BOOK OF ABSTRACTS

Proceedings of the

First Virtual Conference on Mechanical Fatigue

9-11 September 2020
Preface

Dear Colleagues, Dear Friends,

It is with great pleasure that we welcome you to the first edition of the International Conference on Mechanical Fatigue (VCMF 2020).

Due to the covid-19 pandemic, it was not possible to organize the face-to-face event designated "20th International Colloquium on mechanical Fatigue of Metals (ICMFM)". Therefore, it was decided to postpone the 20th ICMFM Conference, which was initially planned for 9 to 11 September 2020 and shift it to the second half of 2021, where a new date will be established soon (more likely also September 2021). The location, namely the Wroclaw City in Poland, as well as the Conference Venue will remain the same.

The first Virtual Conference on Mechanical Fatigue (VCMF 2020) is organised by the University of Porto (FEUP, Portugal), the Wroclaw University of Science and Technology (Poland), University of Electronic Science and Technology of China (China), Siberian Federal University (Russia), and the ESIS/TC12 Technical Committee (European Structural Integrity Society – ESIS), to be held on 9-11 September 2020. This conference is intended to be a forum of discussion of new research concepts, equipment, technology, materials and structures and other scientific advances within the field of mechanical fatigue and fracture. It is expected contributions from engineers, metallurgists, material scientists, among others, allowing a very multidisciplinary discussion.

Contributions were accepted but not limited to the following topics: - Cyclic plasticity and internal structure; - Ultra-low, low-, high- and giga-cycle fatigue; - Mechanisms of fatigue damage; - Fatigue thresholds; - Short and long crack growth; - Fatigue life prediction; - Fatigue behaviour modelling and simulation; - Creep-fatigue interactions; - Probabilistic fatigue and fracture; - Failure analysis and case studies; - Fatigue life extension; - Damage evaluation and fatigue design; - Variable amplitude loading; - Thermal fatigue; - Multiaxial fatigue; - Fatigue in biomaterials; - High temperature fatigue; - Fatigue-corrosion; - Environmental assisted fatigue; - Influence of manufacturing processes on fatigue behaviour; - Structural integrity assessments accounting for fatigue; and, - Applications and design codes (e.g. pressure vessels, metallic bridges, wind towers, offshore structures, etc).

The first edition of the VCMF 2020 event, organized between 9th and 11th of September 2020, gathers more than 60 participants from more than 20 nationalities demonstrating the vitality of this new event. This book gathers the abstracts of the works presented in the conference.

The Organizing Committee of the VCMF 2020 deeply acknowledges all authors that contributed to the success of this event, with their exciting presentations. The members of the Advisory and Scientific Committees are also fully acknowledged for their support to the
conference. Special thanks are also addressed to the Plenary Speakers, Chairmen of the Sessions for their dedication, knowledge and energy brought to this event. Sponsors are also fully acknowledged for their important contributions. Finally, a word of appreciation for the Organizing Committee members as well as students and other FEUP/INEGI/IC staff for their tireless support.

The chair of the Proceedings of the First Virtual Conference on Mechanical Fatigue - VCMF (Book of Abstracts),

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Keynote Lectures
A comprehensive phenomenological methodology for descriptive and predictive probabilistic analysis of fatigue phenomena as cumulative damage processes

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Keywords: fatigue; probabilistic analysis; cumulative damage.

ABSTRACT

Cumulative damage processes are stochastic phenomena in which physical degradation, or loss of physical properties ending with failure or, simply, in a terminal state, are observable. They represent sample functions (or realizations of the stochastic process) to be associated with the evolution of a physical magnitude, which can be identified, provided a previous normalization is applied, with cumulative distribution functions (cdfs) of the generalized extreme value (GEV) distribution family. Such processes are very common in fatigue phenomena and prove to have great interest for description and prediction of states that govern the structural integrity conditions of real components. Usually, only a partial register, or even a small fragment of the damage process is available, according to the specific problem handled. Hence the necessity of robust models to allow the necessary reliable extrapolation (sometimes asymptotic extrapolation) into scenarios out of the scope of the experimental program to be achieved and ensured.

Due to the complexity of modeling such phenomena, microstructural models are not feasible so that phenomenological models are the recommendable alternative. In this work the successive steps of the proposed phenomenological methodology are explained and justified that allow, satisfactorily, descriptive and prospective predictive analysis of different fatigue phenomena to be managed. Its suitability is confirmed by the successive application to a broad spectrum of practical cases to solve well-known problems in fatigue.

The wide variety of fatigue problems already solved with this methodology, and the quality of the fittings achieved justify the universality and utility of this methodology when applied to the practical fatigue design.
Fatigue behavior of 2.25Cr1Mo0.25V steel under strain-controlled and stress-controlled fatigue-creep interaction at elevated temperature

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Keywords: creep-fatigue; dwell effect, cyclic softening, stress relaxation, fatigue life prediction.

ABSTRACT

Large amounts of engineering components used in aerospace, power plants and petrochemical industries experience start-ups and shut-downs during service that may result in fatigue damage [1], whereas dominating steady operations at elevated temperatures usually induce creep deformation or stress relaxation [2], which bring creep damage. In fact, the loading conditions during the service lifetime of engineering components are generally a combination of fatigue and creep, leading to more complicated response of materials and threatening structural integrity harder than either fatigue or creep alone [3]. Correspondingly, researchers worldwide have paid attention to experimental fatigue-creep interaction (FCI) responses of various materials, in the context of elevated-temperature and high-pressure structure design [4]. Strain cycling inherently gives fatigue-type damage, but with the introduction of dwell-periods, creep damage, commonly manifested by grain boundary cavitation, can be induced and leads to interaction between fatigue and creep damages. The effect of stress relaxation, dwell period, dwell position and cyclic hardening/softening on FCI behavior of various materials have been reported and some common features are found [5].

As for 2.25Cr1Mo steel, the ferritic type has been extensively used in pressure vessels and piping systems in power generation industrie. Challenger et al. [6], Brinkman et al. [7] and Jaske et al. [8] thoroughly investigated its fatigue life dependence on strain range, strain rate, strain aging, cyclic wave form and environment, within the temperature range from 316 °C to 600 °C. Compressive hold was found to be more deleterious, and reduction in fatigue life was attributed to combined effects, such as reduced interaction of solid solution hardening and accelerated fatigue crack initiation caused by oxide cracking. In contrast, the bainitic 2.25Cr1Mo steel was reported to show vast different features from the ferritic type, such as continuously cyclic softening and shorter fatigue life with tensile dwell.

However, despite the ambiguity in cyclic behavior and failure mechanism, only limited corresponding research results related to bainitic 2.25Cr1Mo steel can be found in the literature. Therefore, in the present study, the low cycle fatigue (LCF) and FCI responses of a forged bainitic 2.25Cr1Mo0.25V steel are investigated at 728 K. The cyclic mechanical properties and their dependence on strain amplitudes and dwell periods are thoroughly discussed. Detailed optical microscopy and scanning electronic microscopy (SEM) observations are made to identify the failure mechanism[9, 10]. A modified plastic strain energy method, suitable for LCF and FCI conditions, is proposed based on the obtained results.

The modified method can provide endurance predictions for both LCF and FCI loading conditions.

\[
\Delta W_p = \left(1 - \frac{1}{n+1}\right) \cdot \Delta \sigma \cdot \Delta \varepsilon_p \cdot \left(1 + \sum \frac{\sigma_{rel}}{\sigma_a}\right)
\]

(1)

The modified plastic strain energy method provides satisfactory results for both loading conditions since all estimated data fall within the scatter band of 2.
Fig. 1 Comparison of estimated and experimental fatigue lives in LCF and FCI conditions based on the modified plastic strain energy method

REFERENCES


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Analysis of fatigue crack closure with three-dimensional yield-strip model

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Keywords: Fatigue; fracture mechanics; crack closure effects; three-dimensional analytical solution.

ABSTRACT

Plasticity-induced fatigue crack closure is a complex extrinsic mechanism, which has shielding effect on fatigue crack growth due to the change of deformation behaviour near the crack tip. Elber’s discovery of fatigue crack closure, nearly 50 years ago, has been a promising development with the prospect of bringing significant advances in fatigue life predictions of structural components [1, 2]. A large amount of experimental, analytical and computational work has been conducted since this discovery. Unfortunately the original expectations have been largely faded, facing unprecedented difficulties in theoretical modelling. The early two-dimensional crack closure models, which were based on the classical Dugdale (or yield-strip) model, were incorporated in several fatigue life-prediction codes, such as FASTRAN and NASGRO. These codes initially demonstrated encouraging results, specifically in predicting the R-ratio effect in the case of constant amplitude of cyclic loading. However, blind predictions of fatigue crack growth under variable loading conditions are usually disappointing. This is because real cracks are inherently three-dimensional; and the three-dimensional aspects of the problem, e.g. the plate thickness, have a significant effect on the crack closure mechanism. In order to improve fatigue life predictions, the current version of FASTRAN utilises three different constraint factors. These factors are normally identified from appropriate experimental tests [3]. However, it is not necessary that all these factors stay constant or do not vary with the crack advance [4].

There were also many attempts over the past two decades to model fatigue crack growth and plasticity-induced closure mechanism based on direct application of the FE method. The FE based procedures usually employ various automatic finite element re-meshing techniques and node release or crack advance schemes, different cyclic plasticity constitutive equations as well as crack front opening criteria. The direct numerical simulations of fatigue crack growth have been conducted for simple geometries only, such as MCT or CT specimens with none or limited convergence and sensitivity studies. Therefore, it is difficult to evaluate their accuracy and predictive abilities, saying nothing about the efficiency of the direct numerical simulations, which can last from several days to several weeks.

A new theoretical approach is presented here. It is based on the 3D Dugdale model [5], a special formulation of the Distributed Dislocation Technique for boundary-value problems involving material and contact non-linearities and an effective computational method for solving governing equations. These three unique features of the current approach provide the following main advantages in comparison with all other similar developments in this area:

(i) The utilisation of explicit 3D analytical solutions avoids the need for various empirical constraint or correction factors;

(ii) The use of Distributed Dislocation Technique formulation (rather than e.g. weight function method) allows for a very accurate and efficient evaluation of the crack opening profile, plastic and contact stress. In addition, it makes possible the cycle-by-cycle evaluation of crack opening and closure.
In particular, this feature removes uncertainties associated with unavoidable truncation of the fatigue loading spectrum, which is currently utilised in FASTRAN and NASGRO codes;

(iii) The crack advance model is based on the effective Crack Tip Opening Displacement rather than effective Stress Intensity Factor range. The Crack Tip Opening Displacement seems to be more appropriate when utilising strip-yield type models in fatigue and fracture calculations.

REFERENCES


The influence of monotonic damage which precedes cyclic loading

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Keywords: High stress ratio; strain energy; fatigue; damage; monotonic

ABSTRACT

Fatigue damage is almost universally accounted for using the concept of cycles or reversals, and typically the initial monotonic loading which precedes the cyclic loading is neglected under the assumption that the damage is negligible compared to the damage from thousands or millions of cycles. As the mean stress approaches the ultimate tensile strength of a material this assumption may become invalid, as the material approaches a condition of failure before the cyclic loading begins. This work proposes a method for accounting for the damage accumulated during monotonic loading that often occurs prior to high stress-ratio cyclic loading and describes how the remaining specimen life is influenced in terms of stress-amplitude versus life and stress-amplitude versus mean-stress at a constant life. The damage model is based on strain energy and dislocations energy [1]. Results are compared to data from the literature.


REFERENCES

Extended Abstracts
Probabilistic fatigue life evaluation under combined notch and size effects

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Keywords: notch fatigue; size effect; Weibull model; life prediction; failure probability.

ABSTRACT

Fatigue lifing technology has become one of the most important research topics in modern engineering field, and has been made the list of the emerging technologies in 21st century. Fatigue behaviors of complex engineering parts are generally evaluated based on mechanical properties of materials collected from tests on standardized specimens. After nearly a century of development, a relatively sound testing technique on material performance has been built. Nowadays, achieving the transformation between fatigue properties of small-scale laboratory specimens to the structural strength of large-scale engineering components has become an increasingly urgent task in this field. Among factors impeding the smooth transformation, notch and size effects are two dominant elements [1]–[3]. In addition, a significant scatter in fatigue life for material testing also creates barriers in this process, which results in the necessity of advanced probabilistic fatigue models.

For large structures, statistically adequate test replication is neither technically nor economically feasible, so that reliability analysis which cannot be based on the evaluation of statistical data must be developed from physically relevant probability concepts. In this work, by adopting the elasto-plastic FE analysis, fatigue evaluation of notched components considering the combination of notch and size effect are investigated [4]. Combining with the generalized local model [5], a probabilistic framework is proposed for fatigue life assessment of notched components considering size effects, in which the Smith–Watson–Topper damage parameter is utilized as the generalized parameter to address the multiaxial stress state at the notches [6]:

\[ \varepsilon_{n,a} = \frac{\sigma_{n,a}^2}{E} (2N_f)^b + \varepsilon_f (2N_f)^{b+c} \]  

and an effective stress concept is introduced to characterize the inhomogeneous stress distribution on the surface [7]:

\[ \sigma_{eff} = \frac{1}{\rho_{eff}} \int_0^{\rho_{eff}} \sigma(x, \theta = 0) \times \varphi(x, \chi(x)) dx \]  

The extended generalized local model yields the following form:

\[ P_{fail,i} = 1 - \prod_{j=1}^{N} \left[ \exp \left( \frac{\Delta S_j}{\delta_{ref}} \left( \frac{\ln(\varepsilon_{n,a} \sigma_{eff}) - c}{\ln(N-B)} \right)^\beta \right) \right] \]  

From the abovementioned points, a general probabilistic framework for fatigue life assessment of notched components considering size effects is summarized. Finally, experimental data of TA19 central circular hole (CCH) specimens with different scales [8] are utilized for model validation and application, results show that the proposed model yields acceptable correlations with the experimental results, see Fig. 1 and Table 1. The LNV model proposed by Wang et al. is also introduced for comparison [8].
Figure 1 Comparison of experimental and predicted probabilistic lifetimes for different scales of TA19 CCH specimens using the proposed probabilistic framework.

Table 1 Comparison between average absolute errors using proposed model and LNV model (%).

<table>
<thead>
<tr>
<th>Scale (%)</th>
<th>100</th>
<th>80</th>
<th>60</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNV model</td>
<td>6.10</td>
<td>10.45</td>
<td>9.98</td>
<td>6.06</td>
</tr>
<tr>
<td>Proposed</td>
<td>8.93</td>
<td>9.62</td>
<td>6.86</td>
<td>5.66</td>
</tr>
</tbody>
</table>

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ACKNOWLEDGMENTS

Financial support of the National Natural Science Foundation of China (No. 11972110 and 11672070), Sichuan Provincial Key Research and Development Program (No. 2019YFG0348), Science and Technology Program of Guangzhou, China (No. 201904010463) and Fundamental Research Funds for the Central Universities (No. ZYGX2019J040) are acknowledged.
TCD-based Probabilistic modelling of fatigue life distribution of notched components

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Keywords: critical distance, fatigue, size effect, highly stressed volume, probabilistic modeling

ABSTRACT

For engineering components with notches, cracks and other defects, fatigue life prediction is critical for ensuring the structural integrity. In this regard, a probabilistic model coupling Weibull model with the theory of critical distance (TCD) is established for fatigue life prediction of notch components. The influence of size effect on critical distance values and predicting performance is investigated by a novel methodology combining critical distance theory with the highly stressed volume approach. In particular, it was found that a close correlation exists between the highly stressed volume and the critical distance values at a certain number of cycles to failure. The accuracy and reliability of the proposed method were validated based on experimental data of low carbon steel En3B and Al 2024-T351. Predicted \( P-S-N \) curves indicate that the predicted probabilistic scatter band agree well with the experimental results.

ACKNOWLEDGMENTS

Financial support of the National Natural Science Foundation of China (No. 11972110 and 11672070), Sichuan Provincial Key Research and Development Program (No. 2019YFG0348), Science and Technology Program of Guangzhou, China (No. 201904010463) and Fundamental Research Funds for the Central Universities (No. ZYGX2019J040) are acknowledged.
Mode superposition techniques for a priori high stress detection and fatigue hotspot identification

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Keywords: Fatigue; Hot Spot Filter; High Stress Detection; Durability Analysis

ABSTRACT

For the evaluation of a structures fatigue life, the knowledge of detailed stress histories plays a crucial role. In industrial application, the finite element method (FEM) has become the most widely applied tool for numerical stress and subsequent fatigue analyses. Common approaches for the dynamic stress analysis of vibrating structures are based on modal decoupling of the discretized system of equations of motion using the system eigenvectors and the superposition of modal stress fields.

While most computational cost is spent for the evaluation of time dependent global stress fields, the areas that are relevant for durability analyses are limited to highly stressed local regions. For the reduction of processed data, a subsequent fatigue analysis is carried out on these limited regions using the so-called hot spot filters, pointing out highly stressed elements based on threshold values. Available methods can be summarized as posteriori methods, as they root in the calculated stress histories or modal contributions.

From the field of structural health monitoring and damage detection, it is well known that strain modes are powerful means for indication of fatigue cracks. Yet, modal strain and corresponding modal stress can be evaluated from the systems eigenvectors prior to cost intensive stress history analysis.

Fig. 1. Modal displacement (left) and corresponding modal stress (right)

From this point, the a priori detection of high stress regions, that are relevant for fatigue analysis, is an important input for the reduction of computational cost and data as well as for design optimisation or strain gauge placement for experimental validation.

In this paper, a novel approach is developed, based on the superposition of modal fields by means of appropriate prediction of maximum modal contributions. Main influences on modal contributions are identified and suitable parameters for superposition are summarized. As modal fields are scalable, special...
attention is paid to mode normalisation. Combining the developed approach with material data, appropriate threshold values for hot spot detection are presented. For validation, numerical fatigue analyses are carried out on a complex FE-model from automotive industry (courtesy of Volkswagen AG). Fig. 2 shows the results of a performed fatigue analysis and corresponding fatigue hot spots as reference solution.

![Fatigue damage and hot spots](image)

**Fig. 2.** Fatigue damage (left) and corresponding fatigue hot spots (right)

On this basis, the proposed automated hot spot detection algorithm shows reasonable results with low computational cost for the identification of high stress and critical fatigue life regions (Fig. 3).

![Fatigue hot spot detection results](image)

**Fig. 3.** Results of fatigue hot spot detection algorithm
Experimental investigation of corrosion-fretting fatigue performance of steel wires

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Keywords: Corrosion-fretting fatigue; steel wire; fracture; morphology; fatigue Life.

ABSTRACT

Steel wires are usually manufactured into wire ropes and utilized as hoisting devices in mechanical structures for the superiority in high intensity and low bending stiffness [1]. However, premature failure usually occurs on wire ropes in mechanical engineering under alternating stress whilst exposing to environmental erosion [2]. Wires in a rope are subjected to fluctuating external loads, accompanied by fretting wear resulting from inter-wire relative sliding and high contact stress. Simultaneously, the wires are also exposed to aggressive environment during the design lives. Hence, with the interaction of cyclic stress and fretting wear, the wires inevitably suffer from corrosion-fretting fatigue, which can lead to premature cracking and fracture of the wires, even the failure of wire ropes [3].

To investigate the corrosion-fretting fatigue behaviour of steel wires, several coupling tests of corrosion fretting and fatigue have been conducted based on a developed test system. The influence of different corrosion and fretting fatigue parameters on the damage process of wires was investigated. Cracks, fracture surfaces and corrosion/fretting scars of wires were further observed and investigated by using the scanning electronic microscope (SEM) and the energy dispersive spectroscopy (EDS) to identify the characteristic of corrosion-fretting fatigue.

Fig.1(a) shows a schematic of the developed test equipment, which can conduct fretting fatigue testing under constant normal force. The fretting fatigue test equipment consists of a fatigue testing machine and a wear assembly. The upper gripping head of the fatigue testing machine drags the wire specimen back and forth to produce cyclic stress and relative displacement. The wear assembly provides external fretting wear under the action of normal force loading device. Strain gauges were applied to obtain the strain variations of the tested wires, which can be used to evaluated the tangential force. Fig. 1(b) shows the picture of the fretting fatigue testing, where high strength low alloy wires with a diameter of 5mm that are usually used in civil engineering cables were tested.
A sinusoidal loading mode was applied to provide fatigue stress, whose mean stress and stress range are shown in Eq. (1).

\[ \sigma_m = 0.45 \sigma_u - \sigma_a, \sigma_a = 180 \text{MPa} \]

where \( \sigma_m \) and \( \sigma_a \) are mean stress and stress range; \( \sigma_u \) is mean and ultimate stress.

Fig. 2 presents the typical coupling scar and fracture surface of the wires. Similar to the scar induced by fretting fatigue, the coupling scar was about ellipse with the long axis along the sliding direction. The depth of the coupling scar gradually increased from the end to the centre, corresponding to stick zones and slip zone. Observation indicated that the surface structure of the coupling scar was loose, as shown in Fig. 2(a). In order to identify the source of fracture, SEM analysis was conducted on the coupling scars of several wires prior to the end of fatigue test. As shown in Fig. 2(b), there were surface micro cracks at the trailing edge, where fracture evolved. Fig. 2(c) presents typical fracture surfaces of the tested wire due to corrosion-fretting fatigue damage, which reveals that the fracture initiated from the scars.

![Fig. 2. Coupling scar and fracture surface of tested wires](image)

Table 1 gives the fatigue lives of tested wires under different the current intensities. It is observed that the damage of steel wires was accelerated by corrosion, and greater corrosion (greater external current) significantly decrease the service life of the wire in corrosion-fretting fatigue tests.

<table>
<thead>
<tr>
<th>Current intensity</th>
<th>Mean</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.000A</td>
<td>397738.8</td>
<td>22399.3</td>
</tr>
<tr>
<td>0.010A</td>
<td>191329.7</td>
<td>23224.5</td>
</tr>
<tr>
<td>0.015A</td>
<td>159796.3</td>
<td>23117.3</td>
</tr>
</tbody>
</table>

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ACKNOWLEDGMENTS

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Mixed mode (I+II) fatigue crack growth and crack closure effect in 42CrMo4 steel under different heat treatment conditions

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Keywords: Mixed-mode loading, Crack growth, Crack closure, Mechanical Fatigue

ABSTRACT

The presented work contains experimental results of fatigue crack growth rate in 42CrMo4 steel. All performed investigations were focused on fatigue crack growth rate and fatigue crack closure effect under mode I and mixed-mode (I+II) loading conditions. For the experimental campaign, CTS (Compact Tension Shear) specimens were involved. Steel 42CrMo4 was investigated for two heat treatment (HT) states corresponding with two different types of microstructure: normalized and fine-grained martensite. Initial experiments conducted on CT samples under mode I loading conditions for the same kind of steel [1] shown the impact of different HT conditions on results of fatigue crack growth. The obtained results suggested that ductility of the material plays a crucial role in the crack growth rate description, including closure effect. For the different mixity level characterisation, the tests were conducted for angle $\alpha = 30^\circ$ and $60^\circ$ using CTS specimens. During the experimental campaign, the hysteresis loops were recorded using the extensometer and DIC (Digital Image Correlation) system. After the FCGR (Fatigue Crack Growth Rate) tests, the fatigue crack paths study was analysed. For each crack path and crack length the SIFs (Stress Intensity Factors) and J-integral values were computed using Finite Element Method.

REFERENCES


ACKNOWLEDGMENTS

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Fatigue assessment of metallic detail with statistical analysis of material data

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**Keywords:** Fatigue; Local analysis; Statistical approach

ABSTRACT

Structural integrity studies of bridges are fundamental for their maintenance and the fatigue assessment plays an important role on it. In this sense, scientific investigation is needed in order to accurately determine the fatigue life of structural components. The most common method used to determine the fatigue life of a structural component is by implementing a global approach. It is directly dependent on the applied nominal stress level. However, local approaches are able to describe local damage phenomena using local parameters (based on stresses, strains or energy). In this paper is intended to implement a local approach using characteristic material fatigue data. The structural detail analysed herein is presented in Figure 1 and it is representative of a S235 steel plate with a hole in the centre. It should represent a component of a fastened connection. A set of fatigue tests was conducted by Valtinat [1] using this metallic detail. Its experimental results are used in this analysis.

![Metallic detail](image_url)

Fig. 1. Metallic detail.

Fatigue life assessment was conducted using a local approach based on strains using the formulation proposed by Morrow [2] (Eq. 1) where $\Delta \varepsilon_{\text{loc}}$ is the local strain range, $\sigma'_{f}$ and $b$ are the fatigue strength coefficient and exponent, respectively, $\varepsilon'_{f}$ and $c$ are the fatigue ductility coefficient and exponent, respectively, $E$ is the elastic modulus and $N_{f}$ is the number of cycles. Local strain range was assessed using the analytical Neuber approach [3] and the cyclic curve presented in Eq. 2, where $\Delta \sigma_{\text{loc}}$ is the local stress range, $\Delta \sigma_{\text{nom}}$ is the nominal stress range, $K'$ and $n'$ are the strain hardening coefficient and exponent, respectively, and $K_{t}$ is the stress concentration factor with value of 2.4 [4]. The mean values of $\sigma'_{f}, b, \varepsilon'_{f}, c$ and $E$ were determined by Carvalho et al [5] and characteristic values were assessed by implementing a statistical analysis using normal distribution with 75% confidence level and 95% probability – see Table 1.

$$\frac{\Delta \varepsilon_{\text{loc}}}{2} = \frac{\sigma'_{f} - \Delta \sigma_{\text{loc},\text{med}}}{E} (2N_{f})^{b} + \varepsilon'_{f} (2N_{f})^{c}$$  \tag{1}
\[
\left( \frac{\Delta \sigma_{loc}^2}{E} + 2 \frac{\Delta \sigma_{loc}}{2K'} \right)^{1/n'} = \frac{K_t^2 \Delta \sigma_{nom}^2}{E}
\]

\[\Delta \varepsilon_{loc} = \frac{\Delta \sigma_{loc}}{E} + \left( \frac{\Delta \sigma_{loc}}{2K'} \right)^{1/n'}\]

(2)

<table>
<thead>
<tr>
<th>Table 1. Material properties of S235 steel.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E)</td>
</tr>
<tr>
<td>[MPa]</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>Characteristic</td>
</tr>
</tbody>
</table>

In Figure 2 is presented the experimental data. It was analysed with a linear regression resulting in a slope of 3.5. The local approach using Morrow relation is also presented and it is possible to observe a very good correlation between the experimental data and mean curve, while the design curve shows a safe and conservative approach.

Fig. 2. Fatigue analysis of metallic detail.

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The authors would like to acknowledge the Fundação para a Ciência e Tecnologia (FCT) for funding the scholarship SFRH/BD/145037/2019. This research was also supported and funded by: project grant (POCI-01-0145-FEDER-030103) FiberBridge - Fatigue strengthening and assessment of railway metallic bridges using fiber-reinforced polymers by FEDER funds through COMPETE2020 (POCI) and by national funds (PIDDAC) through the Portuguese Science Foundation (FCT/MCTES).
**Stochastic modeling of fatigue crack growth**

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**Keywords:** fatigue; stochastic crack growth; exceedance probability; initial crack size.

**ABSTRACT**

As damage tolerance design has been widely accepted and applied in the industry, fatigue crack growth (FCG) is of paramount significance for life prediction of engineering components. Among FCG modeling strategies, probability-based methodologies are increasingly attractive to show the statistical characteristic of crack growth rate. Yang–Manning model was developed using the second-order approximation of stochastic process for FCG analysis to calculate the crack exceedance probability and fatigue life distribution to reach any crack size. However, it can only applicable for failure probability analysis of pre-cracking specimens. In this work, a probability model is proposed based on the Yang–Manning model considering the randomness of the initial crack. The result of the new model is obtained by the experimental data for standardized specimens of 30NiCrMoV12 steel. In addition, the fatigue failure probability is derived by simply combining a Monte Carlo simulation with statistical analysis of cracks and stochastic process of FCG. The new probability FCG model can provide acceptable predictions of fatigue lifetime for multiple surface cracks propagate independently and the simulation results agree well with the experimental results.

**ACKNOWLEDGMENTS**

Financial support of the National Natural Science Foundation of China (No. 11972110 and 11672070), Sichuan Provincial Key Research and Development Program (No. 2019YFG0348), Science and Technology Program of Guangzhou, China (No. 201904010463) and Fundamental Research Funds for the Central Universities (No. ZYGX2019J040) are acknowledged.
Energy models in fatigue crack growth rate description in terms of mean stress effect avoidance under mode I and mixed-mode (I+II, I+III) loading condition

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Keywords: Fatigue Crack growth rate, Energy approach, Mixed-mode loading,

ABSTRACT

In the paper, the problem of fatigue crack growth description is discussed in terms of the energy approach. Authors presented energy models based on the strain energy density parameter applied to the fatigue crack growth rate (FCGR) description. The main beneficial results of this approach is a generalization of the FCGR curves independently from stress ratio R. The presented method is also strongly connected with the theoretical background of new energy balance for cracked components under mode I loading type condition. Based on hysteresis loops registered during FCGR experiment, Authors demonstrate independence from stress ratio in FCGR description also for mixed-mode loading conditions – as presented in Fig. 1 exemplary FCGR diagram for S355 grade steel (18G2A). In the paper, the experimental details and specimen configurations are discussed in the light of the existed techniques. All models are validated for various metallic materials including constructional steel, high-strength alloys as well as Al-alloys commonly used in engineering applications.

![Fatigue crack growth rate diagram (mode I+III condition) for S355 grade steel (R=0; R=-0.5; R=-1) based on new strain energy density parameter $\Delta S^*$ [1]](image)

REFERENCES

Statistical analysis of monotonic and cyclic experimental data of centenary bridge material

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Keywords: Old metallic materials; Statistical analysis; Bridges.

ABSTRACT

One key aspect related to structural integrity of bridges is the fatigue behavior of its materials and structural components. Residual life calculations of bridges in operation should consider fatigue as a progressive damaging mechanism, therefore a consistent residual life prediction should be based on actual fatigue data from bridge members. Furthermore, the obtained experimental data should be analyzed considering uncertainty and scatter using statistical treatments.

It is intended to present and analyze strain-life fatigue data obtained using samples of original material removed from four Portuguese metallic riveted bridges – see Table 1. Besides the fatigue properties, monotonic and cyclic elastoplastic properties are assessed for the samples of materials.

The oldest bridge is the Eiffel bridge, that was designed by Gustave Eiffel and was inaugurated on 30th of June 1878. This bridge crosses the Lima river, in Viana do Castelo, and serves both road and railway traffic. The second oldest bridge considered in this study was the Luiz I bridge. This bridge was also designed by Gustave Eiffel and was commissioned in 31st October 1886. This bridge crosses the Douro river and links the Porto and Gaia cities. The third oldest bridge included in this study was the Fão road bridge. This bridge was designed by Abel Maria Mota, under the supervision of Reynau, at the end of 19th century and was inaugurated on 7th of August 1892. It crosses the Cávado river at Esposende. Finally, the youngest bridge included in this study was the Trezói railway bridge. This bridge makes part of the Beira Alta railway line and was inaugurated on 20th of August 1956. While the material used in the Trezói bridge is construction steel, the material used in the older bridges is very likely puddle iron. However, at the end of the XIX century and beginning of the XX century, the qualities of the puddle irons changed appreciably.

Table 1. Identification of centenary Portuguese bridges where material under analysis was extracted.

<table>
<thead>
<tr>
<th>Bridge name</th>
<th>Year of construction</th>
<th>Nr. of specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eiffel</td>
<td>1878</td>
<td>27</td>
</tr>
<tr>
<td>Luiz I</td>
<td>1886</td>
<td>15</td>
</tr>
<tr>
<td>Fão</td>
<td>1892</td>
<td>14</td>
</tr>
<tr>
<td>Trezói</td>
<td>1956</td>
<td>10</td>
</tr>
</tbody>
</table>

Monotonic and cyclic material data was obtained by De Jesus et al [1]. They implemented deterministic models to characterize the materials. For monotonic and cyclic elastoplastic behavior Ramberg-Osgood formulation [2] while for strain-life assessment the Morrow equation [3]. In this paper an additional method
will be implemented to assess the strain-life behavior which was proposed by Heim [4] based on monotonic parameters of the material.

In this paper it is intended to analyze a set of experimental data by implementing a statistical treatment using two distribution types (Normal and Weibull) in order to obtained characteristic values of all the variable of the models. Normal distribution function relies on mean and standard deviation parameters while Weibull distribution function depends on the shape and scale parameter whose estimation will be made by several methods, namely: Maximum Likelihood Method (MLM), Method of Moments (MM), Linear Least Squares Method (LLSM) and Weighted Linear Least Squares Method (WLLSM).

The generated data, namely characteristic values of models parameters, are essential for residual fatigue life estimations of old metallic bridges. The coefficient of variation of the parameters will be assessed for all parameters and compared with the values indicated by Jakubczak et al [5].

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The effect of hydrogen on the fatigue properties of high grade pipeline steel

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Key words: high grade pipeline steel; fatigue property; hydrogen embrittlement; spiral weld

ABSTRACT

In recent years, many synthetic natural gas demonstration projects have been put into operation all over the world, and hydrogen is usually contained in synthetic natural gas. X70 and X80 are the most commonly used high grade pipeline steel in construction of natural gas pipelines. The compatibility of high grade pipeline steel with hydrogen directly affects safety and reliability of long-distance pipelines. In order to study the effect of hydrogen on fatigue properties of high grade pipeline steel, fatigue samples were taken from base metal and spiral welds of submerged arc spiral welded pipes. The total pressure was 10/12 MPa and hydrogen fraction was from 0 to 5vol\%. The test results shows that the addition of hydrogen significantly increases the fatigue crack growth rate of base metal, spiral weld, heat affected zone of X70 and X80 pipeline steel, which increases about ten times compared with reference environment nitrogen.
Biaxial stress concentration of pultruded GFRP perforated plate

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Keywords: GFRP; stress concentration; notch stress; biaxial; composite structures.

ABSTRACT

Pultruded GFRP perforated plates are widely used in composite bridge and truss [1-3]. Stress concentration is an inevitable focus of the structural design and analysis [4-5]. This paper investigated the stress concentration of pultruded plate with hole under both uniaxial and biaxial stress. The hole’s radius \(r\), the width \(w\), height \(h\) of plate and lay-up were involved. Biaxial stress parametric Finite Element Model (FEM) of GFRP perforated plates were created as summarized in Table 1. The loading scheme is shown in Fig. 1.

In terms of notch stress in GFRP perforated plate, the stress concentration of \(0^\circ\) ply is significant under unidirection tension. When height to radius ratio is greater than 0.15 (\(2r/h>0.15\)), the stress concentration factor is suggested to be modified based on Tan’s model [6]. The biaxial status of tension-compression is the governing load combination of GFRP perforated plate. The analysis method of biaxial status has been proposed in the paper.

<table>
<thead>
<tr>
<th>Specimens</th>
<th>(w)</th>
<th>(r)</th>
<th>(h)</th>
<th>(2r/h)</th>
<th>(\lambda)</th>
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<tr>
<td>Bia-1</td>
<td>150</td>
<td>10</td>
<td>80</td>
<td>0.25</td>
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</tr>
<tr>
<td>Bia-2</td>
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<td>100</td>
<td>0.20</td>
<td>1.04</td>
</tr>
<tr>
<td>Bia-3</td>
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<td>10</td>
<td>150</td>
<td>0.13</td>
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</tr>
<tr>
<td>Bia-4</td>
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<td>10</td>
<td>200</td>
<td>0.10</td>
<td>0.97</td>
</tr>
<tr>
<td>Bia-5</td>
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<td>10</td>
<td>300</td>
<td>0.07</td>
<td>0.97</td>
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<tr>
<td>Bia-6</td>
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<tr>
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<tr>
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<td>200</td>
<td>10</td>
<td>200</td>
<td>0.10</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Fig. 1. Biaxial stress loading scheme of GFRP perforated plate

REFERENCES


ACKNOWLEDGMENTS

Prediction of crack initiation life in high-strength steel components fabricated by additive manufacturing


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Keywords: multiaxial fatigue; life prediction; crack initiation behaviour; selective laser melting.

ABSTRACT

High-strength steels play an important role in modern automotive industry because of their superior mechanical properties, namely excellent strength-to-weight ratio, high corrosion resistance and low cost. Policies to reduce fuel consumption, air pollution and carbon footprint have led to the development of lighter components [1]. This strategy is often achieved through an optimised design, which may contain abrupt geometrical changes. In the presence of complex cyclic loading, sometimes with a multiaxial nature, these regions are prone to fatigue failure. Therefore, the development of accurate predictive models may be an important engineering tool to improve design.

Selective laser melting is a very popular but unequivocally complex technique for metal processing that creates fully-functional components, directly from three-dimensional digital models, by successive deposition of thin layers of material. Due to the nature of this additive manufacturing process, products are prone to different types of anomalies (e.g. porosities, inclusions, voids, cavities, micro-cracks, shrinkage, lack of fusion, excessive roughness, etc.) increasing the uncertainty concerning the mechanical behaviour [2]. Thus, a good understanding of structural integrity under cyclic loading is pivotal to extend the field of application and develop more sophisticated products.

Multiaxial loading is a critical issue in mechanical design that requires tuned engineering approaches. Particularly with regard to the additively manufactured parts, the development of tailor-made methods for fatigue life assessment is yet in an embryonic stage. In addition, the most efficient multiaxial fatigue models require a huge number of material constants and complex computational simulations, making the process time-consuming and expensive. In this way, there is an urgent need for efficient design solutions, preferably grounded on simple material characterisation tests, and with high accuracy standards.

The present paper aims to introduce a new predictive model based on an one-parameter damage law defined on the basis of the SWT damage parameter [3] from uniaxial low-cycle fatigue tests [4]. The cyclic plasticity at the notch-controlled process zone under multiaxial loading is accounted for by combining the equivalent strain energy density (ESED) concept and the theory of critical distances. The method reduces the multiaxial loading scenario to an equivalent uniaxial loading state by accounting for the von Mises stress range at the critical plane, in the crack initiation site, via the finite element method in a linear-elastic framework. This effective stress enables the calculation of a representative value of the SWT damage parameter which is then inserted into the one-parameter law to evaluate the number of cycles to crack initiation. An interesting feature of the proposed approach is the possibility to use either refined structured meshes or coarse unstructured meshes without loss of accuracy.
Multiaxial fatigue tests were conducted in a 150mm-long hollow cylindrical bars with 5mm-diameter transversal holes. The outside diameter was equal to 16 mm, while the internal diameter was equal to 9 mm. The loading scenarios encompassed three bending moment to torsion moment ratios (B/T) and different nominal stress amplitudes. The specimen geometries were fabricated by selective laser melting from 18Ni300 powder, in a vertical orientation, on the base plate, using a Concept Laser M3 linear printing system equipped with a Nd:YAG fibre laser.

Figure 1 compares the fatigue lives obtained in the experiments with those predicted using the proposed methodology. As can be seen, the predictive capabilities of the proposed methodology are very attractive, with all points within scatter bands with factors of two, either for the structured meshes (Sm) or the unstructured meshes (Um). Furthermore, the proposed fatigue life prediction model, built up with a limited number of material constants, and supported by a linear-elastic framework, is suitable for industrial applications, which is an interesting outcome.

![Graph comparing predicted and experimental fatigue lives](image)

**Fig. 1.** Predicted lives versus experimental lives for the proposed method from structured meshes (Sm) and unstructured meshes (Um).

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**ACKNOWLEDGMENTS**

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Application of data-driven methods to estimating fatigue crack propagation rates

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Keywords: Fracture; Fatigue crack propagation; Structure; Data-driven models; Reliability analysis.

ABSTRACT

The crack growth in metals and structural components are an important variable that should be precisely predicted to avoid any future failure consequences of such structures. However, this phenomenon is considered as a stochastic process. In this regards, a new developed framework using artificial intelligence techniques is utilized to estimate the crack propagation rates. To do so, large replicate experimental results gathered from literature are employed. Moreover, to investigate the performance, efficiency and robustness of the proposed models, several criteria are used such as statistical indicators and uncertainty analysis. In addition, graphical illustrations are also used to compare the actual and predicted fatigue propagation data. The obtained results indicate that data-driven models can be used as powerful tools for such application, in which these models can be integrated in the future for reliability analysis frameworks of various structures.
Numerical and Experimental Investigation on Hysteretic Performance of Composite Girder with Corrugated Web

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Keywords: composite girder; corrugated steel web; quasi-static test; hysteretic performance; finite element analysis.

ABSTRACT

Recently, corrugated steel plates without longitude or transverse stiffeners, showing higher out-of-plane stiffness and shear strength, have been increasingly applied in infrastructure construction, such as roofs, shear walls, industrial buildings and bridges. By replacing the concrete webs in PC bridges or the stiffened flat steel webs in steel-concrete bridges with corrugated steel webs (CSW), the self-weight of superstructure is significantly reduced, and prestressing can be efficiently introduced to concrete flanges due to the low stiffness of CSW, therefore, the strength, stability of the structure, and material efficiency are improved for composite bridge with CSWs.

A large number of researches has been conducted on the static behaviour of steel or composite girder with CSW including bending, shear, torsional and fatigue [1,2], but relatively limit studies related to cyclic behaviour. Based on the ref. [3,4], corrugated steel plates exhibit good seismic performance in steel shear wall and steel coupling beam. However, the hysteretic performance of corrugated steel plate is quite different from the composite girder with CSWs due to the restraining effect of concrete slabs which connected the CSWs by shear connectors. Therefore, it is necessary to investigate cyclic behaviour of composite girder with CSWs.

This paper aims to understand the hysteretic performance of composite girder with CSWs through quasi-static tests and finite element simulations of two specimens (CSW-1 and CSW-2) with different shear-span ratios. The specimens with I-shaped cross section include top and bottom concrete slabs, and corrugated steel web. Fig. 1 shows the structural dimensions and the details of each component. The effective height \( h \) is 2000mm and 4000mm for specimens CSW-1 and CSW-2, respectively. The free end of the test specimen was clamped to a horizontal hydraulic actuator for applying the cyclic lateral loads. The basement was anchored to the strong floor of the laboratory by high strength bolts. The Instrumentation of test specimen consists of load cells, linear variable displacement transducers (LVDTs) and strain gauges. Besides the measurements of displacements and strains for test specimens during the loading process, cracking initiation and propagation on concrete surfaces were observed. The damage process and failure modes, hysteretic curves, load-carrying capacity and ductility, strength and stiffness degradation, energy dissipation capacity, deformation recovery ability were obtained and analysed.

Based on the experimental specimens and loading protocol, the nonlinear finite element analysis (FEA) program ABAQUS was used to simulate the cyclic loading tests of composite girders with CSWs. Fig. 2 describes the finite element mode of test specimens, material nonlinearity (Concrete Damaged Plasticity of concrete) and the interaction between different components were properly considered. Different mesh sizes, element types and interactions were also studied to ensure a reliable and efficiency model.
Fig. 1. Test specimens (unit: mm)

Fig. 3 shows the comparison of load-displacement curves from the quasi-static test and finite element analysis for CSW-1, the agreement of both curves verified the accuracy of finite element model. The experimental and numerical results indicated that the specimen with small shear-span ratio tended to shear buckling of corrugated steel web, the specimen with large shear-span ratio showed typical flexural failure mode. The hysteretic curve is plump, and the ductility coefficient is more than 3 for test specimen CSW-2, indicating good energy dissipation and deformation capacity. However, the hysteretic curve is less plentiful with the obvious pinching phenomenon for CSW-1. With the decrease of shear-span ratio, the load-carrying capacity and elastic stiffness of test specimens are increased, while the ductility coefficient is decreased, the degradation rate of stiffness is accelerated.

Fig. 2. Finite element modes

Fig. 3. Comparison of test and FEA load-displacement curves

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Foreign object damage tolerance and fatigue analysis of induction hardened S38C axles

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Keywords: foreign object damage, railway axle, fatigue strength, K-T diagram.

ABSTRACT

Flying ballast impact damage on railway axles poses a threat to structural integrity and safety of railway operation. A comprehensive evaluation on the influence of FODs on the fatigue strength of axle is a preliminary step for safe running and maintenance of axle under damage tolerance philosophy. In our precious work, a statistical investigation was made focusing on the FODs on actual surface induction hardened S38C axles. In the present work, with aid of compressed-gas gun, FOD was simulated by shooting tungsten steel ball on the studied surface of specimen extracted from surface induction hardened S38C axle. Impact velocity includes 200 m/s, 300 m/s and 400 m/s, and five incident angles are studied for every impact velocity. Both macro and micro morphology of impact damage was observed by SEM, also the cross sections. Fatigue strength of impacted specimen was evaluated by four-point bending fatigue test and the fractography was characterized by SEM. The results show that depth and volume of damaged zone increases as the incident angle enlarge from glanced to normal at a velocity of 200 m/s, leading to almost linearly decline of fatigue limit. Fatigue limit is insensitive to incident angle for specimen impacted at a velocity of 300 m/s and 400 m/s, scattering around 350 MPa, 50% of that of smooth one. Fatigue crack originated from the exit rim for 200 m/s glanced impacted specimen, while multiple cracks propagated from both exit rim and bottom of crater by 300 m/s and 400 m/s. It seems reasonable to give a rough assessment on fatigue strength of damaged specimen by the criteria depth alone. Regardless of the impact conditions, local failure and residual stress, fatigue strength of impacted specimen in this work can be evaluated by K-T diagram.

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Financial support of the National Natural Science Foundation of China (No. 11972110), National Key R&D Program of China (2018YFB1201704-03), and Independent Research Project of State Key Laboratory of Traction Power (2019TPL-T21) and the China Railway Corporation Science and Technology R&D Program (2016J007-H) are acknowledged.
Plasticity and damage characteristic of acoustic emission signals for S460 steel exposed to tensile load

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Keywords: Acoustic emission; Spectral analysis; Digital image correlation.

ABSTRACT

S460 steel is increasingly used in civil engineering, especially in a harsh environment such as offshore structures [1]. Material damage is inevitable for structures subjected to static and dynamic loads during their technical life time. Thus, monitoring material damage is important for providing information regarding critical damage of in-service structures. Non-destructive testing (NDT) techniques have been widely used for damage detection in recent years. Acoustic emission (AE), one of the efficient NDT techniques, can identify material damage based on the rapid release of strain energy as bursts of transient elastic waves. Previous research showed that the AE technique is sensitive and reliable in the detection of the material damage [2,3]. Specifically, AE signals contain information on a number of damage factors, such as material types, plasticity level, loading conditions and microdefects [4].

This paper focuses on the application of the AE technique to identify the tensile deformation of S460 steel. Tensile coupon tests were performed until final fracture with AE monitoring using two VS600-Z2 sensors. As experimentally supportive methods for AE interpretation, specimen elongation measurement and Digital image correlation (DIC) measurement of the surface displacement were used. Spectral analysis was carried out as the frequency spectrum of AE signals is a more reliable description of AE sources [5]. The onset time of a crack is identified from the power spectrum intensity of the AE bursts, see Fig. 1. PP4 is the percentage of power of each AE signals from 700 kHz to 1200 kHz as mathematically expressed by Eq. (1). It indicates that the AE technique is able to distinguish plasticity and damage of S460 material. The results will form the basis of a future fatigue damage assessment of in-service critical structure components.
**Fig. 1.** Applied loading profile correlated with a scatter plot of PP4 values of AE signals recorded during test

\[
PP4 = \int_{0}^{1200 \text{kHz}} U^2(f) \, df / \int_{0}^{1200 \text{kHz}} U^2(f) \, df
\]  

(1)

**REFERENCES**


Comparative study on the efficiency of reliability methods for the probabilistic analysis of local scour at bridge pier in clay sand mixed sediments

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Keywords: Bridge pier; scour; reliability analysis; failure probability, simulation.

ABSTRACT

In this work, the performance of reliability methods for probabilistic analysis of local scour at bridge pier has been investigated. The reliability of bridge pier scour is one of the important issues for the risk assessment and safety evaluation of bridges. Typically, the depth prediction of the bridge pier scour is estimated using deterministic equations, which do not consider the uncertainties related to the scour parameters. To consider these uncertainties, a reliability analysis of bridge pier scour is required. In the recent years, a number of efficient reliability methods have been proposed for the reliability-based assessment of engineering problems based on simulation, such as Monte Carlo simulation (MCS), Subset Simulation (SS), Importance Sampling (IS), Directional Simulation (DS), Linear Sampling (LS). However, no general guideline to recommend the most appropriate reliability method for the safety assessment of bridge pier scour has yet been proposed. For this propose, we carry out a comparative study of the five efficient reliability methods so as to originate the general guidelines for probabilistic assessment of bridge pier scour. In addition, a sensitivity analysis has also been carried out to find the effect of the individual random variables on the reliability of pier scour.
Three-dimensional fractography for conventional and additive manufactured steels after bending-torsion fatigue

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Keywords: multiaxial fatigue, bending-torsion, fatigue fracture, notch effect, surface morphology.

ABSTRACT

This work investigates the effect of multiaxial loading history on surface topography in notched specimens made of high-strength steels processed by both conventional and additively manufacturing techniques. Three bending moment to torsion moment ratios (B/T) were studied, i.e. 2, 1 and 2/3. Fig. 1 shows the geometries and dimensions of the tested specimens [1]: (a) a solid round bar with lateral notch made of conventional 34CrNiMo 6 steel; and (b) a hollow round bar with transversal hole made of 18Ni300 processed by selective laser melting.

![Fig. 1. Specimen geometries used in the experimental campaign: (a) solid bar with lateral notch (34CrNiMo6); and (b) hollow bar with transversal hole (18Ni300). Dimensions in millimetres.](image_url)

The triaxial stress state caused by the combination of the notch geometry and the multiaxial loading scenario, as can be seen in Fig. 2, has a great effect on fracture morphologies. The interconnection between these fracture surface morphologies and the bending-torsion loading is investigated in a quantitative manner using height parameters (Sq and Sz) and material/void parameters.
Fig. 2. Three-dimensional fracture topographies observed in the combined bending-torsion Tests. Solid round bar with lateral notch (34CrNiMo6): (a) B/T=2/3; (b) B/T=1; and (c) B/T=2. Hollow round bar with transversal hole (18Ni300): (d) B/T=2/3; (e) B/T=1; and B/T=2.

Fig. 3 plots two surface parameters (Sq and Sz) against the bending moment to torsion moment ratio (\(\lambda\)) [2, 3].

![Graphs showing Sq and Sz](image)

Fig. 3. Surface parameters versus ratio: (a) Sq; (b) Sz.

It is an attempt to provide a quantitative relationship between the surface texture parameters and the multiaxial variables. Proposed conclusions are essential in the identification of damage mechanisms associated with the failure of mechanical parts.

REFERENCES

Accelerated Fatigue Test Procedure for Leaf-Springs
Applied to Semi-Trailers

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**Keywords:** Design of Experiment; Accelerated Life Testing; rainflow cycle counting; durability; nCode;

**ABSTRACT**

The fatigue endurance assessment of leaf-springs for trailers and semi-trailers is a non-standardized procedure often protected by industrial secrecy that can significantly vary depending on the manufacturer, thus, imposing a barrier to seek for more efficient and safe structures. Hence, the main objective of the present work is to create, starting from experimental evidences, a solid technical basis for the creation of a valid test procedure able to reproduce the damage to failure inferred to a semi-trailer leaf-spring that is faithful to its real operational conditions and allows an accurate prediction of its durability.

In-field data was collected by means of 6 longitudinal strain gauges assembled on the top leaf (Fig. 1) for 210 km of paved highways and 84 km of off-road tracks, with a load 8.245 t of Total Gross Weight (TGW) above the axis of the spring studied, distributed 50% on each side of the axis. Once the data was imported into the nCode software, a rainflow cycle counting \cite{1} was used to set aside how many cycles of each specific stress amplitude \((N_i)\) were suffered by the spring in each region of its length. Then, once each stress amplitude points to a particular fatigue life on the SAE 5160 steel S-N diagram \((N_{f,i})\) \cite{2}, it is possible to calculate the damage \((D)\) through Eq. (1), where the closer \(D\) is to 1, the higher the probability of failure.

\[
\sum_{i=1}^{n} \frac{N_i}{N_{f,i}} = D
\]

With the damage data of external tracks sorted out, the next step was to figure out how to reproduce the same damage on the company’s internal test ground facilities in an accelerated manner. Adopting the conservative damage target that an actual semi-trailer would circulate 50% on-road and 50% off-road during the operational life of a leaf-spring, this respective accumulated damage has been extrapolated from the data collected on field, and the challenge is to set up a test procedure that reaches this same damage utilizing internal tracks.
Given that the internal on-road tracks are in optimal conditions and infer way less damage than an actual highway with its erosion-related imperfections, the test procedure was elaborated aiming to submit the semi-trailer to operate for specific distances in each of the following special tracks: potholes, Belgian stones, body twist and off-road (Fig. 2). Even though circulating only on the off-road track would accelerate the achievement of the targeted damage, different courses were chosen to account for the variability of terrains that a semi-trailer could circulate on, attributing a higher level of accuracy to this study.

Starting from a test block with a particular number of laps in each of the aforementioned special tracks and assessing its respective damage over the spring by the same methodology considered for external tracks, the damage data was extrapolated reaching the ideal number of laps in each track that the semi-trailer must go through to infer a damage as similar as possible to the target assumed before \( D_{\text{target}} \). Then, the Severity factor \( S \), which is the coefficient between the damage of the internal tracks \( D_{\text{int}} \) by the target damage (Eq.2), is calculated for each region of the spring to assess how faithful the internal test routine is to real operational conditions.

\[
S = \frac{D_{\text{int}}}{D_{\text{target}}} \tag{2}
\]

A good data correlation was obtained with \( S \) values close to 1, ranging from 0.89 to 1.06 depending on the region of the spring, demonstrating that the present accelerated fatigue test is valid and adequate to reproduce the actual damage of a standard leaf spring. Future studies include the adaptation of this fatigue endurance test to a laboratory procedure; the microstructural fracture analysis of a spring fractured from the elaborated test versus one from an actually operative semi-trailer; and a study of the vibrational resonant frequencies of the spring calculated numerically in comparison the vibrational data collected on field and filtered by means of a fast Fourier transform (FFT) procedure.

REFERENCES

Metal Additive Manufacturing of End-Use Components and Parts: A Practical Overview

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Keywords: Metals Production Technology, Additive Manufacturing, 3D Printing, Rapid Prototyping.

ABSTRACT

Practical overview of the most common procedures and materials currently available in the production of end-use metal components and parts by Additive Manufacturing (AM) are presented. The latest achievements and news are also discussed with special attention on defining the real production capability of each technological AM option under investigation. As general conclusion, by the present technical re-view it was possible to confirm the proper capabilities of AM in accelerating the development of ready-to-market metal products supporting the overall industrial investment strategy. This is especially true in the case of geometrically complex parts or small/variable production batches. Furthermore, it also emerges that a direct metal 3D printing opens to new possibilities with relevant impacts on the contemporary industry especially if driven by with appropriate changes in the information system and technology.

Additive Manufacturing (AM) is an advanced manufacturing technology in which the final object is made by adding materials, layer by layer. It all starts with three-dimensional object geometry, expressed in a CAD file, which is exported to an STL file or G-Code thanks to specific software tools (such as CATIA, Solidworks, Auto-desk, or many others). This file is entered into Slicing software to process all relevant print settings such as material selection, build time, temperature, speed, and choice of supporting structures and more following the printer set-tings, which is the universal input of all 3D printers [1-5]. Printing the finished piece follows after the settings of the slicing tool based on the print parameters that are set up in such a way that they better meet many different engineering and market needs. The capabilities of AM technology in the production of metal end parts are crucially dependent on the metal input material. Materials suitable for AM are steel (mostly stainless steel and tool steel), super-alloys, titanium, copper and aluminium. These materials are made from the fine metal powder used for most AM processes. Metal powder is also the basis for making filaments for some additive manufacturing processes. Therefore, AM technology is gradually replacing other consolidated techniques in the production of end-use items by conquering different industrial sectors. It mainly happens in the case of functional prototypes, custom tools and components, sports items, toy figures, surgery and medical equipment. Respecting other 3D printing processes, AM in the case of metals needs state-of-the-art solutions, sophisticated and intelligent machines, capable of producing high precision components at the low overall cost. At the same time, the significant factors that affect 3D metal printing, such as software and hardware limitations, energy used, material optimization, real-time process monitoring, and the like, are almost the same as any other 3D printing technology.

Different methods of metal AM process are available that differ in their terminology from the companies and institutes that developed, patented, and marketed them. However, the classification is
mainly done by type of energy, material and type of metal printing equipment. The following four procedures probably represent the current standard in metal AM production of end-use parts: (a) Metal Powder Bed Fusion, (b) Direct Energy Deposition, (c) Binder Jetting, and (d) Metal Extrusion, schematically shown in Fig. 1.

<table>
<thead>
<tr>
<th>Metal Powder Bed Fusion</th>
<th>Direct Energy Deposition</th>
<th>Binder Jetting</th>
<th>Metal Extrusion</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Metal Powder Bed Fusion" /></td>
<td><img src="image2.png" alt="Direct Energy Deposition" /></td>
<td><img src="image3.png" alt="Binder Jetting" /></td>
<td><img src="image4.png" alt="Metal Extrusion" /></td>
</tr>
</tbody>
</table>

Fig. 1. Classification of metal Additive Manufacturing (AM) technology.

The presented metal AM processes in the production of metal components have shown that they have enormous potential capabilities over traditional technological methods of production. Concerning the classification of metal AM technology Fig. 1, the right choice of the AM process for the correct application is critical as it enables a faster, easier and more convenient transition from design to fabrication of complex metal parts. Each of the four AM processes shown is characterized by the manufacturer or scientific institute that developed it. Still, implementation of the market has shown which machines have better production capabilities and advantages. These metal AM printing techniques provide outstanding optimized application capabilities in almost all industrial fields as well as in medical applications, from the design, testing and rapid prototype phases to a wide range of commercial functional component printing. The main disadvantages of the metal AM process are the requirements for postprocessing equipment, which is present in all methods depending on whether the material is powder or filament. Thus, in the Metal Powder Bed Fusion, Direct Energy Deposition and Binder Jetting processes, the following facility requirements are required, namely powder management, ventilation, postprocessing depending on the use case, heat treatment, CNC, EDM, HIP, surface finish and others if necessary. Metal AM extrusion has the least requirements for postprocessing equipment, depending on the case of the printed part: necessary ventilation, CNC, heat treatment and surface finishing. But it has to be said that, although they significantly increase the cost of metal 3D printing, they are not limited, because the benefits of metal 3D printing are great. The analysis showed that metal AM systems in the production of metal components achieve predominantly more favourable design flexibility, shorter fabrication time, high precision of complex shapes and a significantly lower cost of production compared to traditional machining processes.

REFERENCES

Optimisation of Wastes Compaction Parameters in Case of Gradual Wear of the Briquetting Press Rolls

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Keywords: briquetting; fine wastes; roller press; profile wear.

ABSTRACT

In the modern metallurgical, mining, and chemical enterprises, roller presses (Fig. 1) are used to produce briquettes from fine wastes of various bulk raw materials that significantly differ by physical and mechanical properties [1]-[6]. The need to expand the operational capabilities of the presses is caused by the increased volumes of small-fraction raw materials. Roller presses are equipped with the two rolls and replaceable pressing tires (Fig. 1) which are subjected to high contact stresses, intensive wear and are quite expensive parts made of alloy steels, e.g. 40Cr. Tires production includes case carburization and possible subsequent deep cryogenic treatment [7]. The gradual wear of profiles greatly influences the product quality and above the certain level of deterioration makes it impossible the separated briquettes formation with a decreased density as the main parameter of quality (Fig. 2).

Fig. 1. Briquetting press design of the Iron and Steel Institute (a); roller (b); roller assembly design (c): 1 – gear-type replaceable pressing tire; 2 – hub; 3 – driving shaft; 4 – clamping ring; 5 – bearing supports; 6 – synchronising gear.

Fig. 2. Briquettes produced with good (a) and worn (b) tires; parameters of the pressing ring wear (c).

Major efforts are focused on wear forecasting and methods for protecting and restoring parts of industrial equipment, using more wear-resistant alloy steels and ceramic composites. The same applies to the press rolls [8] where attention is also paid to the configuration and calibration [9]-[11] because compacted materials have elastic after-effect [12]. The closest similar example of wear is the rolling mills [13]-[14] where some models are developed for rolls wear prediction and process stability assessment by the electrical drives current [15]. At present, there is no holistic methodology developed to predict the wear of the briquetting press tires. Therefore, authors proposed a model-based procedure for compaction parameters optimization which includes: \( \rho_{\text{bulk}} \) – input bulk density; \( W \) – input humidity; \( Fr \) – fraction size of the particles; \( B \) – binding organic compound percentage; \( \delta \) – wear of rolls; \( \alpha_{pr} \) – pressing angle; \( L \) –
position of the input flow regulator; $K_r$ – compaction coefficient; $\rho_b$ – briquettes density; $P$ – pressing force; $M$ – pressing rolls torque; $I_m$ – drive motor current; $n_{roll}$ – roll speed; $Q$ – press productivity. The real data is recorded and systematized at different stages of tires spatial wear. Experimentally determined wear patterns are correlated with the values calculated by the developed model. The recommended working regimes of the press are tested in an industrial plant through the whole period of one set of rolls operation (11 months) and provided the desired density of briquettes up to 11 mm of tires wear (Fig. 3).

Fig. 3. Predicted (min, max) and real density of briquettes over the tire wear in the industrial press.

Besides the output product quality, the proposed methodology ensures a limited machine loading by the pressing force, mechanical drivetrain torque and electrical motor current. The results of this research form the basis for the condition monitoring and maintaining the mechanical equipment of roller presses in the real production plants taking into account the gradual wear of the pressing rolls tires.

REFERENCES

Safe Operation of Underground Mining Vehicles Based on Cyclic Fatigue Monitoring of Powertrains

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Keywords: load-haul-dump vehicles; powertrain; cyclic fatigue; dynamical model; torsional vibration.

ABSTRACT

This research is dedicated to the problem of automatic monitoring of the operational regimes of heavy load-haul-dumping (LHD) vehicles for blasted minerals transportation in underground mines. The design of powertrains typical for different producers of such machines is shown in Fig. 1.

The torsional vibrations excited in the geared transmissions with cardan shafts are investigated on the multi-body models in automotive applications [1],[2] and industrial plants [3]. The effects of oscillations on cyclic fatigue are considered in [4],[5]. The presence of hydraulic torque converter (TC) in the transmission [6] with a lock-up increases power transfer efficiency at high speeds [7],[8] but makes their investigation as a not trivial task.


Fig. 1. The underground Load-Haul-Dump (LHD) vehicle (a); and design of its powertrain (b): 1 – diesel engine with a torque converter having a lock-up; 2 – gearbox; 3, 4 – front axle with limited-slip differential, brakes and wheels; 5, 6 – rear axle and wheels; 7, 8, 9, 10 – cardan shafts; 11 – intermediate support; 12 – articulation joints bearings; A, B, C, D – couplings with potential angular clearances.

The torsional vibrations excited in the powertrain are investigated in Fig. 2 on a multi-body model (a); and torque converter scheme (b).

Fig. 2. Structure of the torsional vibrations model of the powertrain (a); and torque converter (TC) scheme (b).
The developed nonlinear dynamical model accounts transmission structure change due to speeds shifting and lock-up activation in the TC as well as the influence of angular clearances in the cardan shafts (see Fig. 3). The slowly sampled signals of the monitoring system are combined with the modelled fast data in the range of natural modes of torsional vibrations for model identification based on transient responses.

Fig. 3. Nonlinear characteristics of elements in powertrain: (a) DEUTZ engine (TCD 2013 L6 2V) torque function of rotation speed; (b) torque converter lock-up; (c) backlashes in cardan shafts.

Nonlinearity in different elements of powertrain resulted in the scattering of torsional loads and corresponding wide range of accumulated fatigue cycles depending on scheduled regimes of vehicle operation (material loading, acceleration, quick stopping). These cycles are applied to the Wohler diagram of structural steel, which is used in vehicles production.

Based on these diagrams and on-line data combined with dynamical models, the remaining useful life of powertrain elements are determined and periods of safe operation are predicted. Besides, the obtained results of simulations allowed optimising the most severe working regimes to reduce peak amplitudes of torsional vibrations causing the abrupt failures in the vehicles.

REFERENCES

Experimental Study of the Rolling Friction Coefficient in Highly Loaded Supports of Rotary Kilns

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**Keywords:** rolling contact; coefficient of friction; support rollers; tire; wear.

**ABSTRACT**

The large-dimension rotating technological equipment for firing, grinding, granulating, drying and mixing of various raw materials is widely used in industry, e.g. rotary kilns, ore and coal mills. Such machines may have several support units where the circular tires roll over the support rollers. The total weight, e.g. of rotary kilns, is up to 5000 ton and the load on single support unit approaches to 10 MN. Start-ups of such heavy rotary plants cause significant transient dynamics and low-cycles fatigue in the gears and shafts of drivetrains [1], but even more dangerous is the high contact stresses and excessive wear of tires and rollers. In particular, due to the thermomechanical deformations and creep of shell and its geometric axis cranking the stress state change in the contact zone. The distribution of the contact pressures along the contact length is irregular due to the implicit gaps and classical Coulomb’s law is violated when friction is proportional to applied normal force [2]. In our case, the misalignment of support rollers in relation to the tires can increase the contact pressure to 1000-1600 MPa that leads to additional losses and damages. Typical patterns of wear due to factors of operation and maintenance are considered in [3] and shown in Fig. 1. These issues are investigated in different ways and some practical remedies have been proposed [4]-[9] including deep cryogenic treatment for rolls [10].

Fig. 1. Types of wear in the rotary kiln tires: (a) groove-type pattern when out of alignment; (b) spalling-type pattern due to excessive skewing; (c) gouging-type wear from an obstruction on tire; (d) wear due to lubrication penetration into metal and causing cracks under high pressure.

Since the on-site measurement is a very complicated procedure, the test rig is developed and used for rolling friction coefficient investigation under different conditions of contact loading and lubrication (see Fig. 2a). The geometric, kinematic and contact loading similarity with a real object is provided by the appropriate coefficients. The experiments are performed within a speed range \(v = 0.134-1.34 \text{ m/s}\) and the load \(F = 7.2-42.5 \text{ kN}\) that corresponds to a contact pressure \(p = 193-469 \text{ MPa}\). The rolling friction coefficient \(f_r\) is determined by the torque and applied force values. Relations of rolling friction coefficient from speed and contact stress are shown in Fig. 2b, Fig. 2c respectively. Results of tests are summarized in Table 1. In particular, due to a three-fold increase of speed, the rolling friction coefficient increases by approximately of 50% for the whole range of loads, both for dry and lubricated surfaces. If the load is increased by 3 times, the rolling frictional coefficient is reduce of 40% for dry surfaces and more than 60% for lubricated surfaces.
The values of the contact wear are determined by the sample diameter before and after the tests. The steel grade of samples and their hardness correspond to real conditions. The absolute wear \( U_a \) is sharply rising up to about \( N=15 \times 10^3 \) cycles, then the intensity of wear decreases (see Fig. 2d). Likewise, a specific wear \( (U_i) \) normalized by the number of cycles quickly decreases up to \( N=2 \times 10^4 \) cycles and then stabilizes. It takes place due to the surface layer deformation and strengthening to a certain limit value. The influence of lubrication on the rolling friction coefficient increase (up to 70\%, see Table 1) is greater at the lower loads that is observed at all speeds. In general, the rolling friction resistance increases at the higher rolling speeds that can be explained on the basis of the hydrodynamic theory of lubrication, i.e. the force of oil layer shear must be proportional to the viscosity and the rolling speed.

### Table 1. Rolling friction coefficient \( f_r \times 10^{-2} \) for different surfaces and test conditions.

<table>
<thead>
<tr>
<th>Rolling speed, [m/sec]</th>
<th>Dry surfaces</th>
<th>Lubrication (MS-20)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.4</td>
<td>0.8</td>
</tr>
<tr>
<td>Contact pressure, [MPa]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>270</td>
<td>1.62</td>
<td>2.13</td>
</tr>
<tr>
<td>331</td>
<td>1.30</td>
<td>1.69</td>
</tr>
<tr>
<td>381</td>
<td>1.24</td>
<td>1.49</td>
</tr>
<tr>
<td>409</td>
<td>1.09</td>
<td>1.39</td>
</tr>
<tr>
<td>469</td>
<td>0.98</td>
<td>1.29</td>
</tr>
</tbody>
</table>

The conducted research allows to understand rolling friction losses and the highly loaded contacts deterioration in rotating machines and predict their abrupt failures. Besides, some methods of condition monitoring can be proposed based on obtained relations in case of drive parameters measurement.

### REFERENCES


On stochastic method for scale-structural failure estimating and structure durability at safety operational loading

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Keywords: structural failure; durability; stochastic method.

ABSTRACT

The purpose of this study is to develop the experimental and theoretical foundations of the stochastic method for assessing of longevity and diagnostic periods of the technical conditions of various long structures. The section fracture at the internal pressure of the pumped product, the action of mass forces, temperature field and natural-climatic and technogenic influences, is considered at each moment of time as the sum of probabilistic fracture of its generalized structural elements (of base metal, welded joints, bends, tees, adapters, plugs). For this purpose, the problem is a mathematical representation of the random mechanical loading of structural sections, random chemical and biological effects during soil and stress corrosion, random natural (aerohydrodynamic, geodynamic and seismic) influences and the effects of third parties on structural sections. Further, the constitutive relations are constructed for the distribution function of the element failure probability on the various defect levels at mechanical loading. The considered approach uses the results of studies of the physical and chemical interactions between an aggressive medium and the metal. The fundamental problem is to develop the safe operation criteria for long structures, taking into a account the influence on people, technosphere objects and the environment at possible fracture.

The research relevance is associated with considering of complex processes of multiscale fracture of structural elements at the resource estimation of long structures.

The durability of long structures at operational loading is described by random processes taking into account the potential stochastic element fracture, random mechanical loading, random environmental influences, etc. Therefore, a stochastic approach and methods of the theory of random processes and statistical analysis are chosen. As a toolkit for numerical experiments and solving practical problems, finite element methods of the ANSYS are used.

There is proposed a stochastic method of safe operation assessing on the basis of a system of safe operation criteria for long structures, taking into account the determination of the structural element life using a stochastic model of fatigue scale-structural failure. The model predicts the probability that a certain function of the structure, depending on the density and size of multilevel defects, reaches the limiting values during loading. The basic experiments for identifying of material functions are based on the standard tests of materials for long-term and fatigue strength. Here are plotted the fatigue curves of metals and alloys on defect levels at high-cycle and gigacycle fatigue and various types of proportional loading with a symmetric and asymmetric cycle. The algorithm for durability calculation of various sections of main pipelines on the basis of the proposed method, taking into account the influence of natural and technogenic factors and aggressive media, as well as the negative consequences of their
possible destruction is proposed. The algorithm is implemented for a number of main gas pipelines (for linear parts between adjacent compressor stations, strapping pipelines).

REFERENCES

Fatigue life prediction of rubber-sleeved stud shear connectors using finite element analysis

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Keywords: rubber-sleeved stud; fatigue life; concrete; rubber; finite element analysis.

ABSTRACT

Rubber-sleeved studs (Fig. 1), which are studs wrapped with rubber sleeves, have been found to be prospective to overcome some challenges in the design of steel-concrete composite structures with ordinary stud shear connectors. Results of fatigue push-out tests on rubber-sleeved stud shear connectors implied that the fatigue strength of shear connectors decreases as the rubber sleeve height increases [2]. However, the mechanism of the effect of the rubber sleeve on the fatigue life was unclear.

![Fig. 1. Rubber-sleeved studs [1].](image)

A finite element-based approach was provided for the fatigue life prediction of rubber-sleeved stud shear connectors. 3D nonlinear finite element models of shear connectors were established, as shown in Fig. 2.

![Fig. 2. Finite element model.](image)
After calculating the stress and strain state of the connector by finite element models, the fatigue crack initiation life was predicted based on the critical surface method (Eq. (1)), and fracture mechanics was adopted to predict crack propagation life (Eq. (2)).

\[ \frac{\Delta \varepsilon}{2} = \left( \frac{\sigma_t}{E} \right)^2 \left( N_{\text{init}} \right)^{2b} + \sigma_t \varepsilon_x \left( N_{\text{init}} \right)^{b+c} \]  

(1)

\[ N_{\text{prop}} = \int_{N_0}^{N} \frac{da}{C(\Delta K)^n} \]  

(2)

The prediction method was validated by fatigue push-out test results [2,3], as shown in Fig. 3.

![Fig. 3. Comparison between calculated fatigue lives with experimental results.](image-url)

It was found that the rubber sleeves increase the strain and stress in the stud and thus, the deformation. As a result, it was observed that the SWT damage parameter and stress intensity factor range in the stud increase with the rubber sleeve height, and the fatigue characteristics of shear connectors was changed.

REFERENCES


ACKNOWLEDGMENTS

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Experimental verification of the survivability model under mixed I+II mode fracture for steels of rolling rolls

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Keywords: mixed fracture; survivability; rolling rolls; crack growth.

ABSTRACT

For a considerable of time, the rolling roll operates in a damaged state, when it is slowly destroyed. This process has a mixed character, when at the same time the defect (crack) is affected by deformations of the I, II and III fractures modes. Among them, II mode plays an important role. This type of fracture acts both during the initiation of pits and lamination (spalling) of contact fatigue in the work places of the rolls, as well as on the development of defects arising in the end (neck) zones of the rolls. The contribution from the destruction of the II mode increases with the reduction of the length of the rolls. This situation is typical for pipe mill rolls and continuous casting machine rollers.

When studying the rules of amalgamating reliability indicators, an algorithm was developed to determine the overall level of safety of the object when exposed to it of degradation processes system [1]. This algorithm was used to predict the survivability of rolling rolls under the action of mixed fracture. The latter is presented as the action of a system of degradation processes [2]. Based on the analysis of the resistance of materials to fracture, a calculation model of the parameters of the kinetic diagram of crack growth (CG) for I, II and III modes was proposed. Although the model is put forward at the level of a hypothesis, but the results of its use are quite acceptable.

Therefore, the report is devoted to the experimental study of cyclic fracture processes in the II mode. The aim of the research was:

- verification of the calculated model of resistance to fatigue fracture, steels used for the production of rolling rolls,

- verification of the algorithm for predicting survivability under mixed fracture.

The scheme of four point asymmetrical bending (4PAB) was chosen to determine the fracture parameters at the II mode. This scheme is well combined with the scheme of three-point or transverse bending (3PB), which obtains the parameters of fatigue fracture in the I mode. Prismatic specimens are made of steels 9HS (analogy 90CrSi) and H12F1 (analogy X155CrVMo12-1). The task was to obtain the twice amplitude of SIF ΔK*, which correspond to the rate CG v = 10^{-7} m / cycle. This characteristic is a kind of marker of changes in the rate of CG. A decrease in the value of ΔK* corresponds to an increase in the rate v.

For the selected steels tested the 4PAB-scheme, it was not possible to obtain fracture in the pure II mode. The crack immediately at an angle of approximately 45° grew from the notch towards the zone of tensile stresses caused by bending. Further breaking of the specimen occurs in the direction of support. This crack trajectory is characteristic of metal tests in this scheme and indicates a mixed I + II mode. A
certain specimens, which were tested according to the 4PAB scheme, collapsed into three parts due to an additional break of the I mode fracture by a straight (direct) crack.

The cyclic fracture toughness of H12F1 steel is 10-20% higher than 9HS steel. The tendency of deterioration of fracture resistance at the 4PAB - scheme in the conditions of direct cracks is confirmed. For them, the value of ΔK* is 25-45% less than the pure ΔK*i obtained by the 3PB- scheme. This leads to an increase in the CG rate in 2.5-4.5 times, which reduces the durability and survivability.

![Diagram](image)

**Fig. 1.** Comparative diagram of the cyclic fracture toughness ΔK* of steels 9HS (9HS), H12F1 (H12) at three-point bending (3PB) and at four-point bending for straight (4PAB I and 4PAB II) and oblique cracks (4PAB I + II).

Thus, the steels selected for research are not destroyed in pure II mode. The specimens is destroyed by an oblique crack of the mixed mode. Therefore, a calculation method for determining the parameters of the II mode of cyclic fracture based on test results has been developed. The values of ΔK*ii are 2.6 -2.9 times smaller than the value of ΔK*i for pure I mode. That is, the ratio of indicators ΔK*ic / ΔK*iic is smaller than the ratio ΔK*i / ΔK*ii. Despite the differences in the forms of model and experimental graphs of crack growth, the durability obtained by them is within the natural dispersion inherent for fatigue damage. This indicates the effectiveness of the developed algorithm and the correctness of certain indicators of resistance to destruction.

**REFERENCES**


FE modelling the fatigue behaviour of L-PBF Inconel 718 with as-built surfaces

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Keywords: Laser powder bed fusion, Inconel 718, fatigue, FEA, surface roughness

ABSTRACT

Inconel 718 is a metal alloy characterized by excellent mechanical properties at high temperatures; customized parts of complex geometry are increasingly fabricated by Selective Laser Melting (SLM) and extensive knowledge has been collected on the link between process parameters, material structure and basic mechanical properties [1]. The main interest is however in evaluation of fatigue properties of parts with surfaces in the as-built state since surface improvement in post process is costly and often practically impossible. Previous works have demonstrated that surface roughness has a key influence on high-cycle fatigue properties of components [2] [3], therefore, parameters related to as-built surface quality should be investigated and considered in part design.

The fatigue test method using the miniature specimen geometry shown in Fig. 1a is adopted, [4]. According to this method different specimen orientations with respect to the build direction are fabricated and tested under cyclic bending generating pulsating tensile stress (R = 0) on the flat surface opposite to the notch. Fatigue testing was performed at a frequency of 20 Hz and test run-out fixed at 2x10\textsuperscript{6} cycles. The as-built surface quality of the two specimen orientations shown in Fig. 1b is different: in type A, the top surface is influenced by the hatching and contour strategy; in type C the flat test surface is influenced by the layer thickness and the contour parameters. Specimens were produced using a SLM Solution 280HL system with a layer thickness of 50 µm and an energy density of F = 54.82 J/mm\textsuperscript{3}. After fabrication, the specimens were heat treated with a solution treatment plus a two-step aging treatment.

![Fig. 1. a) Miniature Specimen dimension b) Denomination of miniature specimens and layer direction](image1)

![Fig. 2. Directional fatigue data for as-built Inconel 718 produced by SLM 280HL](image2)
The fatigue results of Fig. 2 show the directional nature of the fatigue behaviour due to the different as-built surface quality as it is affected by fabrication direction. Specifically, fatigue strengths are estimated in 410 MPa for type C and in 315 MPa for type A.

The as-built surfaces are rough containing irregularities, micro notches and partially welded particles depending on process parameters and surface orientation. The role of the actual surface morphology needs to be understood and modelled in order to predict the fatigue performance of metal AM parts, [5]. For example, surface ridges could be considered as micro-notches introducing stress concentrations under load, [5,6]. Therefore, surface profiles were used here to generate FEA models of the near-surface for the different specimens of Fig. 1b. First, actual surface profiles were determined according to two methods: i) metallographic sectioning and LOM observation and profile reconstruction, Fig. 3; ii) Taylor Hobson Talysurf CCI optical surface mapping and profile extraction parallel to stress direction, Fig.4.

![Type A specimen metallographic cross-section and profile reconstruction](image1)

![Type A specimen surface map; selected surface profile](image2)

The elastic stress distribution associated to the experimental surface profiles is determined for the different specimens and profile reconstruction methods, see example of Fig. 5. Different approached to extract representative effective stresses and roughness fatigue models, [7], are investigated and compared to experiments.

![Stress distribution associated to as-built surface roughness](image3)

REFERENCES


Reliability Analysis of Gas Pipeline with Corrosion Defect

Based on Finite Element Method


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Keywords: Corroded pipeline, Finite element analysis, Reliability, Residual life

ABSTRACT

Gas pipelines are facing serious risk because of the factors such as long service life, complex working condition, and, the most importantly, corrosion. As one of the main failure reasons of gas pipeline, corrosion poses a great threat to its stable operation. In this paper, ASME-B31G revised criteria and finite element numerical analysis software are used to analyze the reliability of a special dangerous section of a gas gathering pipeline, and the failure pressure and stress concentration of the pipeline under three failure criteria are obtained. Furthermore, combined with the predicted corrosion rate of the pipeline, the remaining service life of the pipeline is calculated. The results show that the finite element analysis results under the elastic-plastic criterion are close to the calculation results of ASME-B31G. According to the calculation results, the maximum safe internal pressure of the pipeline is 9.53Mpa, and the residual life of the pipeline under the current operating pressure is 38.41 years, meeting the requirements of safe and reliable operation. The analysis results provide reference basis for the reliability analysis of corroded pipelines, which is of great practical engineering value for the safe and stable operation of natural gas pipelines.
Predicting the fatigue life of hydraulic unit under variable operating conditions

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Keywords: hydraulic unit; lifetime; fatigue damage; variable operating conditions.

ABSTRACT

The project lifetime of most hydraulic units is 30–40 years. As practice shows, some of them successfully work for more than 50-60 years while others have premature damages after 10 years or less. One of the main reasons is significantly contrasting the actual operational modes at HPP from project expectations due to modern trends of essential increasing the operational range of hydraulic units [1].

The actual operating conditions play a decisive role in the real lifetime of hydraulic units [2-4]. Despite their short duration, the off-design modes (transient and non-stationary) make a significant contribution to the accumulation of the unit’s fatigue damage due to the high-stress level.

Figure 1 shows the characteristic distribution of relative values for the dynamic stress amplitudes under the whole operating range as the ratio of the average measured amplitude of dynamic stresses to the value of the static stress component at the same operating mode [5] for the most stressed point of the hydraulic runner (the junction zone of the blade output edge and the runner crown). The scale of power is normalized to the nominal value.

![Figure 1](image)

Fig. 1. The characteristic distribution of relative values for the dynamic stress amplitudes under different operating range (the ratio of the average measured amplitude of dynamic stresses to the value of the static stress component at the same operating mode [5]).

The proposed approach requires to divide the whole operating range into characteristic loading blocks for calculating the total accumulated damage. Each such block has a characteristic frequency (ultra-low, low-, high- and very high-) of the external load and a characteristic amplitude as you see in Fig. 1.
The fatigue damages are calculated separately for each block take into account the special fatigue features of material behavior at the characteristic frequencies and the total amount of load cycles. To determine the total exhausted lifetime, the damages at every load block are summarized. The residual lifetime is the difference between allowed damage and exhausted damage.

Table 1 presents the distinction between two scenarios of real operational modes at HPP: "Base mode" with long-term working near the best operational point and "Peak mode" with many start-ups and shutdowns.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Base mode</th>
<th>Peak mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total operating time for the prognostic period,</td>
<td>37 230</td>
<td>37 230</td>
</tr>
<tr>
<td>hours</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average number of start-up and shutdown per</td>
<td>214</td>
<td>29</td>
</tr>
<tr>
<td>year for the prognostic period, pc.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forecast of exhausted service life until the</td>
<td>97.9</td>
<td>94.9</td>
</tr>
<tr>
<td>next overhaul, %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residual lifetime, years</td>
<td>10.3</td>
<td>32.9</td>
</tr>
<tr>
<td>Residual lifetime, years, thousand hours</td>
<td>54.8</td>
<td>175.0</td>
</tr>
</tbody>
</table>

The proposed approach makes it possible to solve correctly the problem of reliable prediction of the lifetime for various scenarios under real operation at HPP. It allows us to capture the most dangerous modes from the point of view of the rapid exhaustion of the service life and realize smart lifetime management.

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ACKNOWLEDGMENTS

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Probabilistic modelling of uncertainties in fatigue reliability analysis of turbine bladed disks

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Keywords: fatigue life; reliability; multi-source uncertainties; geometrical uncertainty; sensitivity analysis

ABSTRACT

Turbine bladed disks normally operate under complex loadings coupling with uncertainties originated from multiple sources, including material variability, load variation and geometrical uncertainty. The effects of these uncertainties on mechanical response are critical for fatigue assessment and reliability evaluation of these components. In this work, a general framework for fatigue reliability analysis is developed by coupling the Latin hypercube sampling with finite element analysis to describe the combined effects of multi-source uncertainties. Fatigue reliability analysis of a full-scale bladed disk under multi-source uncertainties was performed as well as sensitivity analysis for fatigue design. In order to describe the manufacturing errors or tolerances, random dimensions are inputted. Comparing the predicted fatigue lifetime distributions with/without geometrical uncertainty, it shows the geometrical uncertainty matters in structural fatigue reliability. Particularly, sensitivity analysis indicates that the geometrical uncertainty exerts more significant influences on the fatigue lifetime and reliability of the turbine bladed disk than others. The sensitivity factors of distribution parameters of three typical dimensions emerges the influence level of dimensional designed sizes and tolerances on the failure probability, which provides a reference for engineering structural design.

Fig. 1. Huber–Mises–Hencky stress nephogram of 1/40 turbine bladed disk under $\omega_3$=3143rad/s.
**Constructal Design applied to biaxial elasto-plastic buckling analysis of square steel plates with cutout**

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**Keywords:** Elasto-Plastic Buckling, Biaxial, Plate, Constructal Design Method, Finite Element Method

**ABSTRACT**

Plates are thin structural elements where the dimensions in the plane, $a$ and $b$, are much bigger than the thickness, $t$. These components are widely used in civil, naval, aerospace, and automotive engineering applications. In several practical situations the existence of an opening on the plate is required (for inspection, passing pipes or to be used as a weight reduction solution), which modifies its mechanical behavior, due the stress redistribution caused by the presence of the hole \cite{1}.

When plates are under compressive loadings, an instability phenomenon called buckling can occur. Ref. \cite{2} says that a thin plate does not enter in collapse soon after the occurrence of the elastic buckling, but actually it can support loads significantly higher than the critical load without deforming excessively. The load that defines the collapse of plate, regarding elasto-plastic behavior, is called post-critical or ultimate load, $P_u$, represents it.

It is important to mention that to define the ultimate load of plates with cutout is not a simple task; being the computational modeling via Finite Element Method (FEM) an effective approach.

In this context, the main goal of the present work is to optimize the geometry of a centered elliptical cutout on a simply-supported square steel plate subjected to biaxial elasto-plastic buckling. To do so, computational modeling (by FEM), Constructal Design method (CD), and Exhaustive Search technique (ES) are jointly employed.

The CD, based on the Constructal theory, is a method that uses degrees of freedom, restrictions, and objectives, to define different possible geometric configurations for an engineering system, i.e., to define the search space for a geometric evaluation. Thereby, the performance of all proposed geometries is numerically obtained and compared among each other, characterizing an optimization by ES \cite{3}.

When is desired to use FEM for engineering problems solution, a validation and/or verification of computational model might be done. To apply FEM, the commercial software ANSYS® was used through SHELL281 finite element. Ref. \cite{4} proposed equations to solve biaxial elasto-plastic buckling problems, based on square plates with different boundary conditions and cutout shapes. With proposed equations was obtained the ultimate stress, $\sigma_u$, for a plate with $a = b = 125$ mm, $t = 6.25$ mm, circular cutout with $d = 25$ mm, boundary conditions as simply-supported and equal biaxial compressive loads on $x$ and $y$–directions. The analytical solution resulted in ultimate stress equal to 257.13 N/mm$^2$. Applying FEM on ANSYS®, the numerical solution for the ultimate stress resulted in 276.42 N/mm$^2$. This represents a difference of 6.98% between analytical and numerical solutions, what is acceptable as affirmed by Ref. \cite{4}.
Regarding the CD method, with the purpose of adequately comparing the different cutout geometries, a restriction called volume fraction, \( \phi \), is considered. The \( \phi \) parameter is defined as the ratio between perforation volume and plate volume. It is kept constant while the ratio between the axes of the elliptical hole is varied.

For preliminary evaluation this abstract shows the numerical results for a square plate with \( a = b = 1414.214 \text{ mm} \), \( t = 12 \text{ mm} \), boundary conditions as simply-supported and equal compressive loading on \( x \) and \( y \)-direction. The elliptical cutout attends the volume fraction \( \phi = 0.10 \), what means that the volume of material removed represents 10% of the reference plate material; being the reference plate, a no-hole plate having the same dimensions and under the same load and boundary conditions.

Numerical results for the proposed problem show that the ultimate load for the reference plate is 681.60 N/mm. When elliptical holes with \( \phi = 0.10 \) are applied and its dimensions change keeping \( \phi \) constant, the results show that the minimum ultimate load is 532.50 N/mm and the maximum is equal to 617.70 N/mm.

The next step of this research is to apply this methodology for volume fractions of 0.025, 0.05, 0.15 and 0.20, comparing with reference plate. With these results will be possible to evaluate exactly the behavior of ultimate load for perforated square plates, under biaxial elasto-plastic buckling, and also determine the optimum geometry, for elliptical holes, which will provide the best mechanical behavior.

Comparing analytical and numerical results was possible to say that FEM returns, in a short time, results with good accuracy. Also, the presence of a cutout affects the mechanical behavior of the plate, reducing the ultimate load when compared with reference plate. The best condition for the perforated plate with \( \phi = 0.10 \) represents a reduction of 9.38% in the ultimate load related to the reference plate.

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ACKNOWLEDGMENTS

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Local Behavior of a Pultruded GFRP Bridge Deck under Fatigue Load

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Keywords: pultruded GFRP bridge Deck; fatigue test; local behavior.

ABSTRACT

In order to investigate the fatigue behavior of a pultruded GFRP (glass fiber reinforced polymer) bridge deck, four GFRP bridge deck specimens were tested under different fatigue loading levels. The dynamic and residual deflection, dynamic and residual strain distribution, fatigue life, crack propagation pattern, and residual ultimate capacity were measured during the test. Results showed that final failure was caused by the fatigue cracks initiated and propagated along the top flange. The maximum deflection and strain of pultruded GFRP bridge deck obviously increased while the amplitude of deflection and strain of pultruded GFRP bridge deck changed relatively small with the loading cycle increasing. It indicated that the variation of the structure stiffness is very small, and the structural stiffness decreases rapidly during fatigue crack propagation.
Local reinforcing effects of studs with high strength concrete

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Keywords: Composite structure; Stud connector; UHPC; Push-out test; Finite element analysis

ABSTRACT

To investigate the mechanism for the enhanced load bearing capacity of stud connectors owing to the increase of concrete strength, the push-out test is analyzed using elastoplastic finite element models. A distinct failure mode is observed and proofs are collected to explain the mechanism of studs with higher strength concrete. Results show that the stud with ultra-high-performance concrete (UHPC) yields to the plastic failure initiating on the bottom surface of the stud shank and propagating through the cross-section near the weld collar. The failure mode is distinct to that of normal strength concrete (NSC). The local reinforcing effects, like the confinement of the bearing concrete, improved tensile strength and the constraint of the weld collar, provide stronger constraint around the foot of stud shank and account for the distinct failure mode. As a result, the local reinforcing effects should be included to improve the FE prediction accuracy. Underestimating the strength of studs with UHPC, the simplified method specified in practical design codes may lead to a conservative design since the local reinforcing effects are neglected.

1 Introduction

There are many studies on the mechanical properties of headed stud connectors in NSC now. However, the research on their failure mechanisms and mechanical properties with UHPC are still relatively limited. Kim, Jee Sang [1] studied the bearing capacity of studs in UHPC and NSC by push-out test. Wang [2] studied the bearing performance of large-diameter studs in UHPC and NSC by push-out test. Dominic Kruszewski [3] studied the bearing performance of studs in UHPC by push-out test. Cao [4] studied the bearing performance and failure mode of short studs in UHPC. Previous studies by scholars mainly carried out studies on the load-bearing performance of headed stud connectors in concrete by push-out test or FEA. However, there has been no in-depth research on the mechanism for the enhanced load bearing capacity of stud connectors owing to the increase of concrete strength. Therefore, clarifying the failure mechanism and mechanical properties of the studs in different strength concrete is helpful to improve the lack of understanding of the headed stud connector in engineering design.

2 Methodology

In this study, a solid finite element model was established based on the push-out test of headed stud connectors with ordinary concrete. Eurocode 4 recommends the standard push-out test specimens. The height, width and thickness of the concrete slab are 500mm, 400mm and 200mm respectively. The diameter of rebars embedded in the slabs is 12 mm. The flange plate thickness of steel beam is 20mm, and the web thickness is 20mm. The diameter of studs is 19 mm and the height is 100 mm. Considering material and geometrical nonlinearity, material damage and contact interaction, the finite element software ABAQUS was used to simulate the push-out test and further analyze the mechanical behavior of the specimen.
3 Findings and Discussions

The studs in C15 were not sheared break, while the studs in C30–UHPC150 were sheared break. With the concrete strength increasing, the compressive damage range of the concrete at the root of studs gradually decreases, and no obvious damage occurs in UHPC150. After the weld collar is established, the increased cross-sectional area of the root of the stud makes the bearing capacity partially enhanced. The simulated values of the considered and unconsidered weld collar differ from the experimental values by approximately 1.1% and 11.9%, respectively.

As shown in Fig. 1, the ultimate bearing capacity corresponds to the maximum principal strain of the stud, where the minus sign indicates the lower edge. The increase of concrete strength provides stronger constraint around the foot of stud shank, so that the deformation of the stud is reduced, and the proportion of the welding collar participating in the shearing increases. Meanwhile, the angle between the failure surface of the stud and the axis of the stud shank increases. The damaged area gradually moves towards the welding toe. However, the shear cross section of the welding collar is limited. The strength of concrete continues to increase and the ultimate bearing capacity tends to stabilize.

![Fig. 1. Maximum principal strain of stud upper and lower edges](image)

4 Conclusion

1. In FEA simulation stud push-out test, the local reinforcing effect of the welding collar and the concrete at the root of the stud should be considered, which is conducive to improving the FE accuracy.
2. The increase of concrete strength is beneficial to improve the fatigue resistance of the stud. With the yield stress range of the stud, the elastic bearing capacity of stud increases, and the stress around the root of the stud is smaller under the same load, which improves the structural durability.
3. With the strength of concrete enhanced, and the proportion of the welding collar participating in the shearing increases. The stud with UHPC yields to the plastic failure initiating on the bottom surface of the stud shank and propagating through the cross-section near the weld collar. The failure mode is the opposite of normal strength concrete.
4. The simplified method specified in practical design codes may lead to a conservative design since the local reinforcing effects are neglected, which is not conducive to play the performance of UHPC.

REFERENCES

Condition monitoring systems and vibration fatigue

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Keywords: fatigue; vibration; monitoring systems.

ABSTRACT

The object of the research is the methods of organization and functioning of vibration monitoring systems for the state of machines and equipment. Such systems are focused on solving problems of diagnosing equipment defects in order to prevent emergencies. At present, vibration monitoring systems are widely used. Typically, these systems provide continuous monitoring and protection of equipment throughout the entire life cycle of operation. Despite the widespread use of such monitoring systems, a significant number of facts of accidents and catastrophes at industrial facilities are known, associated with manifestations of the influence of vibration. The operation of existing monitoring systems is determined by the requirements of ISO standards. Starting with the first standards in this area (ISO 2372), in the standards that replaced them (ISO 7919, 10816 and others) and later "diagnostic" standards (ISO 13373 and others), the methods used below are based on measurements of the current level of vibration process intensity. In this case, vibration control is carried out according to the parameters of vibration displacement, and more often vibration speed. These measurements are used in the implementation of emergency protection functions. The organization of monitoring systems using such methods practically does not take into account the results of a large volume of research in the field of vibration fatigue of materials and testing of machine elements and equipment for vibration. Vibration fatigue can be considered a special case of cyclic fatigue. An important determinant of cyclic fatigue is the effect of the number of cycles or time of exposure to vibration. Numerous studies show a multiple decrease in the strength characteristics of structural materials when exposed to high-cycle or gigacycle loading. In this case, the processes of gigacycle fatigue can be associated with the formation and development of defects hidden in the volume of the structural material, which practically do not manifest themselves in changes in the current level of vibration intensity. This does not allow modern systems of continuous monitoring of the vibration state to respond to the processes of cyclic fatigue of materials.

Another feature of vibration fatigue processes is associated with the important value of the dynamic forces and mechanical stresses arising in this material. The magnitude of such forces is determined by the acting accelerations. The use of acceleration control is not typical for vibration monitoring systems. Although the accelerometers used in such systems are convenient for such control, the acceleration signals from them, as a rule, through integration are converted into signals of speed or displacement. In this case, a large amount of information is lost about the presence of high-frequency vibration components, which determine the magnitude of dynamic stresses. Such dynamic stresses \( \sigma(t) \) are defined as

\[
\sigma(t) = \rho L \Delta l(t) \cdot 4\pi^2 f^2
\]

where \( \rho \) is the specific density, \( L \) is the thickness of the considered area of the material, \( \Delta l(t) \) is the deformation, and \( f \) is the frequency of the acting vibration. The quadratic dependence on frequency determines the rapid growth of mechanical dynamic stresses with increasing frequency even at small
deformations. The contribution of such high-frequency vibration processes to material destruction processes is confirmed by many practical examples. Rapid destruction of the material occurs during bubble cavitation. A significant decrease in the strength of materials is also observed under the conditions of their cyclic loading test in the presence of additive high-frequency deformations, which have a small amplitude.

The considered features of the manifestation of vibration fatigue make it possible to recommend supplementing the methods of vibration monitoring of machines and equipment with means of controlling the dose of vibration. It is also advisable to provide measurement of the impact of high-frequency vibrations by collecting data on the acting accelerations. Such additions do not require a significant increase in equipment in the vibration monitoring system. Since high-frequency vibrations are often localized for relatively small areas, in some cases it may be necessary to increase the number of vibration sensors and control channels. In a budgetary option, this can be achieved by expanding the use of MEMs accelerometers and multichannel ADCs with a configurable input structure in the data acquisition device of the monitoring system.

At the same time, the reliability of the emergency protection of equipment can be increased by dividing it into a fast one that responds to circulating and high-frequency components. Standard Failover Protection responds to vibration measurements in the vibration monitoring frequency band. "Diagnostic" emergency protection responds to vibration measurements taking into account the fatigue strength reduction of structural materials and equipment elements.
Experimental identification of viscoelastic properties

of plates made of quiet aluminum

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Keywords: Damping properties; Viscoelastic models; Fractional derivatives; Vibrating plates; Quiet Aluminum.

ABSTRACT

1. INTRODUCTION

Accurate evaluation of damping properties of layered thin walled structures, as plates or shells, is a relevant problem for several industrial applications in the field of vibration control and noise reduction. Accurate modelling of modal properties also plays a fundamental role for describing metal fatigue, caused by forced vibration on structural components. The interest in the identification of equivalent viscoelastic models from vibration has therefore strong motivations, but it is generally a difficult task, since often the basic models are not accurate enough [1].

In this study an indirect approach is adopted, based on the concept of modal damping ratio ($\zeta_n$), focusing the attention on its behaviour as a function of the related natural frequency ($\omega_n$). To overcome the difficulty of finding analytical expressions for $\zeta_n$ in case of non–elementary dissipative models, a method of general validity has been developed, introducing the concept of equivalent modal damping ratio applied to the circle–fit technique [2]. This identification method is based on the assumption that the Nyquist plot of the mobility for any mode $n$ can be approximated by a circumference, which is still acceptable when considering non–elementary dissipative models such as fractional derivative models [3]. The Fractional Kelvin model [1] is then applied to the analysis of plates made of Quiet Aluminum.

2. IDENTIFICATION METHOD

According to the circle–fit technique [2], circular experimental Nyquist plots of the Mobility allows the estimate of the modal damping ratios $\zeta_n$, which applying the integer order Kelvin model are given by:

$$\zeta_n = \frac{1}{2\omega_n} \left[ \frac{\omega_n^2 - \omega_0^2}{\omega_2 \tan(\gamma_2) + \omega_1 \tan(\gamma_1)} \right]$$

(1)

where $\omega_0$ is the natural angular frequency and the other symbols refer to Fig. 1a. Notice that $\omega_0 = \Omega_0$ only for the integer order Kelvin model, but more in general it is $\omega_0 \neq \Omega_0$, as in Fig. 1a.

The experimental estimates of $\zeta_n$ as function of the natural frequencies $\omega_n$ usually show a behaviour which is very far from the linear ones predicted by either the integer order Kelvin model or the hysteretic model [3]. As a consequence, in order to fit such experimental curves, more refined models are needed. The Fractional Kelvin model is here adopted, which in the frequency domain reads:

$$E(\omega) = E_0[1 + (i\omega)^\alpha]$$

(2)

where $E_0$ is the equivalent static Young’s modulus, $\alpha$ is a non–integer or fractional derivative order and $\tau$ is a characteristic time. At this stage a definition of general validity is needed for $\zeta_n$, in order to create a link between the experimental damping estimates of Eq. (1) and the viscoelastic parameters of the selected model, as in Eq. (2). The proposed definition is:

$$\zeta_n = \frac{1}{2} \omega_n \frac{\text{Im}[R(i\omega_0)]}{\omega_0} \Rightarrow \text{Im}[E_0 R(\omega_{2n})] = \frac{\Delta_{2n} \Delta_{1n}}{\Delta_{2n} \omega_{2n} \Delta_{1n} \omega_1}$$

(3)

where $\lambda_n$ is a modal parameter. Assuming that $\lambda_n$ can be separately estimated (considering a model for the
undamped structure) then the static Young’s modulus $E_0$ simply represents a scaling factor. Eqs. (1) and (3) provide a link between the selected viscoelastic model and the evaluation of $\zeta$ via circle–fit technique. Through Eq. (3), the parameters of the loss modulus $\text{Im}[E(\omega)]$ of an equivalent material, directly proportional to the energy-loss per cycle, can therefore be experimentally estimated.

Fig. 1. Nyquist plot of Mobility, general scheme for mode $n$ (a). Modal damping ratios $\zeta_n$ vs natural frequencies $\omega_n$ (b). Experimental identified data (dots) and Fractional Kelvin model interpolations (continuous).

3. EXPERIMENTAL RESULTS

A square plate made of Quiet Aluminum has been tested, with side length $l = 300$ mm, thickness $h = 2$ mm and total weight $P = 0.52$ kg. The experimental estimates of $\zeta$ are displayed vs the natural frequencies $\omega_n$ in Fig. 1b. On the experimental data (dots) are superimposed the curves $\zeta_n (\omega_n)$, plotted using the following identified parameters in the Fractional Kelvin model:

$$\frac{E_0}{E_{0,\text{Al}}} = 0.825 \quad \alpha = 0.219 \quad \tau = 4.829 \times 10^{-5} \text{ s} \quad (\rho = 2889 \text{ kg/m}^3, \quad \nu = 0.33)$$

where $E_{0,\text{Al}} = 7.1 \times 10^{10} \text{ [N m}^{-2}]$ is the standard Young’s modulus of Aluminum.

The accuracy of the identified parameters has then been successfully assessed by comparison of numerical with experimental FRFs (modulus of Mobility).

The proposed identification procedure is also suitable for application in the finite element method, for studying dissipative effects in layered thin walled structures of general shape. Among applications, accurate modelling of modal properties would improve the results of vibration-based methods for estimating fatigue in metal or metal-composite structures like QA panels.

REFERENCES

Fatigue reliability estimation framework for turbine rotor using multi-agent collaborative modeling

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Keywords: fatigue reliability; low cycle fatigue; agent model; neural network

ABSTRACT

In the start-idle-take-off-cruise-stop cycle of gas turbine engine, turbine rotor operates in extreme working environment of high temperature, high pressure and high speed for a long time, its weak locations (i.e., blade root, disk core, tenon groove, etc.) often occurs fatigue fracture and throw out accident [1-2]. Moreover, due to multi-uncertain variables, the fatigue life of turbine rotor often shows large dispersions in practice [3]. Therefore, fatigue reliability estimation is desired to quantify the reliability-based fatigue life of turbine rotor. At present, fatigue reliability estimation has been widely used in probabilistic life prediction of engineering structures [4-5]. However, for turbine rotor involves complex geometric modelling and load traits, the limit state function often shows high-complexity and strong-nonlinearity, which leads to the current fatigue reliability estimation methods (i.e., Monte Carlo method, surrogate modelling method, etc.) presents unacceptable accuracy and efficiency [6]. Therefore, an efficient fatigue reliability estimation approach of turbine rotor is lacking and desired.

Under the circumstances, to improve the accuracy and efficiency of fatigue reliability estimation of turbine rotor, a multi-agent collaborative modelling (MACM) approach is proposed by absorbing the strengths of improved differential evolution (IDE) algorithm and wavelet neural network (WNN) into decomposed-collaborative strategy. The fatigue reliability estimation framework is presented in respect of MACM approach. Furthermore, the fatigue reliability estimation of a typical turbine rotor is considered as one case to evaluate the presented approach. The basic theory of MACM is introduced as follows:

For a given training set \( \{ x, y(x) \}_{i=1}^{n} \), \( x \in \mathbb{R}^d \), \( y(x) \in \mathbb{R} \), wavelet neural network (WNN) function \( f(x) \) is to approximate the nonlinear relationship between input random variables \( x \) and output response \( y(x) \). After network training of IDE algorithm, the mathematical model of WNN is structured as

\[
y(x) = \sum_{j=1}^{s} w_j \cos \left( \frac{1.75}{a_j} \left( \sum_{i=1}^{n} w_{ji} x_i - b_j \right) \right) \exp \left( -0.5 \left( \frac{1}{a_j} \sum_{i=1}^{n} w_{ji} x_i - b_j \right)^2 \right)
\]  

where \( \exp(\cdot) \) denotes the error function between real output \( y \) and simulated output \( y(x) \).

Considering the WNN model and decomposed-collaborative strategy, to reduce the modeling complexity, the MACM approach is presented: Assuming that multi-layer probabilistic estimation is decomposed into \( r \) layers, where \( x^{(p)} \) denotes input variables in the \( p \)-th layer, \( Y^{(p)} \) expresses as output response, then the decomposed WNN model is constructed as

\[
Y^{(r)} = f \left( x^{(p)} \right) = \sum_{j=1}^{s} w_{ji} \phi_{ji}^{(p)} \left( \frac{1}{a_{ji}} \left( \sum_{i=1}^{n} \phi_{ji}^{(p)} x_i^{(r)} - b_{ji}^{(p)} \right) \right)
\]  


where $\hat{a}_j^{(p)}$, $\hat{b}_j^{(p)}$, $\hat{w}_j^{(p)}$ and $\hat{v}_j^{(p)}$ are the optimal parameters of WNN training function in the $p$-th layer.

Regarding the output responses $\{Y_i\}_{i=1}^N$ of all layers as the input variables $\vec{x}$ of whole surrogate model, the output response $\vec{Y}$ of the whole surrogate model, a collaborative WNN model, is denoted as

$$\vec{Y} = \sum_{j=1}^N \phi_j \left( \frac{1}{\partial \phi_j} \left( \sum_{i=1}^m w_{ji} \vec{x}_i - \vec{v}_j \right) \right)$$

where $a_j$, $b_j$, $w_j$ and $v_j$ are the optimal parameters of multi-layer WNN training function.

With the presented MACM approach, the fatigue reliability estimation of turbine rotor is performed: At first, material properties, multi-physical interaction (MPI) loads and parameters of improved Manson-Coffin model [6] are regarded as input random variables, low cycle fatigue life $N_f$ is considered as output response; Secondly, few training & testing samples are generated by adopting Latin hypercube sampling technique and MPI finite element simulations; Moreover, the MACM model is built by extracted training & testing samples and IDE algorithm; Finally, the reliability-based fatigue life (6050 aviation cycles) is obtained by employing the proposed MACM model and massive sampling. The fatigue reliability estimation of a typical turbine rotor is shown in Fig. 1.

![Fatigue reliability estimation of turbine rotor](image)

**Fig. 1.** Fatigue reliability estimation of turbine rotor (a) MPI loading sketch (b) Fatigue life probabilistic distribution.

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**Numerical Study of FPSO Platform Brackets for Different Geometric Configurations Subjected to Environmental Loads**


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**Keywords:** Mooring Systems; Brackets; Computational Modeling; Geometrical Investigation; Mechanical Behavior.

**ABSTRACT**

Mooring systems are responsible to maintain the position of oil production platforms under environmental loads. One of the mooring system components is the bracket, which is a robust structure composed of thick steel plates responsible to fix the mooring system in the vessel. One important subject in this problem is the achievement of design solutions for the employed plates, which would lead to reductions on the costs for mounting and maintenance of the structure in the vessel [1].

The present work has two main purposes, the development of a computational modelling of brackets used for support of fairleads subjected to the maximum environmental load and the achievement of theoretical recommendations about geometrical configurations that reduce the von Mises maximum stress in the plates of brackets. In this sense, different geometric configurations are studied for superior brackets using plates commonly employed in real applications. The studied geometries are based on the existent brackets of P-66 Petrobras platform. More precisely, three different configurations for the base of superior brackets are compared: rectangular, rectangular/triangular and rectangular/trapezoidal. Figure 1 depicts a global view of the mooring system, the brackets and the view of the plates used in superior and inferior brackets. All configurations have the same area constraint being investigated in the light of Constructal Design [2].

![Fig. 1. Illustration of the bracket component of mooring system in the vessel and the scheme of the different configurations for the basis plate used in the brackets.](image)

The methodology is defined in the following steps:
1 – estimate the environment loads (wind, sea currents and waves) over a FPSO platform with a spread mooring type composed of 24 lines using data available in the Campos basin (Brazil) by Det Norske Veritas (DNV) standards [3];

2 – Apply the found loads in the idealized domain (based on existent brackets of P-66 Petrobras platform) and calculate the stress distribution in the solid domain using a code based on the Finite Element Method (FEM), more precisely ANSYS Mechanical APDL [4,5];

3 – Compare the application of the same load for three different configurations with the same overall area of the basis plate in the light of Constructal Design Method [2].

The brackets studied here are composed of AH36 steel plates, with a yielding limit of 355 MPa. It is considered 10 mm thick plates (four times lower than that commonly found in real applications) in the basis of the bracket. The hole, where the axis that connect the two brackets is placed, has a radius of 150 mm. Moreover, it is 650 mm distant from the hull and centralized in the x-direction of the plate. The height of the vertical plates of the bracket is also constant at 600 mm.

The results for the ultimate limit state (ULS), where the full environmental load is shared between 24 mooring structures distributed along the hull, and accidental limit state (ALS), where the distribution for only 20 mooring structures are taken into account, obtained in the domain of the three superior brackets studied here are presented in Table 1. More precisely, it is shown the results for the maximum von Mises stresses.

Table 1. Results of ultimate limit state (ULS) and accidental limit state (ALS) for three different configurations of superior brackets.

<table>
<thead>
<tr>
<th>Configuration/Limit State</th>
<th>ULS (MPa)</th>
<th>ALS (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectangular</td>
<td>248.51</td>
<td>279.55</td>
</tr>
<tr>
<td>Rectangular/Triangular</td>
<td>338.04</td>
<td>380.09</td>
</tr>
<tr>
<td>Rectangular/Trapezoidal</td>
<td>333.78</td>
<td>382.43</td>
</tr>
</tbody>
</table>

The rectangular structure led to a mechanical performance nearly 35% and 38% superior than that achieved with rectangular/trapezoidal and rectangular/triangular bases, respectively, showing that the investigation of geometry can be an important strategy for design of the brackets found in mooring systems. Future studies are recommended for analysis of other project conditions and considering dynamic loads in the problem.

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Durability Assessment of Multi-axial Strain Loads for Rural Road Condition in Time Domain

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\textbf{Keywords:} power spectral density; multiaxial strain; strain life; linear regression; fatigue life

\section*{ABSTRACT}

The aim of this study is to characterise the multiaxial strain loading signal in order to assess the durability of the coil spring in time domain. Coil spring experiences vertical axial loading during their service at the mounting that results in tension-compression force. However the internal reactions in the coil spring consist of direct shear force and a torsion due to its movement when subjected to cyclic loading. Therefore, it is necessary to consider not only tension and compression loading for fatigue life analysis but must also consider the shear force and torsion. In this study, the strain signal in x-axis, 45°, and y-axis is analysed to show that the shear force, torsion and tension-compression are correlating with each other. Strain signal in x-axis refer to 0° while strain signal in y-axis refer to 90°. All the strain signals in 0°, 45° and 90° axis are in same plane.

Figure 1 shows the durability assessment process of multi-axial strain loads for rural road condition. A rosette strain gauge were attached to the suspension system coil spring in order to obtain signal in 0°, 45° and 90° axis. The strain gauge was connected to a data acquisition instrument and the random strain signal was recorded. Global statistical value was determined to compare the energy content in time domain with frequency domain. The, fatigue life from random strain signal in 0°, 45° and 90° axis were correlated using simple linear regression method.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
Angle of strain load (°) & Mean (µɛ) & SD(µɛ) & RMS (µɛ) & Kurtosis(µɛ) \\
\hline
0 & -3343 & 1728 & 3763 & 4.27 \\
45 & -3116 & 6707 & 7395 & 4.07 \\
90 & -3228 & 2669 & 4189 & 3.83 \\
\hline
\end{tabular}
\caption{Global statistical value.}
\end{table}

Mean, kurtosis, root mean square (RMS) and standard deviation were used to find the behaviour of strain signal. Mean value shows tensile or compression behaviour of the signals. The RMS and kurtosis values as shown in Table 1 could determine the total vibrational energy content and the sensitivity to high amplitude events in the data [1]. The skewness shows the distortion of signal data distribution.
Figure 2(a) illustrates the kurtosis and RMS of the strain data. The strain signals possess kurtosis values exceeding 3, indicating high damage experienced by the coil spring [2]. Strain in 0° axis gives the highest value of kurtosis at 4.27µε followed by strain in 45° and 90° axis. Meanwhile, strain in 45° axis provides the highest value of RMS followed by strain in 90° and 0° axis. Thus, strain in 0° axis shows the highest kurtosis with lower vibrational energy content due to constant amplitude of the strain data.

Figure 2(b) shows that the power spectral density (PSD) is in the frequency range of 0 Hz to 4 Hz that indicated the vibration occurred at low frequency. The strain signal in 45° axis had the highest energy of $8.06 \times 10^6 \mu\varepsilon^2$/Hz followed by the strain in 90° $(1.21 \times 10^6 \mu\varepsilon^2$/Hz) and 0° $(4.86 \times 10^5 \mu\varepsilon^2$/Hz) axis. Therefore, there are significantly different energy content in 0°, 45° and 90° axis. Furthermore, the area under curved in PSD has same trend with kurtosis value.

![Fig. 2](image)

**Fig. 2.** (a) RMS and kurtosis parameters of coil spring (b) PSD of multiaxials strain gauge. (c) Fatigue life of multiaxial strain gauge of each axis.

Fatigue life prediction was computed using strain-life models: Coffin-Manson (CM), Morrow and Smith-Watson-Topper (SWT) as shown in Figure 2(c). In Table 1, the mean values of a signals showed negative value where the compression condition exhibits on coil spring. Thus this can be related with the Morrow model which predominant to compressive. Based on the Morrow model, the fatigue lives of strain in 0°, 45° and 90° axis were $6.07 \times 10^6$, $9.55 \times 10^4$ and $8.87 \times 10^5$ cycles/block, respectively. Fatigue life in 45° axis had the lowest fatigue life which contained the highest vibrational energy. The fatigue life prediction for the CM, Morrow and SWT model had the same trend for the strain signals in 0°, 45° and 90° axis.

![Fig. 3](image)

**Fig. 3.** Correlation of fatigue life for different strain axis: (a) 90° vs 0°, (b) 45° vs 0°, (c) 45° vs 90°.

Figure 3 displays the data correlation of fatigue life in 0°, 45°, and 90° axis. The fatigue lives were well correlated with each other since the $R^2$ values exceeded 0.8. The fatigue life in 45° axis shows only ‘good’ relationship with 0° and 90° axis with $R^2$ values of 0.81 and 0.87 due to the torsional effect in coil spring. The models are reliable to predict fatigue life if the $R^2$ value is higher 0.8 which can be classified as ‘good’ whereas those with $R^2$ value of more than 0.9 is classified as ‘very good’ [3]. Therefore, there are significant differences between the strain signal in 0°, 45° and 90° axis. The correlation shows that the difference angle of strain load resulting the change in behaviour of the multiaxial strain signals which is related to the response of coil spring during operation condition.

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**ACKNOWLEDGMENTS**

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Durability Assessment of Variable Amplitude Loading using Effective Strain Approach

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Keywords: effective strain; load sequence effect; strain signals; variable amplitude; durability.

ABSTRACT

Fatigue failure is commonly occurs on components that is subjected to vibration loadings, especially suspension coil spring of automobile. Coil spring is an important component of the suspension system that provide good vehicle control and ride quality. The consequence of the coil spring failure can be catastrophic which could result in the loss of lives. Therefore, durability test of the coil spring is necessary to predict the useful fatigue life under different loadings and conditions. Time-domain method including the stress-life and strain-life approaches were conventionally used for durability prediction. Nonetheless, these methods were found to be the conservative prediction of fatigue life as the load sequence effect of the loading histories is not considered \cite{1}. The main issue is to determine the fatigue life of coil spring subjected to variable amplitude loading by considering the loading sequence effect. Therefore, this study aims to assess the durability of coil spring using effective strain approach by considering the load sequence effect in variable amplitude strain histories.

Fig. 1 illustrates the process of signals acquisition to capture strain signal in order to predict the durability of the coil spring. Strain histories of coil spring were collected via road tests under various road conditions (university campus, industrial area and highway). In this study, durability of the coil spring was predicted using strain-life models including Coffin-Manson, Morrow and Smith-Watson-Topper (SWT) models. An effective strain damage (ESD) model was proposed to evaluate the durability of components by considering the load sequence effect \cite{2}. The material of the coil spring is SAE 1045 carbon steel. To study the load sequence effect using the ESD model, the important material property is the crack closure decay parameter \( m \) of the metal that represents the decay of crack opening stress after an overload. El-Zeghayar et al. \cite{3,4} had experimentally determined the \( m \) parameter of SAE 1045 carbon steel to be 0.008. The strain signals obtained under various road conditions were also shown in Fig. 1.

Durability prediction models

\begin{align*}
\text{Coffin-Manson model:} & \quad \varepsilon_{ef} = \frac{\sigma'_0}{E} (2N_f)^{1/m} + \varepsilon'_0 (2N_f)^{1/m} \\
\text{Morrow model:} & \quad \varepsilon_{ef} = \left( \frac{\sigma'_0 - \sigma_m}{E} \right) (2N_f)^{1/m} + \varepsilon'_0 (2N_f)^{1/m} \\
\text{Smith-Watson-Topper:} & \quad \varepsilon_{esd,ef} = \frac{\sigma'_0}{E} (2N_f)^{1/mb} + \varepsilon'_0 (2N_f)^{1/mb} \\
\text{Effective strain damage model:} & \quad \Delta \varepsilon_{ef} = \frac{A}{E} (N_f)^{1/m} + \Delta \varepsilon
\end{align*}

Fig. 1. Process of strain time histories acquisition and fatigue life prediction
Experimental results illustrated that highway had less high amplitude events compared to other signals, indicating less fatigue damage contributed to the coil spring. The highway signal showed in the longest fatigue life of around $10^5$ blocks of loading. Meanwhile, the lowest fatigue life of between $1.19 \times 10^3$ to $2.93 \times 10^3$ was found in the industrial road signal. This can be owing to the high amplitude events that frequently occurred on the industrial road that had contributed to the fatigue damage to the coil spring. Fig. 2 shows the fatigue life correlation between the fatigue life predicted by ESD model and strain-life models. It can be found that the strain-life models had predicted a conservative fatigue life especially in the campus and industrial road signals that contained many high amplitude events. The fatigue life of highway signals predicted using ESD model is close to the predicted value using strain-life models. This is mainly because the load sequence effect was not dominant in the durability prediction from the highway signal due to the absence of high amplitude event [5].

As a conclusion, the load sequence effect was found to have more significant effects in strain signals that had many high amplitude events. Under such condition, strain-life models were found to have predicted a more conservative fatigue life. For a strain signal that had smooth load profile such as the highway signal, the load sequence effect was not dominant in the durability prediction and hence the ESD model obtained very close fatigue life as the strain-life models. Therefore, it is important to considered the load sequence effect during the fatigue life prediction to prevent an over conservative prediction.

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The authors are gratitude to the funding from the Ministry of Education Malaysia (Grant: FRGS/1/2019/TK03/UKM/01/3) and Universiti Kebangsaan Malaysia (UKM) (Grant: DIP-2019-015).
Acoustic Emission Characteristics for Determining Fatigue Damage Behaviour

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Keywords: fatigue damage; acoustic emission; reinforced concrete beam; absolute energy.

ABSTRACT

Fatigue in a concrete structure is a process of damage accumulation owing to the repetitive application of loads. The repeated of the loads may not produce any effect at an earlier stage. Over several cycles, as the loads continuously applied, the damage generates intrusions and extrusions that resemble a crack which led to a disaster when the damage becomes large to propagate catastrophically. Acoustic emission technique has been used for detection of fatigue damage in a concrete structure employing sensors that fixed on the selected positions. From the signal captured by the sensors, it gives information on the condition of the structure, where the increase in acoustic emission characteristic is generally associated with the rise of new structural damage. Investigation of different types of sensors in terms of their frequency, signal and sensitivity has been investigated by Meserkhani et al. [1] and Bhuiyan et al. [2]. Meserkhani et al. [1] found that the general-purpose sensor with the frequency range of 35 – 100 kHz produced better absorbing acoustic emission energies than the other sensors. Bhuiyan et al. [2] found that all sensors represent a similar pattern of acoustic emission hit. Although types of sensors are essential in acoustic emission monitoring, acoustic emission characteristic at certain sensor positions also needs to be taken into consideration. However, the effect of the sensor’s position was not investigated in-depth primarily related to the acoustic emission energy on concrete either absolute energy or signal strength. In the present study, the absolute energy is highlighted. The absolute energy is true energy which is calculated by squaring the digitised acoustic emission signal and integrating the results during a hit [3]. To develop a comprehensive understanding of the acoustic emission activities, acoustic emission signal collected at different locations of sensors become the key that needs to be taken into account. In doing so, the present study investigates the acoustic emission absolute energy of reinforced concrete beam subjected to fatigue loading at different position of sensors. A constant-amplitude sine wave load cycle (frequency of 0.5 Hz) was applied to the beam size 150 mm x 150 mm x 750 mm. Four sensors (CH1 to CH4) were used and the positions of the sensors on the beam are illustrated on the schematic diagram in Fig. 1.

For fatigue test, maximum load, Pmax, and minimum load, Pmin, were based on the ultimate load, Pult, value. The Pult, was taken by averaging the ultimate load of five beams under monotonic loading. The average Pult was 158.85 kN. Hence, the Pmax and the Pmin was 0.8Pult and 0.2Pult, respectively. The fatigue test in conjunction with acoustic emission monitoring performed with this load range until failure. Then, the acoustic emission absolute energy was analysed and compared for all sensors. Fig. 2 shows the absolute energy, cumulative absolute energy with respect to normalised cycle (N/Nf) that collected from CH1 to CH4. Generally, the fatigue test developed three stages of fatigue damage; initiation, propagation and unstable fracture stages. CH1 which located at the edge of the beam received the highest absolute energy at the initiation stage of fatigue damage compared to other sensors. It is because the Pmax applied to the
beam-induced formation of the first fatigue crack, which propagated beyond the neutral axis. The energy was then reduced instantly and almost constant throughout the cycle. Xu [4] stated that early microcracks generate a higher signal as the flexural cracks form. From Fig. 2, CH2 to CH4 produced a similar pattern of acoustic emission characteristics. However, CH3 and CH4, which located at the top of the beam, represent high acoustic emission characteristics at the propagation stage compared to other sensors. These sensors captured signal from the development of more flexural cracks in the beam. At the unstable fracture stage, CH2 received the highest energy before the failure of the beam.

**Fig. 1. Position of the sensors on the beam surface**

**Fig. 2. The relationship between absolute energy and cumulative absolute energy and N/Nf for a) CH1, b) CH2, c) CH3 and d) CH4**

**REFERENCES**


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The authors would like to express their thanks to Universiti Teknologi MARA, Cawangan Pulau Pinang and Universiti Teknologi MARA, Malaysia for providing financial support towards the publication of this manuscript.
Multiple Linear Regression Parameters for Generating Fatigue-based Entropy Characteristics of Magnesium Alloy

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Keywords: constant loading; entropy; fatigue; magnesium alloy; stress ratio

ABSTRACT

The selection of magnesium alloy for applications in, for example, the aerospace, automotive and electronic industries, is becoming more important as this material offers admirable features. Since magnesium alloy is a relatively new material compared to mild structural steel and aluminium, further investigations are needed to ensure its safe application. A major problem with structural systems is fatigue failure since there is no significant indication that failure is about to occur. Therefore, crack propagation plays a key role in determining the life span of a component. In a conventional test, many unknown input parameters are required. Therefore, the dissipation of energy is introduced to predict the life span of a material. This relationship can also be described through the introduction of multiple linear regression (MLR). MLR is used to predict the value of a variable based on the values of two or more other variables. If the total generation of entropy can be approached through regression, then fatigue life can be predicted. Hence, this paper was aimed at describing the MLR relationship in order to predict the total entropy generation of magnesium alloy, AZ31B.

This study utilised the commercial AZ31B magnesium alloy. Compact tension (CT) test specimens were prepared according to the recommendations of E647-95 for associating the temperature variation by means of entropy evolution. Before applying the fatigue tests, the surface of the specimens facing the thermal sensor was coated with a layer of black paint to improve the thermal emissivity and to reduce the error rate. All the specimens were tested using a constant amplitude sinusoidal loading of 2600 N and 2800 N, and stress ratios (ratio of minimum to maximum load) of R = 0.1, 0.4 and 0.7, respectively at a constant frequency of 10 Hz. During the test, the temperature trend of the specimens was detected with an infrared sensor that had been set up.

For the load of 2600 N, just after the cycles reached $4.34 \times 10^3$ for a stress ratio of 0.1, the crack began to grow, followed by $3.73 \times 10^3$ and $2.28 \times 10^3$ cycles for stress ratios of 0.4 and 0.7, respectively. The final crack cycle was lower when a higher stress ratio was applied. This also affected the fatigue crack growth rate, causing it to increase as the mean stress value changed [1]. As the crack growth increased, the total entropy was calculated until the specimen fractured completely. The total entropy generation when a load of 2600 N was applied was 3.424, 3.101 and 2.922 MJm$^{-3}$ K$^{-1}$ for stress ratios of 0.1, 0.4 and 0.7, respectively. According to Fig. 1, the total entropy generation increased as a higher stress ratio was applied indicating entropy generation lead to a lower fatigue life[2]. This trend was followed by the load of 2800 N, when stress ratios of 0.1, 0.4 and 0.7 were applied to the specimen.
Four different conditions that need to be evaluated for multiple regression to give a valid result are the normal probability plot, versus fits, histogram and versus order [3]. The results are shown in Fig. 2. The versus fits plot shows that the average of the residuals remained approximately 0, the variation of the residuals appeared to be roughly constant, and there were no excessively outlying points. There was little in the histogram of the residuals to suggest a violation of the normality assumption.

The MLR analysis being applied for producing a meaningful entropy prediction model. The datasets comprising the entropy generation values of the CT specimens, stress ratio (R), and load applied (P), as shown in Eqn. 1, were used to establish the MLR-based entropy models. The MLR-based entropy generation model or also known as the predicted entropy (γ) was obtained as:

$$\gamma = 5.827 - 0.001148P + 0.8044R$$

Table 1 shows the percentage of difference between the experimental and predicted data for new load conditions. The difference is less than 10%, and this indicates that the calculated entropy generation well predicts the experimental data under new load conditions. This explains that most of the experimental entropy generation were near to similar predicted values.

Table 1 The percentage of difference entropy generation with respect to the experimental data

<table>
<thead>
<tr>
<th>Stress ratio</th>
<th>Experimental entropy, $MJJm^{-3}K^{-1}$</th>
<th>Predicted entropy, $MJJm^{-3}K^{-1}$</th>
<th>% of differences</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>2.536</td>
<td>2.608</td>
<td>2.83%</td>
</tr>
<tr>
<td>0.4</td>
<td>2.607</td>
<td>2.849</td>
<td>9.29%</td>
</tr>
<tr>
<td>0.7</td>
<td>2.956</td>
<td>3.090</td>
<td>4.55%</td>
</tr>
</tbody>
</table>

Entropy generation was deployed as an effective way of measuring the crack growth behaviour of a material with changes in the temperature during the fatigue process. An approach to develop an MLR relationship between the entropy generation, applied load, and stress ratio was shown in this work. The results were indeed encouraging, indicating that the entropy values obtained from the experiment and regression model were in good agreement.

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Very high cycle fatigue behavior of a compressor blade titanium alloy at elevated temperature

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Keywords: TC17 alloy; very high cycle fatigue; elevated temperature; S-N curve; crack initiation.

ABSTRACT

TC17 titanium alloy is a kind of $\alpha + \beta$ two-phase titanium alloy rich in $\beta$ stable element. It is widely used in aviation components (such as blades, turbine disks, etc) for the advantages of high strength, low density, corrosion resistance and good weldability. These aviation components usually work in complex environment including high temperature and high speed rotation, and they have to satisfy requirements of long life and high reliability.

The mechanical properties of TC17 titanium alloy at room temperature (RT) and elevated temperature (400 °C, ET) were investigated by static tensile tests. The results showed the tensile strength at elevated temperature was significantly reduced. However, the plasticity was not obviously affected by temperature and showed a certain degree of work hardening as shown in Fig. 1, where the strain-hardening capacity was expressed as follows [1],

\begin{equation}
H_c = \frac{\sigma_y - \sigma_f}{\sigma_y} = \frac{\sigma_y - \sigma_f}{\sigma_y} - 1
\end{equation}

Table 1 represented the hardening capacity of titanium alloy at different temperatures. The hardening capacity was extremely low at the RT, which was consistent with the low hardening capacity of most titanium alloy, ignoring the manufacturing process [2]. Compared with the HT, its hardening capacity was relatively large, indicating that the hardening capacity of the titanium alloy was sensitive to temperature.

![Graph of engineering stress-strain curves](image)

Fig. 1 The engineering stress-strain curves.
The very high cycle fatigue behaviors of TC17 alloy at RT and ET were studied by use of self-developed ultrasonic fatigue test system as shown in Fig. 2. The obtained S-N curves showed different tendencies with linear decrease at RT while double-line decrease at ET. There was an obvious inflection point at 107 cycles, where the fatigue limit was reduced by 100 MPa at ET compared to that at RT as shown in Fig. 3. Further studies had shown that the reduced fatigue strength at the ET might be related to the reduction of the critical resolved shear stress of the grains, thereby accelerating the movement of dislocations and increasing the slip system [3-5].

Observation of the fracture surface after fatigue failure revealed that there were two failure modes at RT, namely, surface crack initiation failure and subsurface crack initiation failure as shown in Fig. 4, while there was only one failure mode of surface crack initiation at ET as shown in Fig. 5. According to the experimental results, both the fatigue strength and crack initiation mechanism were affected by temperature. Elemental analysis of the crack initiation site showed that very high cycle fatigue failure at ET was caused by dual effects of mechanical fatigue and oxidation. The high-temperature environment promoted crack initiation and also accelerated oxidation of the material at crack tips which could promote crack propagation.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Ultimate Tensile Strength, MPa</th>
<th>Yield Strength MPa</th>
<th>Elongation, %</th>
<th>Hardening capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT-01</td>
<td>1079</td>
<td>1036</td>
<td>16.1</td>
<td>0.04</td>
</tr>
<tr>
<td>RT-02</td>
<td>1076</td>
<td>1030</td>
<td>15.0</td>
<td>0.04</td>
</tr>
<tr>
<td>RT-03</td>
<td>1051</td>
<td>1011</td>
<td>16.0</td>
<td>0.04</td>
</tr>
<tr>
<td>Average</td>
<td>1069</td>
<td>1026</td>
<td>15.7</td>
<td>0.04</td>
</tr>
<tr>
<td>HT (400 ℃)-01</td>
<td>838</td>
<td>695</td>
<td>15.6</td>
<td>0.21</td>
</tr>
<tr>
<td>HT (400 ℃)-02</td>
<td>860</td>
<td>697</td>
<td>14.5</td>
<td>0.23</td>
</tr>
<tr>
<td>HT (400 ℃)-03</td>
<td>889</td>
<td>722</td>
<td>13.2</td>
<td>0.23</td>
</tr>
<tr>
<td>Average</td>
<td>862</td>
<td>705</td>
<td>14.4</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Table 1 Tensile test data of TC17 alloy at the RT and ET.

Fig. 2 The ET ultrasonic fatigue test system: (a) sketch; (b) spot diagram.
Fig. 1 S-N curves of TC17 titanium alloy in the VHCF regime at different temperatures.

Fig. 2 Fracture diagram of subsurface crack initiation at the RT ($\sigma_a = 500\text{MPa, } N_f = 1.1757 \times 10^8$): (a) Overall view of fracture surface for specimen; (b) Magnified view of subsurface crack initiation site; (c) Facet on the crack initiation site.

Fig. 3 Crack initiation on the specimen surface at the ET ($\sigma_a = 380 \text{ MPa, } N_f = 7.1244 \times 10^8$): (a) Overall view of fracture surface for specimen; (b) Enlarged view of crack initiation location; (c) Surface crack initiation site.

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Causes of cable fracture failure in high temperature and high pressure deep well and the way to avoid it

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Keywords: cable fracture; failure analysis method; fluid mechanics method; cause analysis; High temperature and high pressure deep well.

ABSTRACT

During the operation of high temperature and high pressure deep wells, especially in gas wells, cable fracturing and abnormal loading are common phenomena. In this paper, the failure analysis of the broken cable and the stress analysis of the direct reading well test cable were carried out by adopting the failure analysis method and fluid mechanics method. It was found that the change of fluid state, pressure and temperature in wellbore was the principal reason for the abnormal load of cable. The essence of rope fracture is strength failure. The transverse force produced by opening the well for production by exploiting tree valve is smaller than that produced by opening valve at choke manifold for production. When the high pressure gas flows upward, the weighting rod was pushed upward, then will fall freely after a certain height. The impact load generated is at least twice the weight of the weighting rod. Therefore, the main reasons of cable fracture in high-temperature and high-pressure deep well wireline operation are as follows: the combined action of transverse force, impact force, weighting rod and cable weight make the stress of wellhead cable greater than the strength of cable material, resulting in the cable breaking at the wellhead. In order to prevent the direct reading well test cable from breaking, the gate valve on the flank of Christmas tree shall be opened first, and then the valve at the choke manifold shall be opened. During the construction of direct reading well test, it is necessary to optimize the control of the opening of the nozzle and operate smoothly.
Failure Mechanism Analyses and Remedy Methods for Multi-packers Tubular Strings in Complex Wells

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Keywords: Multi-packers tubular strings; complex well; straddle operation; failure analysis.

ABSTRACT

To solve the failure problems of packer failure and tubing string channeling during staged oil testing and fracturing of horizontal wells in high-temperature and high-pressure deep wells and tight reservoirs, three key factors for successful straddle operation were revealed in the paper. By adopting the small deformation beam theory and force method, the buckling configuration and statically indeterminate axial force of multi-packer straddle string were analyzed, and the critical load and buckling configuration of finite span tubing string under borehole constraint were obtained. The additional bending moment and additional bending stress of bending string between spans can be calculated, and its strength safety can be checked based on the previous conclusions. The reasonable combination of tubing strings can be realized. Based on the material analysis and mechanical analysis of the rubber cylinder of the compression packer, the improvement measures of the rubber cylinder material of the packer are put forward, and the calculation method of the allowable working pressure difference in the straddle operation is put forward under the condition of the safety of the rubber cylinder strength. Under the condition of ensuring the strength safety of rubber cylinder, the calculation method of allowable pressure difference and the method of establishing the differential pressure are put forward. On the basis of three monographic researches, the main causes of straddle operation failure, tool bending and packer rubber barrel channeling are found out. The guiding opinions on the selection of straddle operation tools, tubing string combination and operation parameters are put forward. The allowable operation pressure difference is determined with the consideration of the strength safety of downhole string and tools, packer rubber barrel and rubber barrel framework.
A study of the fatigue failure mechanism in steel and composite rebars

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Keywords: fatigue, microstructure, fractography, S-N curves, rebars.

ABSTRACT

The growing interest in new materials - especially composite materials in the manufacturing and application of reinforcing bars in the building industry - leads to the development of the fatigue database for steel and composite materials. In the presented paper, Authors compare the fatigue endurance and failure mechanism of two different rebars; steel and composite in bending fatigue experiment (\(R=0.1\), rebar diameter 10mm). For the investigation, two types of rebars were selected; steel and composite (GFRP). After tests, the failure mechanism was investigated (Fig. 1) using scanning electron microscopy (SEM). Also, the fracture topography was analysed using the focus variation microscope Alicona Infinite Focus, and optical 3D measurement device, which allows the acquisition of data sets with a large depth of focus. Surface texture studies were carried out mainly on the propagation and rupture areas of the fracture, using areal and volumetric parameters, according to ISO 25178.

![](image.png)

Fig. 1. SEM images (scanning electron microscope) of the tested GFRP rebars microstructure; before (on the left) and after test (on the right) with fatigue crack

ACKNOWLEDGMENTS

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Modification Optimization-Based Fatigue Life Analysis and Improvement of EMU Gear

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Keywords: fatigue life analysis; fatigue life improvement; modification optimization; S-N curve.

ABSTRACT

This paper revisits the fatigue life improvement problem, a well-known problem in structural design optimization, and implements a modification optimization-based fatigue life analysis approach, to improve fatigue life of EMU gear. The corrected method of stress amplitude, average stress and S-N curve are proposed in consideration of the low stress cycle, material difference and other factors. The accurate fatigue life prediction of EMU gear is carried out by corrected S-N curve and transient dynamic analysis. Moreover, the gear modification technology combined with intelligent optimization method is adopted to investigate the approach of fatigue life analysis and improvement. It is found that the proposed fatigue life analysis and improvement approach results in higher accuracy of fatigue life prediction in most situations than would otherwise be achieved by traditional method. It is concluded that by applying the proposed approach to the EMU gears, the fatigue life is significantly improved.

1. Objectives

Accurate fatigue life prediction of the transmission gear is beneficial to the operation and safety improvement of the vehicle [1]. The transmission gear is easy to produce unbalanced loadbearing in the meshing process due to the complex load cases of EMU, which reduces its fatigue life [2, 3]. So, this paper proposes a gear modification optimization-based fatigue life analysis method of EMU.

2. Employed methods

For achieving the research objectives mentioned above, a fatigue life calculation method based on gear modification is investigated. The gear transmission performance is analysed based on the transient dynamics, employing direct integration as the solving method. The control equation is shown in Eq. 1. As for solving the problems of unbalanced loadbearing and excessive contact stress in the results, the gear modification is introduced. The S-N curve, stress amplitude and average stress are corrected by comprehensively considering the influence factors for improving the accuracy of fatigue life calculation. The S-N curve and average stress modification are shown in Fig. 1 and Fig. 2, respectively. The meshing cycles of transmission gear which can be obtained by the proposed method is finally transformed into service kilometres.

\[ [M][\tilde{\sigma}_{\alpha-\omega}] + [C][\tilde{\sigma}_{\alpha-\omega}] + [K(\omega)][\tilde{\sigma}_{\alpha-\omega}] = \{F_{\alpha-\omega}\} \]  

(1)
3. Results

The results show that the fatigue life of gear is 56.47 million kilometres, which increases by 19.4% than before. Simultaneously, the contact stress decreases by 17.7%. The contour plot of fatigue life analysis is shown in Fig. 3. It can be seen from Fig. 3 that the fatigue life of transmission gear after modification satisfy the design requirements. Moreover, the gear modification improve the unbalanced loadbearing of transmission gear. The correction of S-N curve, stress amplitude and average stress solves the problem that the actual stress life curve does not conform to the traditional curve. The fatigue life of EMU transmission gear is predicted more systematically and completely under the premise of ensuring safety and economy while considering the difference of test materials.

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Very high cycle fatigue failure mechanism of TC17 electron beam welding joint at elevated temperature

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Keywords: TC17 EBW joint; very high cycle fatigue; elevated temperature; failure mechanism

ABSTRACT

Welding structure is widely used in the key parts of modern aeroengine. They usually work in harsh environment such as high temperature, high speed and so on, and need to meet the requirements of long life and high reliability. In this paper, very high cycle fatigue crack initiation and propagation mechanisms of the TC17 electron beam welding (EBW) joint at elevated temperature (400°C) were studied.

The fusion zone (FZ) and heat affected zone (HAZ) were characterized by EBSD, as shown in Fig.1. It could be found that the FZ was composed of columnar β-phase crystals with the maximum size of 500 μm. The equiaxed β-phase crystals existed near the fusion line with the size about 100 μm, while free α-phase crystals and equiaxed β-phase crystals existed at the HAZ.
The fatigue test results show that the S-N curve of the EBW joint decreased linearly at room temperature (RT) at the regime of $10^5$-$10^9$ cycles (as shown in Fig. 2), while it showed a bilinear decline tendency with an obvious inflection point near $10^7$ cycles at 400℃. The fatigue strength of the EBW joint at $10^9$ cycles was about 240 MPa at 400℃, which was greatly reduced by 20% compared with that at room temperature. Due to inhomogeneous heat distribution and rapid cooling during the welding process, a large number of welding pores were formed in the welded joint. The fatigue life of the welded joint was mainly determined by the number, size and position of welding pores\cite{1,2}, which caused great discreteness to the very high cycle fatigue data of EBW joints.

Microscopic observation of fracture surfaces showed that almost all fatigue cracks initiated at the pores inside the welded joint, and there were radial ridges along the crack propagation direction, showing the transgranular fracture mode, as shown in Fig. 3 and Fig. 4. Further investigation showed that an obvious facet with the size of about 400 μm existed near the pores where the crack initiated in each welded joint. The facet showed no characteristics of the fine grain zone, therefore, it could be inferred that the formation of the facet was caused by the β-phase columnar crystal at the FZ.

It was found that the characteristics of fatigue crack initiation zone of the welded joint at elevated temperature was obviously different to that at room temperature\cite{1}. This indicated the
fatigue failure mechanism of the welded joint was obviously affected by the high temperature. The fatigue crack initiation zone was observed by an infinite focus measurement machine (IFM). It was found that the facet at the crack initiation zone had an angle of $45^\circ$ with the crack propagation direction, which indicated that the formation of the facet was related to the critical shear stress in the grain. The critical shear stress was changed by the temperature, which caused the short crack at the initiation zone to propagate along the $45^\circ$ direction in the $\beta$-phase columnar crystal, and finally formed the facet morphology.

Fig. 3 Fracture morphology (inside crack initiation)

Fig. 4 Fracture morphology (near surface crack initiation)
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Effect of build orientation on fatigue performance of additively produced structural components: a numerical methodology

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Keywords: Metallic Additive Manufacturing; Topology Optimization; Building Strategy; Residual Stress; Fatigue Life Prediction; Multiaxial Criterion.

ABSTRACT

The main goal of the present research is to propose an integrated methodology to address the fatigue performance of topology optimized components, produced by additive manufacturing \cite{1}\cite{2}. The main steps of the component design will be presented, specially the methods and parameters applied to the topology optimization and the post-smoothing process. The SIMP method was applied in order to obtain a lighter component and a suitable stiffness for the desired application. In addition, since residual stresses are intrinsic to every metallic additive manufacturing process, the influence of those stresses will be also analysed. The Laser Powder Bed Fusion was numerically simulated aiming at evaluating the residual stresses the workpiece during the manufacturing process and to investigate how they could influence the fatigue behaviour of the optimized component. The effect of the built orientation of the workpiece on the residual stresses at some selected potential critical points is evaluated.

A case study of a bracket was selected to demonstrate the methodology \cite{3}. Figure 1 illustrates the boundary conditions and optimized bracket using SIMP/ABAQUS software. Figure 2 shows the results of some simulations: i) structural simulation of the bracket using ABAQUS; ii) residual stress field simulations for three different build directions using Additive Manufacturing software from ESI. The figure also represents some potential critical points in terms of maximum stresses from structural analysis or from maximum residual stresses. Figure 3 represents the fatigue life predictions for the selected points in the bracket and for build direction \#2. One can realize the effect of tensile residual stresses that tend to reduce fatigue life. However, changing the build direction, one can generate favourable compressive residual stresses that lead to longer fatigue lives.

Fig. 1. Bracket: boundary conditions (left) and optimized bracket using SIMP/ABAQUS method (right).
Fig. 2. Numerical simulations: structural and AM simulations of the bracket for three distinct directions and selection of potential points.

Fig. 3. Fatigue life prediction for bracket considering 6 potential critical points. Effects of constructive residual stresses from build orientation #1.

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Finite Element Analysis of Distortions and Residual Stresses in Metallic Laser Powder Bed Fusion

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Keywords: Laser Powder Bed Fusion, Metallic Additive Manufacturing, Residual Stresses, Finite Element Method

ABSTRACT

Additive Manufacturing (AM) has experienced significant growth since its inception [1], allowing the production of near net shape components [2] with applications in the aeronautical [3], biomedical [4] and automobile [5] industries. Capable of producing outputs with almost no geometrical restrictions [6], good static properties [7], [8], generally requiring little human interaction [9] and effective at producing on-demand parts in situations in which inventory space is limited [10], AM is also afflicted by multiple disadvantages that greatly impact fatigue behaviour [11]. Defects are common in AM, and more specifically to laser powder bed fusion (LPBF) due to the nature of the process, where a travelling heat source melts the metallic powder, turning it into a melt pool that subsequently cools down: this process may lead to balling [11], key-hole porosity [12] and lack-of-fusion [13]. Additionally, due to the inherently thermal nature of the process, AM produced parts display residual stresses, defined as stresses that remain in a body in the absence of external loads [14]. Residual stresses emerge through inelastic deformation caused by thermal expansion and contraction, generally being of tensile nature near the component’s surface and compressive in its core [15], as observable in Fig 1. Due to their influence in mechanical behaviour [14], [15], must be accounted for during the product development stage, inspiring finite element method (FEM) software packages to offer their metallic additive manufacturing solutions. In this research work, the most used modelling techniques are presented, alongside their implications and variables; then, numerical simulations with differing objectives are performed: firstly, convergence studies are conducted to measure the mesh’s influence residual stress computation; then, several geometrical and manufacturing parameters are analysed: laser speed, hatch spacing, pre-heat temperature and cooldown temperature’s influence is assessed. Comparisons between two software packages are established, using three distinct physical models: a one layered component; a component with very simple geometry, thus relinquishing the need for support structures and minimising the mesh’s effect; a benchmark unit developed by the National Institute

Fig 1: Numerical (top) and experimental (bottom) comparison between longitudinal residual strain $\varepsilon_{xx}$ (left) and vertical residual strain $\varepsilon_{zz}$ (right) contour plots, extracted from y=2.5mm plane in Iconel 625 benchmark bridges
of Standards and Technology (NIST), designed for the study of residual stresses. This also allows the validation of the overall process, establishing an analogous case in distinct software packages. The analysis of the displacement and stress field with the progressive removal of a workpiece from its baseplate is analysed and compared to experimental values. Lastly, comparisons between the residual strain field with experimental values obtained by NIST are conducted for the benchmark component, as shown in Fig 1, allowing final conclusions on the validity and broadness of the provided solutions to be made.

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Fatigue behaviour of maraging steel produced by additive manufacturing

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Keywords: Metal Additive Manufacturing; Fatigue behaviour; 18Ni300 Maraging steel; Miniature specimens.

ABSTRACT

Current trend in additive manufacturing (AM) processes are creating new design strategies and methodologies for structural components. Metallic parts can be manufactured according to layer-by-layer deposition from a 3D model with high geometric flexibility, which can result in significant reductions of weight keeping the structural functionality of the component. In fact, this process allow significant design optimization and simplification on the production of customized components. Nevertheless, those components must be designed and manufactured in order to fulfil the geometrical and shape requirements as well as structural integrity. In detail, phenomena such as residual stress, porosity and stress concentration may have impact in the fatigue strength, which must be investigated.

The current investigation aims at exploring the fatigue behaviour of the 18Ni300 Maraging steel, produced both by conventional manufacturing processes and by a specific additive manufacturing process, the Selective Laser Melting (SLM), also recognized as Laser Powder Bed Fusion (LPBF). The fatigue characterization of those materials was based on an experimental program using four point bending cyclic aiming at evaluating the S-N curves, testing miniature notched specimens. Taking into account the reduced dimensions of the specimens, a gripping mechanism was designed and adapted to an existing fatigue testing machine. Miniature specimens obtained from AM process, were tested according different specifications, such as as-built, machined and aged condition.

The calibration of the experimental set-up was performed using quasi-static experimental results, which was compared to the numerical ones, obtained from FEM analysis. It should be noted that the computation of S-N curves is dependent of the elastoplastic stress conditions observed around the notch, which can be calculated through numerical simulations. The cyclic curves of both materials were also obtained based on tensile/compressive tests on smooth specimens using progressively applied strain ranges on same specimen. Finally, porosity and admissible defects existing in the samples were analysed through microstructural observations.
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The following projects are fully acknowledged for their financial support to this research work: i) Add.Strength project entitled “Enhanced Mechanical Properties in Additive Manufactured Components” funded by the Programa Operacional Competitividade e Internacionalização, and Programa Operacional Regional de Lisboa funded by FEDER and National Funds (FCT) (Reference PTDC/EME-EME/31307/2017); ii) MAMTool project, entitled “Machinability of Additive Manufactured Parts for Tooling Industry”, funded by the Programa Operacional Competitividade e Internacionalização, and Programa Operacional Regional de Lisboa funded by FEDER and National Funds (FCT) (Reference PTDC/EME-EME/31895/2017).
Fatigue Behavior of Cold-Formed Z-Rails for Rack Structures


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Keywords: Rack Structures; Cold Forming; Fatigue Testing; Stress Analysis; Numerical Analysis.

ABSTRACT

Nowadays, in the field of logistics engineering, rack structures prepared for automatic shuttles that are responsible for the intensive transportation and storage of various goods and products are used to deal with the logistics of a large warehouse. These shuttles are automated and can work non-stop in a 24/7 economy.

In order to move through the rack structure, the shuttles run along cold-formed steel rails, which are prone to fatigue phenomena due to the passage of moving shuttles. Moreover, cracks due to material fatigue have already been observed in these applications, as shown in Fig. 1. These rails are manufactured through the cold roll-forming process, which occurs at room temperatures, much lower than the required temperatures for material recrystallization. On effect, the final product contains internal residual stresses that may play a role in their fatigue/structural performance.

To ensure safety inside a warehouse that contains a racking structure, fatigue design codes should include S-N curves for the mentioned applications. Currently, the Eurocode 3 [1] does not cover the fatigue behavior of thin cold-formed elements, like the mentioned rails. The Eurocode 3 does cover the subject of thick hot-rolled elements; however, residual stresses are not relevant in these cases.

Fig. 1. Observed cracking in a cold-formed steel rail.
Within this background, the FASTCOLD European project arises with the aim to develop fatigue design rules for cold-formed steel members and their connections. The project also aims to provide a classification of cold-formed structural steel details according to their fatigue strength, similar to the ones from Eurocode 3 for thick hot-rolled steel details.

Within the FASTCOLD project, a new experimental fatigue testing setup was developed at the Faculty of Engineering of the University of Porto in order to conduct full-scale fatigue tests on a specific rail, the Z-rail. Both stress and fatigue analyses were conducted on the Z-rail to obtain insight on its fatigue behavior and to generate S-N curves.

Using the mentioned fatigue testing setup, experimental lifetimes (in terms of number of load cycles endured) were determined for Z-rail specimens, allowing the construction of S-N curves, and aiming for the classification of this detail (\(\Delta \sigma_C\) and \(m\) parameters from Eurocode 3).

Finally, the conducted stress analysis on the Z-rail, in the form of a parametric study, presents equations that facilitate the stress range computation for the construction of S-N curves.

**REFERENCES**


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Probabilistic analysis applied to multiaxial fatigue
criteria for the S355 steel

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Keywords: fatigue; multiaxiality; probabilistic analysis; steel

ABSTRACT

In real case scenarios, such as in bridges or wind towers’ details, the fatigue stress state is multiaxial not only due to the loading conditions but also to the geometry. Hence, it is important to consider the multiaxiality during fatigue damage assessment. Several multiaxial fatigue models have been developed since the middle of the 20\textsuperscript{th} century, based on different variables and considering different factors as responsible for fatigue damage and consequently failure [1]–[4]. Furthermore, it is valuable to complement this fatigue assessment with a probabilistic analysis, which is usually based on the normal or Weibull distributions, as it is suggested by ISO and ASTM [5], [6]. Thus, this work aims to study and apply several probabilistic approaches to different multiaxial fatigue models: Sines\textsuperscript{[1]}, Findley\textsuperscript{[2]}, McDiarmid \textsuperscript{[3]} and Dang Van’s\textsuperscript{[4]} models. These fatigue models’ formulations are described in Table 1.

<table>
<thead>
<tr>
<th>Model</th>
<th>Condition of failure</th>
<th>Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sines \textsuperscript{[1]}</td>
<td>$\tau_{a,oct} + k_f(\sigma_{h,mean}) = s$ \textsuperscript{(1)}</td>
<td>$s$: damage parameter; $k_f$: material constant; $\sigma_{h,mean}$: hydrostatic mean stress; $\tau_{a,oct}$: octahedral shear stress.</td>
</tr>
<tr>
<td>Findley \textsuperscript{[2]}</td>
<td>$(\tau_{\theta,a} + k_f \sigma_{\theta,max})_{\max} = f$ \textsuperscript{(2)}</td>
<td>$f$: damage parameter; $\tau_{\theta,a}$: maximum shear stress amplitude on a $\theta$ plane, $\sigma_{\theta,max}$: maximum normal stress on a $\theta$ plane; $k_f$: material constant.</td>
</tr>
<tr>
<td>McDiarmid \textsuperscript{[3]}</td>
<td>$\frac{\tau_{\theta,a} + \sigma_{\theta,max}}{2\sigma_{\theta}} = 1$ \textsuperscript{(3)}</td>
<td>$\sigma_{\theta}$: ultimate tensile strength; $\tau_{\theta,a}$: reversed shear stresses for case A (cracks along the surface) or B (cracks from the surface).</td>
</tr>
<tr>
<td>Dang Van \textsuperscript{[4]}</td>
<td>$\tau_{a,max} + k_d \sigma_{\theta,max} = d$ \textsuperscript{(4)}</td>
<td>$d$: damage parameter, $\tau_{a,max}$: maximum shear stress amplitude; $k_d$: material constant; $\sigma_{\theta,max}$: maximum hydrostatic stress.</td>
</tr>
</tbody>
</table>

Regarding the probabilistic analysis, three different approaches were studied. Primarily, it was applied the methodology described in ISO 12107 standard [5], so the fatigue life, $N$, at a given damage parameter level, $DP$, was assumed as a random variable which logarithm ($X = \log(N)$) follows a normal distribution defined by a mean value, $\mu_X$, and a standard deviation, $\sigma_X$. Thus, the mean curve S-N curve for a certain population is defined as:

$$\hat{\mu}_X = \bar{b} - \bar{a}Y$$

(4)

where $Y = \log(DP)$ and $\bar{a}$ and $\bar{b}$ are estimated constants. The lower limit to the S-N curve corresponding to a probability of failure $p_f$ for the population at a confidence level (CL) of 1-$\alpha$ and for a certain number of degrees of freedom $v=n-2$ is estimated by applying the following equation:

$$\hat{X}_{(p_f,1-\alpha,v)} = \bar{b} - \bar{a}Y - k_{(p_f,1-\alpha,v)} \hat{\sigma}_X \sqrt{1 + \frac{1}{n} + \sum_{i=1}^{n} \frac{(Y_i - \bar{Y})^2}{\bar{Y}^2}}$$

(5)

where $k_{(p_f,1-\alpha,v)}$ is the one side tolerance limit for a normal distribution, $n$ is the number of data items, $\bar{Y}$ and $\hat{X}$ are mean values and $\hat{\sigma}_X$ is the population standard deviation of $X$. After that, it was implemented
the ASTM E739 standard’s methodology [6] which is very similar to the one described in the ISO’s standard. However, instead of defining tolerance intervals, ASTM defines confidence intervals calculated through the equation below:

\[
\hat{b} - \hat{a} \bar{Y} \pm \sqrt{2F_p \hat{\delta}_F \left( \frac{1}{n} + \frac{(Y - \bar{Y})^2}{\sum_{i=1}^{n}(Y_i - \bar{Y})^2} \right)}
\]

where \(F_p\) is a parameter of F-distribution. Finally, the Weibull distribution of two parameters was applied to estimate the probability of failure and the probabilistic curves through the following equation:

\[
\log(\text{DP}) = \frac{\log\left(N\beta\left(-\ln\left(1 - p_f\right)\right)^{1/\delta}\right)}{b} - \frac{\hat{a}}{b}
\]

where \(\delta\) is the shape parameter and \(\beta\) is the scale parameter [7].

In Figure 1 can be seen the mean curve and the probabilistic curves plotted according to ISO 12107, ASTM E739 and considering the Weibull distribution for the Dang Van model applied to biaxial and axial experimental fatigue data of S355 structural steel.

![Fig. 1. Mean curve and probabilistic curves calculated for the Dang Van’s damage parameter](image)

\[\text{REFERENCES}\]


\[\text{ACKNOWLEDGMENTS}\]

This work was financially supported by base funding - UIDB/04708/2020 and programmatic funding - UIDP/04708/2020 of the CONSTRUCT - Instituto de I&D em Estruturas e Construções - funded by national funds through the FCT/MCTES (PIDDAC).
Crack closure effects on fatigue crack propagation under constant amplitude loading for the 6061-T651 aluminium

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Keywords: aluminium alloy; fatigue crack growth rates; crack closure effects; constant amplitude

ABSTRACT

The fatigue crack growth laws that include crack closure effects are based on the relationship between the fatigue crack growth rates \( (da/dN) \) and the effective stress intensity factor ranges \( (\Delta K_{\text{eff}}) \). It is well known that the crack closure phenomenon near the crack tip plays an important role in fatigue life predictions. In this sense, many relations for the quantitative parameter, \( U \), to take into account crack closure effects have been postulated [1-3].

This paper opens a discussion over some crack closure models for constant amplitude loading, such as Elber, Schijve, Newman, Correia etc., included in literature [4-14]. In the current study, the experimental fatigue crack growth data under constant amplitude loading of the 6061-T651 aluminium alloy were collected from the literature [15-17].

A comparison between the various crack closure models was made using fatigue crack growth rates \( \text{versus} \) effective stress intensity factor ranges. Additionally, a study on the influence of applied stress \( R \)-ratio on the relation \( K_{op}/K_{max} \) was carried out (see Fig. 1).

---

**Fig. 1.** Influence of stress \( R \)-ratio on \( K_{op}/K_{max} \) relation using several models.
According to the analytical results and experimental crack closure measurements for this aluminium alloy under consideration, the crack closure effects are more significant for stress R-ratios below 0.5. The Correia and Codrington-Kotousov models [5,11,13] are in accordance with experimental measurements [17], and the other applied models seem to be overestimating the relation $K_{op}/K_{max}$ for this aluminium alloy.

REFERENCES


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Thanks Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - CAPES (Brazil) for the financial support.
Probabilistic Fatigue Analysis of CFRP reinforced small-scale metallic plates


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Keywords: Fatigue; metallic component; CFRP; Statistical approach; Retrofitting.

ABSTRACT

The fatigue maintenance of metallic structural components is a critical issue. Bonding CFRP patches is regarded in several industries such as Aerospace engineering as an efficient technique to repair cracked structural elements and delay the fatigue crack propagation rate. However, little is known about the effectiveness of the application of bonded CFRP in retrofitting non-damaged metallic elements subjected to fatigue loading. This involves the full fatigue life of the metallic component that includes the crack initiation and propagation phases. The full fatigue life of the metallic component can be longer than the fatigue life of the adhesive layer, and pre-mature debonding can occur. Thus, the effectiveness of the composite patch in extending the fatigue life can be significantly reduced. Monfared et al. [1] tested notched specimens without initial pre-crack under fatigue loading, where some of the specimens were retrofitted with CFRP. The result showed that the fatigue life could be extended by a factor 1.7-2.06 depending on the CFRP configuration and the stress range. Pastor et al. [2] investigated the effect of bonding composite patches before the crack appears in aluminium plates. The rationale behind consists of deviating the stress flow from the critical zone and reduce stress concentration. Thus, the critical zone can be relieved from crack appearance. The results showed a significant extension of the lifetime for patched over un-patched specimens. Except for higher loads were the adhesive layer progressively failed which reduced the performance of the retrofitting scheme. Ghafoori et al. [3] provided an analytical procedure to design the CFRP reinforcement based on Young’s modulus or the pre-stress level and the dimension of the CFRP plates, such that the structural component can be shifted from a “finite-life” regime to the “infinite-life” regime using the constant life diagram approach. Recently, Wang et al. [4], [5] tested experimentally steel and aluminium plates featuring a hole in the middle under fatigue loading, where some of the specimens were without reinforcement used as reference, and others were retrofitted with CFRP sheets. The authors compared the results with fatigue resistance curves available in design code such as BS8118 and ASHTOO. The fatigue life could be significantly increased at loadings with lower stress level. Fatigue test results of metallic elements usually display significant scatter especially in the fatigue crack initiation phase. The composite patch provides additional uncertainties related to the resistance of the bonding layer especially at high level of stress where debonding can occur before fatigue damage appears. Probabilistic methods are necessary to quantify this inherent variation and to develop design guidance. This paper presents a probabilistic analysis conducted on the data of Wang et al. [5] without and with CFRP (i.e. T6-H-P0-SD3L). The Weibull distributions as well as the model developed by Castillo & Fernández-Canteli were adopted in order to provide probabilistic S-N curves. Figures 1 and 2 present the probabilistic S-N fields using the Weibull distribution and the Castillo & Fernández-Canteli model, respectively, for specimens with and without CFRP. As it can be seen, the specimens with CFRP experienced longer fatigue life for lower stress levels, where runouts could be achieved at $\Delta \sigma = 200 M\text{Pa}$. However, at higher stress levels the improvement was less significant. The
Castillo & Fernández-Canteli could capture well the fatigue limit, where after the runouts a flat plateau is presented in the curves. Whereas in the case of the Weibull model the curves continue to decrease.

Fig. 1. Probabilistic fatigue life prediction based on Weibull distribution: (a) Without CFRP; (b) With CFRP.

Fig. 2. Probabilistic fatigue life prediction based on Castillo & Fernández-Canteli model: (a) Without CFRP; (b) With CFRP.

REFERENCES


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This research was supported and funded by: project grant (POCI-01-0145-FEDER-030103) FiberBridge - Fatigue strengthening and assessment of railway metallic bridges using fiber-reinforced polymers by FEDER funds through COMPETE2020 (POCI) and by national funds (PIDDAC) through the Portuguese Science Foundation (FCT/MCTES); and, base funding - UIDB/04708/2020 and programmatic funding - UIDP/04708/2020 of the CONSTRUCT - Instituto de I&D em Estruturas e Construções - funded by national funds through the FCT/MCTES (PIDDAC).
Global-Local Fatigue Life Assessment based on Hot Spot Stress and Elastoplastic Local Strains Methodologies: Comparative Study

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Keywords: Fatigue; Sub-modelling; Elastoplastic Local Strain; Hot Spot Stress.

ABSTRACT

Railway bridges are susceptible to fatigue failures, once these bridges are subjected to permanent loading and high variable loads resulting from the passage of trains. [1]. There are several approaches to evaluate the structural component submitted to the fatigue process. The present paper analyses the fatigue failure process based on Hot Spot Stress methodology and the methodology based on elastoplastic local strains. The global-local approach was used to assess the detail in both methodologies. According to recommendation IIW [2], the Hot Spot stress extrapolation must be done considering the appropriate mesh refining as stated in the recommendation, the location of the extrapolation points, and the approximation - linear or quadratic. The flowchart for the application of the Hot Spot Stress methodology is presented in Fig. 1 [3].

![Flowchart of dynamic sub-modelling and fatigue evaluation – Hot Spot Stress.][1]

In the methodology using elastoplastic local strains, the elastoplastic quantities are calculated from the multilinear kinematic hardening model using the ANSYS Mechanical APDL software. This material model is based on the Besseling model, also known as the sublayer model, in which the Bauschinger effect is included. [4] [5]. A local strain approach is applied, similarly to that presented in [6]. The flowchart in Fig. 2 presents the second methodology evaluated.
The comparison between the two presented methodologies indicates a difference between the achieved fatigue life values due to the considerations of each methodology. In the Hot Spot Stress methodology, only the elastic stresses are considered, not including the effects of plasticity and stress field rearrangement of the analysed region.

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The authors are grateful to Federal University of Minas Gerais (Brazil) and University of Porto (Portugal). This research was also supported and funded by: project grant (POCI-01-0145-FEDER-030103) FiberBridge - Fatigue strengthening and assessment of railway metallic bridges using fiber-reinforced polymers by FEDER funds through COMPETE2020 (POCI) and by national funds (PIDDAC) through the Portuguese Science Foundation (FCT/MCTES); and, base funding - UIDB/04708/2020 and programmatic funding - UIDP/04708/2020 of the CONSTRUCT - Instituto de I&D em Estruturas e Construções - funded by national funds through the FCT/MCTES (PIDDAC).
Evaluation of the stress concentration factor for a welded KT-joint

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Keywords: Fatigue; stress concentration factor; offshore welded KT-joints; FEM analysis.

ABSTRACT

The determination of stress concentration factors (SCFs) in a welded tubular joint is a relevant parameter to be considered in the fatigue design of offshore structures. One way to obtain this factor is through parametric equations restricted to basic loading cases: as axial loading, in-plane bending, and out-of-plane bending. These equations can be extracted from recommendations, for example, the DNVGL-RP-C203 [1]. The stress concentrations (SC) generally occur in regions close to geometric discontinuities. Offshore structures are subjected to this phenomenon and it occurs close to the weld and the intersections of the members. According to Ghanameh [2], and as observed in several studies [3,4,5], stress concentrations can lead to maximum stresses exceedingly greater than the nominal stress. Therefore, numerical simulations can be an interesting tool to predict the SCF and lead the results closer to the real.

The consideration of the weld fillet on the numerical model may modify the SCF estimation. Minguez et al. [6] carried out a comparative numerical study considering the influence of the weld for a T-type joint and it was evidenced the importance of including the weld geometry in order to avoid overestimations in SCFs. Similarly, Hectors and De Waele [7] evaluated the SCFs of a T-joint including the weld geometry, comparing these values to experimental data and parametric equations found in the literature. The results showed that a model without a weld can result in overly conservative estimates of SCFs.

Therefore, this study aims to evaluate the influence of the weld fillet geometry modeling on a KT tubular joint. For this, two different models were evaluated: the first considering solid elements and; the second also composed of solid finite elements but with the inclusion of the weld geometry. The study was conducted from the analysis of loads applications obtained from a real offshore structure and the results of the stress concentration factors were compared with the parametric equations provided in the DNVGL-RP-C203 recommendations [1].

REFERENCES


Predicted distribution in measured fatigue life from expected distribution in cyclic stress-strain properties using a strain energy based damage model

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Keywords: Probabilistic analysis; strain energy; fatigue damage.

ABSTRACT

In practice, fatigue properties such as stress-life and strain-life are often fit from a relatively small amount of data, making accurate statistical analysis a challenge. Using a strain energy based damage model to predict strain-life and stress-life curves from individual specimens\,[1], a set of curves can be created to more accurately reflect the range of strain life values that would come from more extensive testing. This work examines how the expected variation in stress-strain properties could be used to predict the set of curves, if the strain hardening behaviour of the individual specimens is unknown.

![Strain-life distribution](image)

Fig. 1. An example of the expected distribution in strain-life based on a +/- 5\% variation in K', n', and elastic modulus.

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Stress Concentration Factor Evaluation for Tubular KT-Joints

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Keywords: Stress concentration factor; Hot spot stresses; Analytical solutions; Numerical solutions; Offshore jacket structure

ABSTRACT

In the last few decades, offshore field has grown so fast especially after the notable development of technologies, explorations of oil and gas in deep water and the high concern of offshore companies in renewable energy mainly Wind Energy. Fatigue damage was noticed as one of the main problems causing failure of offshore structures. The purpose of this research is to focus on the evaluation of Stress Concentration Factor for 2 tubular KT-Joints in offshore Jacket structure using different calculation methods. The work is done by using analytical calculations, mainly Efthymiou’s formulations, and numerical solutions, FEM analysis, using ABAQUS software. As for the analytical formulations, the calculations were done according to the geometrical parameters of each method using excel sheets. As for the numerical model, 2 different types of tubular KT-Joints are present where for each model 5 shell element type, 3 solid element type and 3 solid-with-weld element type models were built on ABAQUS. Meshing was assigned according to International Institute of Welding (IIW) recommendations, 5 types of mesh element, to evaluate the Hot-spot stresses. 23 different types of unitary loading conditions were assigned, 9 axial, 7 in-plane bending moment and 7 out-plane bending moment loads. The extraction of Hot-spot stresses and the evaluation of the Stress Concentration Factor were done using PYTHON scripting and MATLAB. Furthermore, this research will help us to compare different results of Stress Concentration Factor different methods.

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This research was supported and funded by: base funding - UIDB/04708/2020 and programmatic funding - UIDP/04708/2020 of the CONSTRUCT - Instituto de I&D em Estruturas e Construções - funded by national funds through the FCT/MCTES (PIDDAC); and Construction Institute (CI).
A comparative study on fatigue lifetime assessment based on stress and strain local criteria applied to an offshore structure

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Keywords: Fatigue; S-N curves; Offshore structures; Simplified fatigue analysis; Local criteria.

ABSTRACT

The wind power market in the offshore industry has been growing because it provides for decarbonization while contributing to economic growth in many countries proving it will continue to be a leading solution against climate change globally. Wind power, especially in offshore, is considered to be one of the most promising sources of ‘clean’ energy towards meeting the EU targets for 2020 and 2050. To ensure that the structure will fulfil its function, the design of fatigue is crucial to ensure an adequate service life, since it is responsible for more than 80% of the structural failures, most of the catastrophic and without warning. In this paper, different approaches are used in the fatigue damage evaluation of an offshore structure and compared. These approaches can be based on a linear hypothesis and in the S-N curves presented in the fatigue design recommendations as in DNVGL-RP-C203, API, or ABS. In the simplified fatigue approach, fatigue damage is estimated assuming that the stress follows a Weibull distribution for a long-term response. Due to the sensitivity of the estimated damage to fatigue in the Weibull parameters, the spectral assessment of fatigue has become more popular in offshore structural analysis. In this paper, fatigue lifetime assessments based on fatigue local criteria, such as stress and strain damage parameters, are applied to an offshore jacket-type structure. A comparison between the simplified fatigue analysis, proposed in DNVGL-RP-C203 recommendations, and fatigue lifetime assessments based on local approaches, are made. The local approach is based on Neuber’s rule combining with the Ramberg-Osgood description. For the application of the Neuber’s rule, the stress concentration factor values are calculated, according to Efthymiou’s analytical equations, for the connection under consideration. The local stress criterion used in this study is based on Basquin law, and, in the application of the local strain criterion is supported by Coffin-Manson relation.

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Fatigue damage assessments based on local stress and strain approaches applied to Hercílio Luz steel bridge

A. Mourãoᵃ, R. Cabralᵇ, J.A.F.O. Correiaᵃ, Z. Liuᶜ, D. Ribeiroᵇ, H. Carvalhoᵈ, T. Bittencourtᵃ, R. Calçadaᵃ

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ᶜDepartment of Civil Engineering and Engineering Mechanics, Columbia University, USA.
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ᵉUniversity of São Paulo, Brazil.

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Keywords: Fatigue damage; local fatigue criteria; global-local modelling; steel bridges.

ABSTRACT

Nowadays, ancient metallic bridges are faced with ever-increasing performance demands, through a combination of higher load intensity and/or operational service life. Since this type of ancient bridges is more than not lacking an explicit fatigue design, hence, fatigue damage and life assessment analysis are of major importance. A reason behind the increment in ancient bridges’ service life may be due to economical or cultural aspects, where the Hercílio Luz bridge is included being the oldest connection between the island of Santa Catarina and the mainland as well as the longest suspension bridge in Brazil. Built in 1926, the bridge contains a total of three spans, ranging from 131.05 and 114.45 m in the extremities and a centre span of 339.47 m, comprised of two longitudinal stringers, transversal bracing systems, with a total width of 16.45 m, including sidewalks on either side.

Taking advantage of the global model created in 2-beam elements, in this research is used a multiscale fatigue approach, integrating beam-to-solid elastoplastic material submodelling allowing for an accurate gathering of local information around the critical joint’s rivet holes, from the work of Liu et al. [1]. Given the fact that the global analysis is conducted using moving standardize fatigue trucks, resulting in a set boundary conditions which are later on integrated into the local modelling of the critical detail, these results in a stepped stress/strain state around the rivet hole whereas local fatigue damage stress, using Basquin’s Law with consideration of the mean stress effect, present in Eq. (1), and strain criteria, by means of the Coffin-Manson law, referenced in Eq. (2). Additionally, Palmgren-Miner’s linear cumulative damage rule is applied.

\[
\Delta \sigma = (\sigma_f - \sigma_m)(2N_f)^{b}
\]

\[
\Delta \epsilon = \frac{\Delta \epsilon_e + \Delta \epsilon_p}{2} = \frac{\sigma_f^c}{E}(2N_f)^{b} + \frac{\epsilon_f}{E}(2N_f)^{c}
\]

Granted that the structure in question has been subjected to retrofitting in critical regions, the new replacement material, structural steel S355, both mean and design cyclic parameters, presented in Table 1, will be used towards predicting fatigue life.
The stress/strain state in the riveted areas of the critical detail was analysed for several orientations, as such, a detailed damage and fatigue life estimation could be conducted for each direction as well as the rivet as a conglomerate of every damage per direction, as such, Table 2 provides the summarized results of 4 riveted section where local fatigue damage proved most debilitating whereas Fig. 2 represents the elastoplastic stresses as well as elastic-, plastic-strains for the most critical riveted section, respectively.

Table 2. Summarized fatigue life estimation results for the top critical riveted areas.

<table>
<thead>
<tr>
<th>Critical Riveted Area</th>
<th>FAT Life&lt;sub&gt;a&lt;/sub&gt;</th>
<th>FAT Life&lt;sub&gt;c&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hole 1</td>
<td>&gt; 100 (∞)</td>
<td>53.6</td>
</tr>
<tr>
<td>Hole 12</td>
<td>&gt; 100 (∞)</td>
<td>67.8</td>
</tr>
<tr>
<td>Hole 13</td>
<td>&gt; 100 (∞)</td>
<td>58.0</td>
</tr>
<tr>
<td>Hole 15</td>
<td>&gt; 100 (∞)</td>
<td>46.3</td>
</tr>
</tbody>
</table>

Fig. 1. Stress/Strain state around rivet hole number 15.

Table 1. Monotonic and cyclic properties of structural steel S355.

<table>
<thead>
<tr>
<th>$\sigma_f/E$</th>
<th>$b$</th>
<th>$\varepsilon_f$</th>
<th>$c$</th>
<th>$f_u$</th>
<th>$f_y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Design</td>
<td>0.0045</td>
<td>0.0028</td>
<td>-0.089</td>
<td>0.7371</td>
<td>0.0234</td>
</tr>
</tbody>
</table>

* experimental, † EN10025
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Probabilistic strain-life properties obtained by Linear regression analysis and distribution functions

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Keywords: Strain-life curve; probabilistic analysis; linear regression analysis; distribution functions.

ABSTRACT

The application of modern higher strength structural steels provides a wide range of benefits when compared to puddled iron, which can still be widely found in infrastructures such as ancient railway bridges, as well as more recent mild steel grades. Given the higher strength values for which the structural steel can be characterized, lighter, slenderer, and higher performance demands can be met.

Regardless of the materials monotonic properties, the increase in the yield strength does not necessarily translate towards fatigue resistance, which allied to the fact that these structures inherently slender, fatigue damage is a major concern for the long term operational life.

In order to perform a fatigue life estimation of a structure or detail, several approached may be employed, from these fracture mechanics, as well as local approaches such as stress-, strain- and energy-based approaches serve as an alternative to the deterministic global S-N curve, more simplistic methodology, presented in design standards. However, for the application of the latter, there is the need to understand the material’s fatigue properties.

With this in mind, a comparison between the S355 mild structural steel and the S690 high strength steel grades, present in EN10025 [1], backed up by an experimental program performed under strain control for smooth specimens per specification of the ASTM E606 [2] is presented in the works of Jesus et al. [3].

By using a local strain-based approach, such as the Basquin and Coffin-Manson relations, in Eq. (1) and (2), respectively, the fatigue strength coefficient and exponent, \( \sigma_f \) and \( b \), respectively; fatigue ductility coefficient and exponent, \( \varepsilon_f \) and \( c \), respectively, and the number of reversals to failure, \( 2N_f \).

The strain-life curve using Morrow’s relation, in Eq. (3), can be achieved by adding both elastic- and plastic-strain contributions.

\[
\frac{\Delta \sigma}{2} = \sigma_f (2N_f)^b \quad (1)
\]
\[
\frac{\Delta \varepsilon_p}{2} = \varepsilon_f (2N_f)^c \quad (2)
\]
\[
\frac{\Delta \varepsilon}{2} = \frac{\Delta \varepsilon_e}{2} + \frac{\Delta \varepsilon_p}{2} = \frac{\sigma_f}{E} (2N_f)^b + \varepsilon_f (2N_f)^c \quad (3)
\]

Given the uncertainty of the data in fatigue analysis, namely, service loading, fatigue properties of the material as well as the actual geometrical characteristics of the detail under consideration, a certain level of reliability is to be expected when approaching fatigue from a design perspective. Thus, EN1993-1-9 [4]
standard presents S-N curves for a specific constructional detail for a 95% probability of survival and a 75% confidence level, considering the deviation and the sample size for the Normal distribution. In this study, probabilistic strain-life analyses based on Normal and Weibull distribution functions were conducted using the principles recommended by ISO12107 standard [5]. In Figure 1, the probabilistic strain-life curves for both materials under consideration, S355 and S690 steels, using the presented analyses are shown. The strain-life properties of both materials are presented in Table 1.

![Fig. 1. Strain-life probabilistic curves: a) S355 mild steel, b) S690 high strength steel.](image)

**Table 2.** Probabilistic strain-life properties based on Normal and Weibull distribution functions.

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_f/E$</th>
<th>$b$</th>
<th>$\varepsilon_f$</th>
<th>$c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S355</td>
<td>Mean</td>
<td>0.0045</td>
<td>0.7371</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Normal</td>
<td>0.0028</td>
<td>-0.089</td>
<td>0.0234</td>
</tr>
<tr>
<td></td>
<td>Weibull</td>
<td>0.0034</td>
<td>0.2689</td>
<td></td>
</tr>
<tr>
<td>S690</td>
<td>Mean</td>
<td>0.0067</td>
<td>0.7396</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Normal</td>
<td>0.0038</td>
<td>-0.087</td>
<td>0.004</td>
</tr>
<tr>
<td></td>
<td>Weibull</td>
<td>0.006</td>
<td>0.3354</td>
<td></td>
</tr>
</tbody>
</table>

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Determination of the fatigue limit and initial crack length by means of fracture mechanics

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ABSTRACT

The fatigue design of metallic components is usually based on two different approaches, namely total life and damage tolerance. The former takes into account both the initiation and propagation stages. The latter is based on fracture mechanics and needs an initial defect, which propagates until the critical size under cyclic loading, provided it is large enough. In this case, a residual life rather than a total life is obtained. The overall lifetime of a cyclically loaded structure involves four consecutive stages: a) crack initiation; b) propagation of microstructurally short cracks; c) propagation of physically/mechanically short cracks; d) propagation of long cracks. Considering the propagation from the short crack regime, the damage tolerance approach can be extended to adequately calculate the total life of a component.

As stated in [1], the fatigue strength of metallic materials containing defects depends on the non-propagation condition of small cracks emanating from these defects. In this work, the presence of mechanically short cracks from the beginning of the component's life is considered. A pre-existing defect is a practical assumption as discussed in [2]. Consequently, the methodology of analysis must be able to treat adequately local ligament yielding effects typical for short cracks and must include the thorough description of the crack closure effect up to the long-crack regime. In the analysis based on long cracks, the linear-elastic condition is mostly satisfied which allows the use of the linear elastic parameter ΔK for describing the crack driving force. On the contrary, this assumption is not adequate for mechanically short cracks because the crack depth is in the order of the plastic zone. Instead, an elastic-plastic driving force should be considered. Furthermore, the gradual build-up of the plasticity-induced crack closure effect must be considered, which implies a transition from the intrinsic (effective) threshold value, ΔK_{th,eff}, to the long-crack threshold, ΔK_{th,LC}. The effect of crack closure on the fatigue crack propagation threshold can be described as follows:

\[ ΔK_{th} = ΔK_{th,eff} + ΔK_{th,op} \]  

The effective component is a material parameter which is dependent on the elastic properties and crystal lattice. The gradual build-up of crack-closure is described by ΔK_{th,op} which is a function of the plastic properties, grain-size, environment conditions, load ratio and crack-depth. The crack closure can be characterized experimentally by the so-called cyclic R-curve (see [3]). Some other crack closure effects, such as roughness or oxide-debris induced, might be incorporated as well.

The knowledge of the cyclic R-curve can be useful to determine the largest non-propagating crack size at the material fatigue limit [4]. This is realised by means of the so-called cyclic R-curve analysis, which is schematically depicted in Fig. 1: the tangent criterion between the driving force and the cyclic R-curve define the transition between crack arrest and propagation. In this regard, a_0 is defined as that crack depth which will only grow into a non-propagating crack due to the development of crack closure.
The procedure outlined briefly here has been successfully applied to the determination of the fatigue limits of steel weldments [5]. Considering the stochastic distribution of the weld geometric parameters (namely, weld toe radius, the flank angle, and the excess weld metal) it is possible to perform a full probabilistic cyclic R-curve analysis and determine this way the statistical distribution of the initial crack size at the weld toe at the fatigue limit (see Fig. 2)

![Fig. 1. Schematic view of a cyclic R-curve analysis. The transition crack arrest/no arrest is given when the tangency criterion between crack driving force and cyclic R-curve is fulfilled. \( \Delta \sigma_e \) is the fatigue or endurance limit.](image1)

![Fig. 2. Cumulative probability of the initial crack size at the weld toe at the fatigue limit.](image2)

**REFERENCES**


Rotating Bending Fatigue of Spheroidal Cast Irons

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Keywords: Metal Alloys, Foundry, Spheroidal Cast Iron, Mechanical Properties, Fatigue Behavior, Fatigue Limit.

ABSTRACT

Cast iron probably represents one of the most widely utilized constructive materials in our modern industrial world. This is due not only to the excellent mechanical and tribological properties but also to a certain flexibility of the same. In fact, it can be produced in various types of metal alloy, which differ significantly in properties: from the poorly performing, but economic white cast iron, to the excellent resistant nodular cast iron. In this study, several preliminary results on the experimental measurement of fatigue resistance are proposed for two distinct families of cast iron, the ductile and the vermicular. While the former is well known, with a great variety of applications, vermicular cast iron is almost unfamiliar at the moment in terms of utilization, despite different potentials. This experiment compares the results of the Rotating Bending Fatigue test for cast iron specimens made under foundry process conditions as identical as possible in the way to reduce bias.
Early Evidences on the Rotating Bending Fatigue Properties of Ductile and Vermicular Cast Irons

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ABSTRACT

Cast iron probably represents one of the most widely utilized constructive materials in our modern industrial world. This is due not only to the excellent mechanical and tribological properties, but also to a certain flexibility of the same. In fact, it can be produced in various types of metal alloy, which differ significantly in properties: from the poorly performing, but economical white cast iron, to the excellent resistant nodular cast iron. In this study, several preliminary results on the experimental measurement of fatigue resistance are proposed for two distinct families of cast iron, the ductile and the vermicular. While the former is well known, with a great variety of applications, vermicular cast iron is almost unfamiliar at the moment in terms of utilization, despite different potentials. This experiment compares the results of the Rotating Bending Fatigue test for cast iron specimens made under foundry process conditions as identical as possible in the way to reduce bias.
The effect of the amount of fatigue samples on the estimation of p-S-N fields applied to metallic structural details

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Keywords: Fatigue; S-N curves; probabilistic modelling; structural details.

ABSTRACT

The stochastic behaviour of fatigue life of metallic materials and components promoted the development of probabilistic models that are able to predict failures resulting from the fatigue damage caused by cyclic loading, together with the need to improve the safety and reliability protocols of engineering design. The complexity of the problem in failures predictions caused by fatigue phenomenon is influenced by the sample size (samples amount) of the fatigue data and by the dispersion effect of these data in high-cycle fatigue regimes. In this way, the statistical adjustment/fitting models must be able to perform a good estimation even with few experimental fatigue data. ASTM-E739 [1] standard is widely used by the scientific and technique community because it is based on a linear regression analysis of the logarithmic data for the stress range and number of cycles to failure, followed by a statistical analysis for each stress level in order to obtain the Normal distribution function of the number of cycles to failure. On the other hand, the probabilistic fatigue model developed by Castillo & Fernández-Canteli [2] is being widely used by researchers for its statistical robustness and general application capacity in fatigue life problems of mechanical/structural components and for different materials, regardless of the failure mechanism. It turns out that the reliability of these models must be questioned as the amount of experimental fatigue data becomes scarce. For this, this scientific work has the purpose of carrying out exhaustive analyses of the probabilistic fatigue models proposed by ASTM-E739 [1] and Castillo-Canteli [2] subject to a decrease in the samples size (samples amount), and, therefore to compare the models’ performance when estimated with all experimental fatigue data. The performance of the generated probabilistic fatigue curves, considering all samples amount, will be compared with the fatigue failure probabilities estimated for each stress level.

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