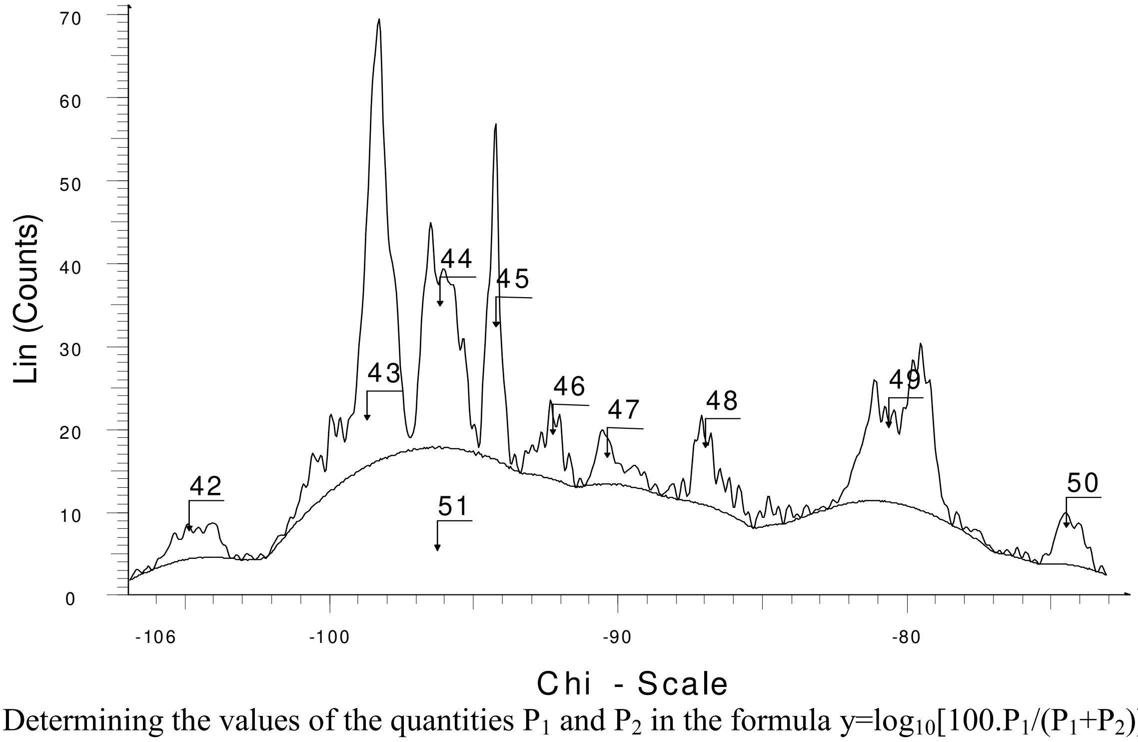

Determining the values of the quantities P_1 and P_2 in the formula $y=\log_{10}[100.P_1/(P_1+P_2)]$ (see text): P_1 = the sum of areas under the solitary peaks rising up above the background = P(42) + P(43) + … + P(50) = 121.2 ; P_2 = the area under the continuous background = P(51) = 186.2 ; y = 1.59. Here, e.g., P(43) means the area under the peak designated “43”, etc.

Notes :

Notes :