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IRAS 25

Book of Abstracts

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FATIGUE RELIABILITY ANALYSIS OF STRUCTURES WITH HIGH DIMENSION AND LOW FAILURE PROBABILITY

Dr. Shun-Peng Zhu, Professor in Mechanical Engineering at University of Electronic Science and Technology of China (UESTC), China. He received his Ph.D. degree in Mechanical Engineering from UESTC in 2011, and worked as PIF Fellow of Politecnico di Milano, Italy from 2016 to 2018 and research associate at University of Maryland, United States in 2010. His research which has been published in scholarly journals and edited volumes, over 150 peer-reviewed journal papers, explores the aspects: fatigue reliability; probabilistic Physics of Failure modeling; multi-physics damage modeling and life predictions. He received Second class Natural Science Research Awards of Sichuan Province (2022) and Chinese Society of Aeronautics and Astronautics (2022) and Chinese Society of Theoretical and Applied Mechanics (2025), First Prize of Technological Invention of China Association of Inventions (2022), three Most Cited Paper Awards of FFEMS Journal (2018–2022), Robert Moskovic Award (2024) and Award of Merit (2019) of ESIS-TC12, Top 100 Most Influential International Academic Paper Award of China (2018), Polimi International Fellowship (2016), Hiwin Doctoral Dissertation Award (2012), Best Paper Awards of 6 international conferences. He is featured as Elsevier Most Cited Chinese Researchers in the field of Safety, Risk, Reliability and Quality since 2018 and serves as Co-Editor-in-Chief of International Journal of Structural Integrity, editorial board member of several international journals like EFA, IJFatigue, FFEMS and book series.

RISK ANALYSIS OF PIPELINE INLET ELBOWS IN HYDRO POWER PLANT PERUĆICA BASED ON FRACTURE MECHANICS AND STRUCTURAL INTEGRITY APPROACH

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Key words: Risk analysis, Fracture Mechanics, Structural Integrity, Pipeline Inlet Elbow, Hydro Power Plant

Hydro power plant "Perućica" in Montenegro has been monitored in 2024 by NDT (Ultrasonic testing – UT, and magnetic particles – MT) with a focus on defects found in inlet elbows of units 6 and 7. Having in mind the importance of this power plant, especially from point of view of potential catastrophic consequences in the case of a failure, the elbows with defects were carefully analysed by means fracture mechanics parameters and structural integrity assessment to estimate risk of its further use [1].

In the lower and upper elbow of unit 7 indications have been detected during first magnetic particle testing. At the lower elbow "A-side" a crack with length of 500 mm and depth up to 20 mm was detected.

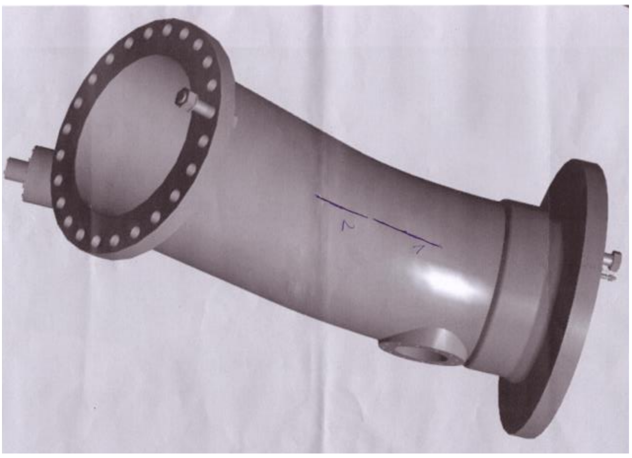

Fig. 1. Lower elbow "A-side" a crack

Available data:

- Material – cast steel GS 45 (DIN 1681), yield strength 245 MPa, tensile strength 480 MPa, elongation 29.5%, estimated fracture toughness 1580 MPa $mm^{\frac{1}{2}}$ [2],
- Loading: working pressure 5.9 MPa, testing pressure 8.4 MPa,
- Geometry: elbow radius R = 400 mm, thickness t = 42–52 mm.
- Crack: length 200 mm, depth 20 mm.

Stress intensity factor was determined for a surface crack of depth a = 20 mm and length $2c$ = 500 mm: $K_I = Y(a/t,\, c/a)(pR/t)\sqrt{\pi a}$ = 1,76(52.4) $\sqrt{20\pi}$ = 731 MPa√mm, where $Y(a/t,\, c/a)$ is taken for $a/t = 20/42 = 0.47$ and $c/a = 25$. The ratio $K_I/K_{Ic} = 0.46$, in that case, so there is no danger of brittle fracture.

The ratio of net stress and critical stress in the crack cross-section is: $S_R = \sigma_n/\sigma_F = 52.4 \times 1.91/362.5 = 0.28$, where σ_F is taken as half-sum of yield and tensile strength. Thus, the coordinates of a working point in Failure Assessment Diagram (FAD) are (0.28; 0.46), Fig. 1, in the safe region with failure likelihood 0.47.

Even in the case of very conservative assumption that the crack is along the whole elbow length, working point coordinates would be (0.28; 0.74), giving failure likelihood 0.75.

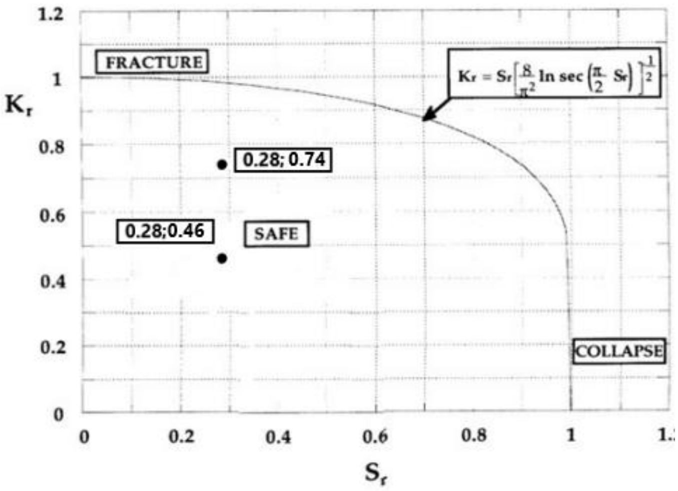

Fig. 2. Failure Assessment Diagram for two cracks

Consequences of the failure are regarded as significant for people, equipment and environment, category 4 [3]. Based on likelihood and consequence, risk matrix is made, Table 1, indicating high level of risk.

Table 1. Risk matrix for elbow A7

		Consequence					
		1	2	3	4	5	Risk level
Likelihood	≤0.2						very lowk
	0.2–0.4						low
	0.4–0.6				surface crack 20 × 500 mm		medium
	0.6–0.8				edge crack depth 20 mm		high
	0.8–1.0						very high

Based on these results, one can conclude that the inlet elbow A7 is safe for further operation, even in the presence of relatively large crack. This conclusion is also based on the fact that there is no mechanism of crack growth (practically no corrosion and fatigue). Anyhow, since the risk is of high level, repair welding was recommended and performed.

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RISK ANALYSIS OF PIPELINE BRANCH IN HYDRO POWER PLANT PERUĆICA BASED ON FRACTURE MECHANICS AND STRUCTURAL INTEGRITY APPROACH

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Key words: risk analysis, fracture mechanics, structural integrity, pipeline branch, hydro power plant

After regular monitoring of pipelines in hydro power plant "Perućica" in Montenegro in 2024 by NDT (VT, MT, UT), focus was on defects found in unit 6A branch, Fig. 1. Having in mind potential catastrophic consequences in the case of a failure, the branch with defects was additionally analysed by means fracture mechanics parameters and structural integrity assessment to estimate risk of its further use [1].

According to the report [2], the most critical defect is MWB60-4 inside the upper welded joint K3, with length 150 mm and depth 7 mm, located at the mid-thickness from 14 to 21 mm.

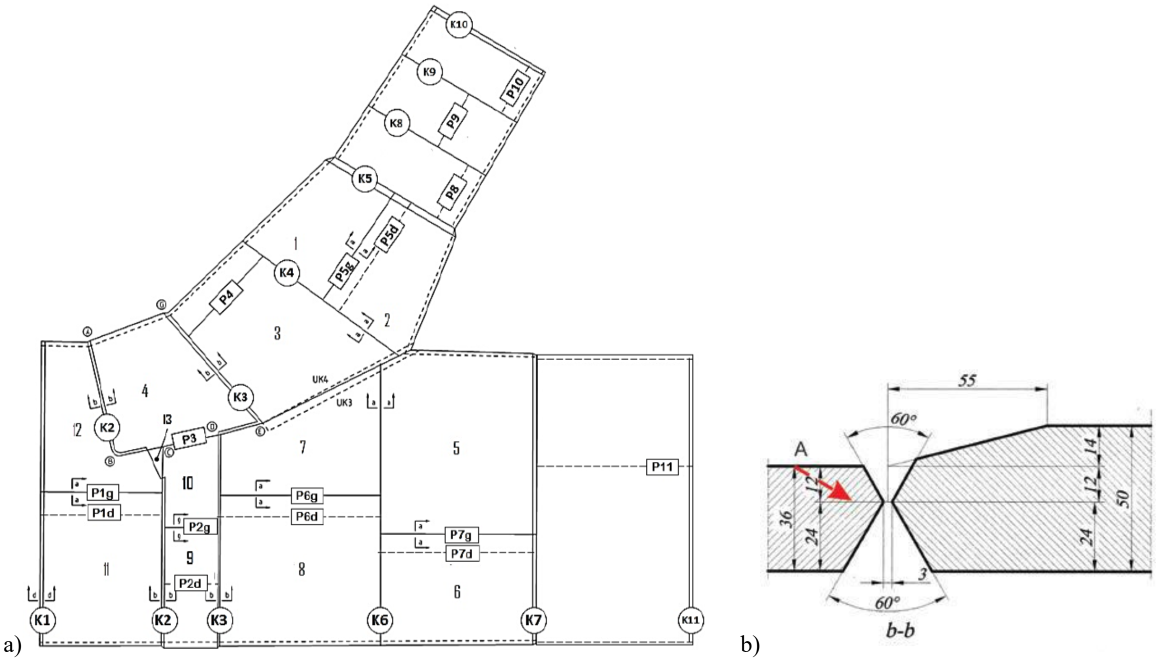

Fig. 1. Branch of unit 6A: a) geometry, b) cross section of welded joint K3 [2]

Available data:

- Material – HSLA steel Nioval 50, yield strength 500 MPa, tensile strength 640 MPa, elongation 20%, estimated fracture toughness 1580 MPa $\mathrm{mm}^{\frac{1}{2}}$,

- Loading: maximum stress 115 MPa [3]
- Crack: length 150 mm, depth 21 mm.

Stress intensity factor was determined for a central crack $2a = 7$ mm along the whole welded joint (conservative assumption): $K_I = S_{max}\sqrt{\pi a} = (115)\sqrt{3.5\pi} = 381$ MPa√mm, so that the ratio $K_I/K_{Ic} = 0.24$, meaning that there is no danger of brittle fracture.

The ratio of net stress $\sigma_n = 115 \times 36/29 = 142.7$ and critical stress in the crack cross-section $\sigma_c = 570$ MPa is: $S_R = \sigma_n/\sigma_F = 142.7/570 = 0.25$, where σ_F is taken as half-sum of yield and tensile strength. Thus, the coordinates of a working point in Failure Assessment Diagram (FAD) are (0.25; 0.24), Fig. 1, in the safe region with failure likelihood 0.25.

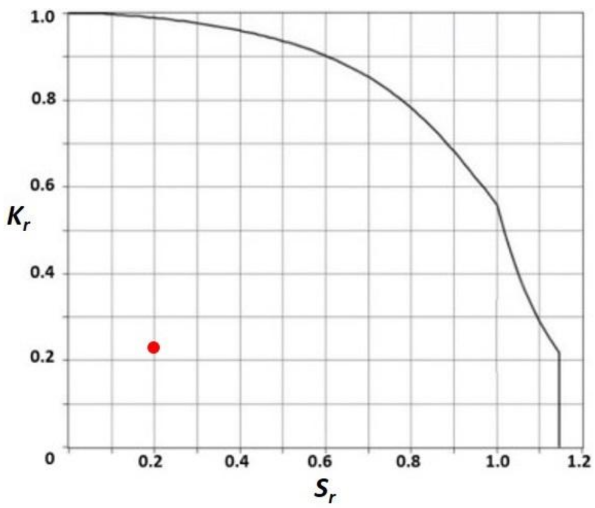

Fig. 2. Failure Assessment Diagram for two cracks

Consequences of the failure are regarded as significant for people, equipment and environment, category 4 [1]. Based on likelihood and consequence, risk matrix is made, Table 1, estimating risk as the medium.

Table 1. Risk matrix for elbow A7

		Consequence					
		1	2	3	4	5	Risk level
Likelihood	≤0.2						very low
	0.2–0.4				central crack 7 mm		low
	0.4–0.6						medium
	0.6–0.8						high
	0.8–1.0						very high

Based on these results, and the fact that there is no mechanism of crack growth (practically no corrosion and fatigue), one can conclude that the unit 6A branch is safe for further operation.

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INFLUENCE OF THE WELDING PROCESS ON THE STRESS CORROSION CRACKING OF HIGH-STRENGTH STEEL WELDED JOINTS

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Keywords: stress corrosion cracking, welded joints, high-strength steel, GMAW, LBW, fracture

High-strength steels (HSSs) were developed to create structures that conjugate high load-bearing capacity with lightness. Nowadays, HSSs represent a set of materials widely used in engineering for structures that grow in height and make lightness a key design element. In recent years, HSSs have seen a rapid increase in their use for the creation of complex structures such as bridges, infrastructures, offshore platforms and earth-moving machinery. The high mechanical properties achieved by these materials (460–1300 MPa as yield strength) are attributed to the process by which they are produced. In general, they undergo an initial hot-rolling process, followed by quenching to generate a fine-grained microstructure and to relax the residual stress caused by the lamination process. When they are used near saline watercourses, sea or in the open ocean, these materials are subject to corrosion phenomena which, combined with the loads to which these structures are subjected, promote the Stress Corrosion Cracking (SCC) phenomenon [1, 2]. Currently, the different elements of HSS structures see welding as the most common joining process, even though this can generate issues directly affecting the structural strength and the final life. The various welding processes can be very invasive for these types of steels, as they strongly modify the local microstructure around the fused zone and generate high residual stresses. Moreover, the fragile microstructure generated in the heat affected zone (HAZ) makes welded HSS structures very susceptible to the SCC phenomenon [3, 4]. Any non-metallic segregations or inclusions, coupled with the high residual stresses, can be a source of crack initiation leading to brittle fracture. Besides, different welding processes generate different thermally altered zones, leading to a different impact on the component's life [5, 6]. Traditional welding processes, such as the Gas Metal Arc Welding (GMAW), generate large thermally altered zones and require a filler material to join the elements, while more innovative processes, such as the Laser Beam Welding (LBW), allow welding without filler material and with a more localized temperature input. The aim of this study was to analyze the response of butt-welded joints made of STRENX700E HSS subjected to the SCC phenomenon recreated in the laboratory. Tensile specimens were soaked for 24 hours in a solution of inorganic salts in deionized water in proportions and concentrations representative of the ocean water [7, 8]. Afterwards, they were tested while immersed in the solution using a very low strain rate to increase the testing time, in turn promoting the corrosion effects. Results were cross-compared with air-tested specimens highlighting the influence of the welding process on the mechanical properties against SCC, providing important feedback for future constructions near salty watercourses.

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STRUCTURAL INTEGRITY AND DURABILITY OPTIMIZATION OF WAAM CARBON STEEL ELEMENTS FOR FATIGUE-SENSITIVE COMPONENTS

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Key words: Structural Optimisation, Metal Fatigue, Wire Arc Additive Manufacturing, ER70S-6 carbon steel

1. INTRODUCTION

Recent studies have advanced the integration of Wire Arc Additive Manufacturing (WAAM) with structural optimization; however, fatigue criteria remain overlooked despite their critical role in components subjected to cyclic loading [1, 2]. This research explores a structural optimization strategy that explicitly incorporates fatigue criteria to enable the design of resource-efficient components capable of withstanding time-varying loads. To this end, a two-level optimization methodology is proposed. The study is directed to components fabricated from WAAM ER70S-6 carbon steel and validated by optimizing two well-known benchmark geometries from the literature: an L-bracket and a cantilever beam.

2. RESULTS AND DISCUSSION

Topology optimization (TO) was used in the first optimization level to remove non-essential material from the initial geometry (Shape 0, Fig. 1a), under a design load of 2 kN applied to the right end the parts. TO was performed using a sensitivity-based algorithm with the Solid Isotropic Material with Penalization (SIMP) interpolation technique. The objective function was the minimization of strain energy density, with constraints defined by a target volume fraction of 0.30 and a maximum centroidal von Mises stress of 375 MPa. The output was post-processed using CAD software to smooth the geometry, as shown by the dashed lines in Fig. 1b. This refined model, denoted Shape 1, was then used in the subsequent DSO step.

The second optimization level involves the durability-based shape optimization (DSO), which targets specific geometric features of the component that may act as sources of crack nucleation. The DSO used experimental S–N data for WAAM ER70S-6 carbon steel previously obtained by the authors and a fully reversed constant amplitude load with a maximum value of P_{max} = 2 kN, applied at the right end of the parts, as in the first step. The DSO also employed a sensitivity-based algorithm to minimize damage, calculated per Miner's rule. Post-processing of the optimization output was also necessary, with the final geometry defined as Shape 2 and shown in full lines in Fig. 1b.

Once the optimization process was concluded, geometrically nonlinear elastoplastic finite element analysis (FEA) and fatigue numerical analyses were conducted to evaluate the results. The FEA was performed using *Abaqus* with a quad-linear constitutive material model and a ductile damage criterion [3]. The fatigue assessment was conducted using the software *fe-safe*, again based on experimental S-N data obtained by the authors for WAAM carbon steel. A comparison of the results is shown in Table 1.

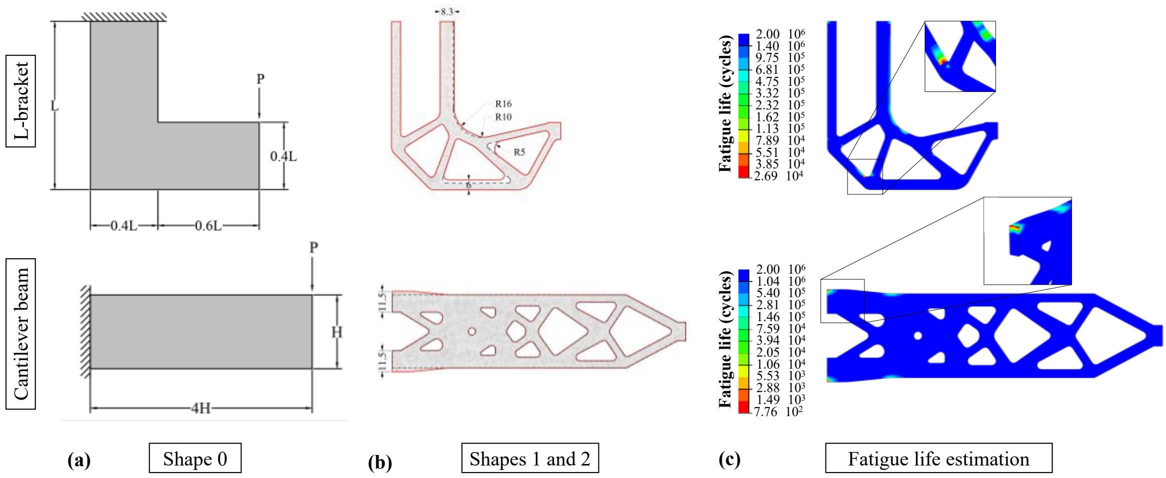

Fig. 1. (a) non-optimized geometries, (b) TO and DSO geometries in dashed and full lines, respectively, and (c) numerical fatigue life assessment

The results prove important improvements in fatigue life and strength following optimization for both geometries. The L-bracket's fatigue life increased after the DSO, with a volume fraction reduction from 1 to 0.37. The ultimate load for Shape 2 reached 3.45 kN, which remains above the design load; the specific ultimate load did not change significantly. For the cantilever beam, fatigue life showed minor variations due to sensitivity to mesh and boundary conditions but still improved with the DSO relative to the TO results. The ultimate load remained above the design load, with a value of 4.71 kN for Shape 2, while the specific ultimate load exhibited an improvement from 28.2 kN/kg (Shape 0) to 37.8 kN/kg (Shape 2).

Table 1. Comparison of optimized shapes for the geometries investigated.

	L-bracket			Cantilever beam		
	Shape 0 (non-opt.)	Shape 1 (TO)	Shape 2 (DSO)	Shape 0 (non-opt.)	Shape 1 (TO)	Shape 2 (DSO)
Volume fraction	1	0.35	0.37	1	0.61	0.62
Fatigue life [cycles]	3.00×10^1	7.91×10^2	2.69×10^4	2.81×10^2	$1.51 \times 10^1 - 1.21 \times 10^2$	$7.76 \times 10^2 - 3.34 \times 10^4$
Ultimate load, P_u [kN]	9.30	2.9	3.45	5.64	3.66	4.71
Specific ultimate load [kN/kg]	46.5	41.9	46.3	28.2	29.9	37.8

3. CONCLUSIONS

The results demonstrate that the framework effectively supports the design of WAAM components for structural applications. Incorporating fatigue criteria into the optimization process significantly improved the component's ultimate strength and lifespan, highlighting the value of durability-based refinement. Overall, the approach enhances structural reliability while promoting material efficiency and sustainability in fatigue-sensitive parts. Other metrics and examples will be analysed to reinforce these conclusions.

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The main research fields are:

1. Fatigue of civil engineering materials and lifetime estimation.
2. Two-parameter fracture mechanics.
3. Numerical modelling and calculations of fracture-mechanics parameters.

EFFECT OF SPECIMEN GEOMETRY ON HIGH CYCLE FATIGUE LIFE OF S460 NL

Presented study deals with the risk volume assessment. The study uses FEA of various sample geometries and fatigue testing of four different geometries in order to validate findings resulting from FEA. The numerical simulations show quite homogeneous distribution of stresses within the gauge length of tensile samples, which leads to a large risk volume.

EFFECT OF SPECIMEN GEOMETRY ON HIGH CYCLE FATIGUE LIFE OF S460 NL

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Key words: fatigue, S460 NL, geometry, S-N curve

1. INTRODUCTION

The volume at which the crack is most likely to start is known as the risk volume. Given the specific geometry of the samples for fatigue loading (three and four point bending and tensile tests performed on rectangular and round specimens), this is a significant problem. Additionally, the distribution of stress within the risk volume provides crucial information for describing and predicting fatigue behavior. The risk volume was computed and compared to fatigue testing findings for S460NL high strength steel samples with various geometries. Gathered information on fatigue and the microstructure's development in relation to the estimated risk volume sizes will be considered.

The fatigue characteristics of engineering materials are being thoroughly researched worldwide in an effort to reduce fatigue failure. Several standards were created to guarantee the comparability and reproducibility of fatigue properties across various laboratories (as ASTM, etc.). The standards outline the fundamentals of sample design to reduce potential variations in experimental outcomes. However, in the past decades, non-conventional testing methods were introduced for fatigue properties determination which brought new challenges, see [1–3].

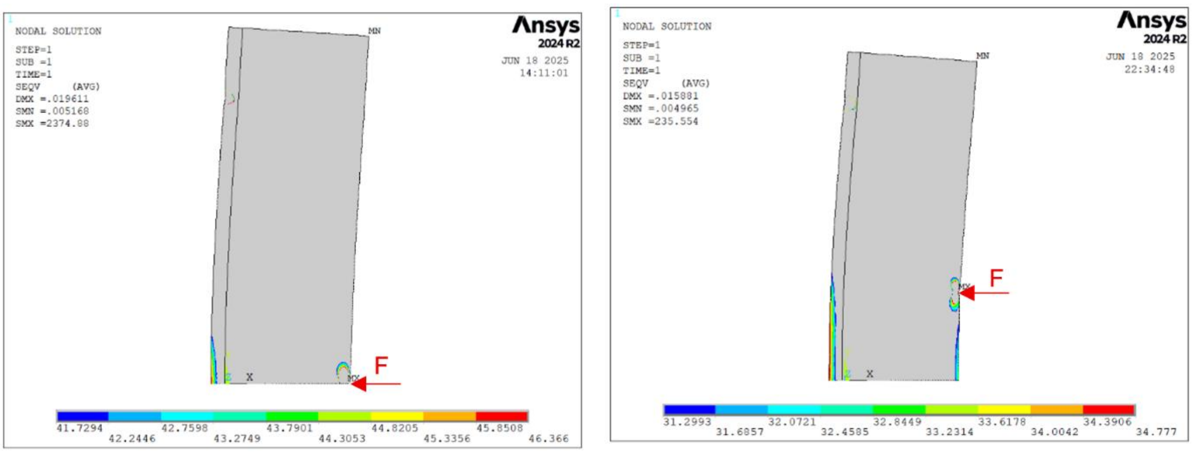

Fig. 1. Distribution of stress for three (left) and four (right) point bending specimens within the risk volume FEA model 2D and symmetrical half.

Based on the FEA (Finite element analysis) performed in the ANSYS software, distributions of stress within whole samples were determined. The shapes and sizes of the risk volumes, defined according to and the details of stress distribution are shown in [1].

Figure 2 shows fatigue test results performed during three and four points bending and tensile tests at round and rectangular specimens from S460 NL steel. The fatigue limit was determined from run-out tests, as the load level at which the samples can withstand 10^7 loading cycles without failure. Data were evaluated by Basquin law.

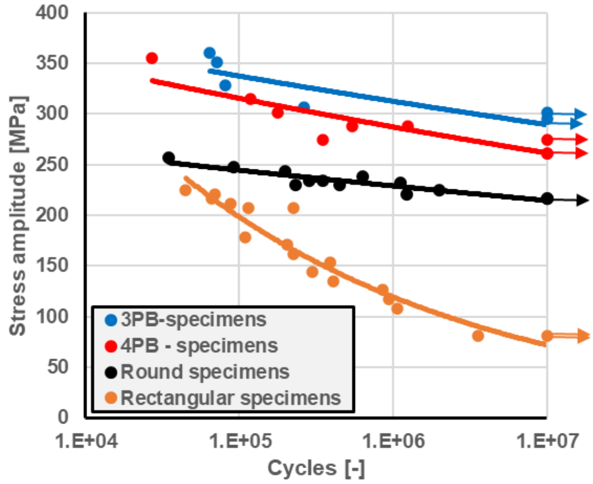

Fig. 2. Fatigue results of three and four point bending and tensile test for round and rectangular specimens. Arrows symbols represent runout samples, reaching the lifetime over 10^7 cycles

2. CONCLUSION

Presented study deals with the risk volume assessment. The study uses FEA of various sample geometries and fatigue testing of four different geometries in order to validate findings resulting from FEA.

The numerical simulations show quite homogeneous distribution of stresses within the gauge length of tensile samples, which leads to a large risk volume.

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INFLUENCE OF LOADING SPECTRA AND FATIGUE LIFE ASSESSMENT CALCULATION DOMAIN ON THE SAFETY OF COMPLEX STRUCTURES

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Keywords: fatigue life assessment, loading spectra, complex structures, structural safety, damage accumulation

1. INTRODUCTION

Fatigue failure remains a leading cause of structural degradation in components subjected to variable amplitude loading. As such, accurate fatigue life assessment is essential for ensuring the safety and reliability of mechanical and aerospace systems. Central to this are the domain of assessment – time vs. frequency – and the type of loading spectrum that is considered. This paper compares the performance and suitability of various fatigue life assessment methods applied to common synthetic and service-derived loading spectra in terms of safety and risk of their use.

2. METHODOLOGY

Fatigue life estimation was performed using both time-domain and frequency-domain approaches. In the time domain, the Rainflow counting algorithm was used to extract stress cycles from time histories, which were then processed using the Palmgren–Miner linear damage rule. In the frequency domain, methods such as the Dirlik model and Zhao–Baker model were implemented to estimate damage directly from power spectral densities (PSD), eliminating the need for time series reconstruction [1, 2].

Three commonly used loading spectra were applied:

- Block loading with regular amplitudes to simulate simplified test cycles;
- Gaussian random loading, representing stochastic excitations;
- Loading spectra derived from real-world datasets: FALSTAFF (fighter aircraft), TWIST (transport aircraft), and WISPER (wind turbine blades) [3, 4].

All calculations were applied to metallic material models with predefined fatigue curve data.

3. RESULTS AND DISCUSSION

Under block loading, time-domain and frequency-domain methods yielded comparable results, with differences under 5%, since the stress range distribution remained relatively narrow and periodic. Gaussian spectra, by contrast, revealed greater divergence: the Dirlik model consistently predicted shorter life than Palmgren–Miner, particularly under high-frequency broadband excitations. This aligns with previous findings that Dirlik is more preferable for stress range probability distributions in wide-band processes [5].

When applying mission profiles, results varied depending on the spectrum complexity. For example, the TWIST spectrum led to earlier damage onset than FALSTAFF due to more frequent overloads, which affect residual stresses and crack closure effects – factors more accurately captured by time-domain methods. The frequency-based models struggled with non-Gaussian and non-stationary properties of real-world spectra, unless preprocessed via empirical transformation.

Time-domain methods, although computationally more demanding, provided more detailed cycle tracking and incorporated transient overload effects. Frequency-domain methods were more efficient but demanded assumptions about stationarity and spectral shape that limited their use in irregular load histories. Hybrid methods, combining time-domain cycle identification with frequency-domain PSD-based correction factors, showed promise but remain under development.

4. CONCLUSIONS

This study demonstrates that the choice between time and frequency domain fatigue life estimation methods must be aligned with the nature of the applied load spectrum. Time-domain approaches are more robust under non-stationary, mission-specific loadings, while frequency-domain methods offer computational efficiency for design-stage fatigue screening. For safety-critical applications, especially those involving loading spectra such as TWIST or WISPER, time-domain modeling remains the gold standard.

Further research should focus on improving the adaptability of frequency-domain models to non-Gaussian and multiaxial loadings, possibly through machine learning-enhanced PSD interpretation or surrogate modeling techniques.

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ASSESSING THE INFLUENCE OF SURFACE ROUGHNESS AND RESIDUAL STRESSES ON THE FATIGUE BEHAVIOUR OF 42CRMO4+QT STEEL

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Key words: roughness, residual stresses, predictive modelling, fatigue life, machining procedures

ABSTRACT

Currently, fatigue remains the main cause of failure in mechanical components during service. Furthermore, the significant statistical dispersion observed in results from experimental campaigns highlights the critical need for precise material characterization to determine fatigue behaviour. Numerous standards exist to standardize these experimental characterization tasks, such as DIN 50100, ASTM E466-15, or ISO 1099. These standards, while recognizing the importance of minimizing surface integrity defects because of their significant impact on fatigue life, do not provide specific recommendations on the machining process, nor do they address the impact of these variables on ultimate fatigue life. Therefore, investigating optimal manufacturing conditions and their effects on roughness and residual stresses is crucial for acquiring reliable experimental data on fatigue life characterization. In the present study, a four-step methodology is proposed to assess the impact of surface integrity on fatigue life. Firstly, a predictive model is developed to establish the relation between machining conditions and surface integrity parameters. Secondly, the aforementioned model is optimized to define different scenarios combining varying levels of both roughness and residual stresses. Based on this optimization, specimens of 42CrMo4+QT steel were machined accordingly to the previously selected cutting scenarios and subjected to fatigue loading ($R = 0.1$) until failure. The outcomes of each scenario were then critically evaluated, facilitating a comprehensive comparison and discussion of how residual stress and roughness influence ultimate fatigue life.

A HYBRID MODELING-BASED RELIABILITY OPTIMIZATION METHOD FOR COMPLEX ENGINEERING STRUCTURES

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Key words: reliability-based design optimization, surrogate models, local variance, stability metrics

Analysis of research status

Practical engineering designs are usually influenced by a multitude of factors, many of which are uncertain, such as material properties, variations in the manufacturing process, and changes in loads. Uncertainties can introduce certain risks into the design, such as the design's performance falling short of expectations, increased costs, and reduced safety. By considering uncertainties, designers can gain a better understanding of and manage these risks, thereby reducing the likelihood of design failure. Taking uncertainties into consideration enables designers to more comprehensively evaluate the performance of a design.

For the optimization design and reliability calculation of complex multi-variable structures, the sources of uncertainties encompass several aspects, as shown in Table 1.

Table 1. The sources of uncertainties

Type	The sources
Type I	Uncertainty in material parameters
Type II	Uncertainty in geometric parameters
Type III	Uncertainty in boundary conditions
Type IV	Uncertainty in model parameters.
Type V	Uncertainty in environmental conditions

Therefore, in structural analysis and optimization design, it is necessary to comprehensively consider the effects of uncertainty factors and apply appropriate methods to model and analyse them in order to enhance the robustness and reliability of the results.

The application of surrogate model techniques in reliability analysis is a research area that has attracted significant attention, providing effective methods and tools for engineering practice. A surrogate model, also known as a metamodel or an approximation model, is a simplified model used to replace complex, time-consuming computational models or simulation models. It can rapidly and efficiently conduct predictions and analyses by establishing a relationship between inputs and outputs. The application of surrogate model techniques in reliability analysis is of significant importance and holds broad development prospects. The RBDO problem can be formulated by introducing probabilistic constraints into traditional deterministic optimization problems. After replacing the limit-state function with a surrogate model, the mathematical model can be described as follows:

$$\begin{aligned} &\text{find} \quad \boldsymbol{d} = \left[d_1, d_2, ..., d_n\right]^T \\ &\min \quad f(\boldsymbol{d}, \boldsymbol{x}) \\ &\text{s.t.} \quad P_f(\hat{G}_j(\boldsymbol{d}, \boldsymbol{x}) \le 0) \le P_{j,t}(j = 1, ..., N_p) \\ &\qquad \boldsymbol{d}^L \le \boldsymbol{d} \le \boldsymbol{d}^U \end{aligned} \tag{1}$$

where $\boldsymbol{x} = [x_1, x_2, ..., x_m]^T$ represents the vector of random variables. $\hat{G}_j(\boldsymbol{d}, \boldsymbol{x})$ denotes the surrogate model corresponding to the *j*-th limit state function, and when its value is less than 0, it indicates that the structure is in a failure state. $P_f(\hat{G}_j(\boldsymbol{d}, \boldsymbol{x}) \le 0)$ represents the probability of failure for the *j*-th limit state function, while $P_{j,t}$ represents the allowable failure probability for the *j*-th limit state function, which is specified arbitrarily.

The main research contents of this paper

To address the aforementioned issues, this paper presents a reliability-based design optimization method that employs a multi - model adaptive ensemble surrogate strategy. This method aims to enhance the accuracy and efficiency of surrogate modeling through innovative design concepts and algorithms while ensuring the reliability of the optimization results. The method is mainly divided into three stages.

In the first stage, an adaptive ensemble surrogate model is constructed. This model combines local variance and stability metrics to augment the model's robustness. Local variance is utilized to reflect the prediction uncertainty of the model in different regions, while stability metrics are employed to evaluate the model's stability under various data perturbations. In the second stage, an optimization design framework that considers multiple damage modes of complex engineering structures is established. In the third stage, a decoupling strategy is adopted to solve the optimization framework and obtain the optimal design solution.

Finally, to verify the effectiveness and superiority of the proposed optimization framework, this paper selects the support structure of offshore wind turbines as a case study. As shown in Fig. 1, the computational results of the last numerical example in this study are presented. The results demonstrate that the proposed optimization framework can significantly improve the accuracy and efficiency of surrogate modeling.

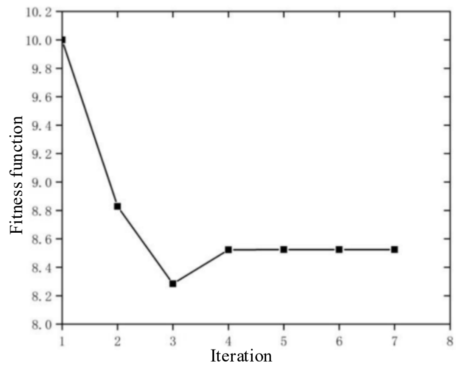

Fig. 1. The iterative process of the objective function in engineering examples

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MATERIAL CHARACTERISATION OF CLINCHED JOINT SUBJECTED TO CYCLIC LOADING

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Key words: clinch joint, microstructure of materials, fatigue loading

CLINCHED JOINTS

Steel structures in civil engineering are usually joined with the use of bolts, nuts, or welds. All types of joints have been used and studied for more than a century. Their mechanical properties, limitations, and areas of use are well known. However, with wider use of thin-walled steel structures alternative means of joining solutions have been sought and adopted. One of the attractive options is cold joining. Among possible methods of cold joining the clinching has been developed for use in many industries (automotive, aerospace). It can be characterized as a mechanical joint of two or more members created by cold forming with the use of a punch and a die. The advantages of the clinched joints are fast connections, low cost and weight, possibility to join different materials, easy to automate, the material is usually strengthened at the joint due to shaping etc.

MATERIAL CHARACTERISATION

Clinched joints are loaded by static or cyclic forces. As the use of clinch joints is increasing, detailed knowledge of material response to deformation used within the joint production as well as withing operational loading is required.

Detail of the typical joint cut is shown in Fig. 1.

Fig. 1. Clinch joint detail (cut) [1]

Specimens for investigation are taken from the C-profile, where the cold joining has been applied. Microstructure of base material and its changes due to clinching process and due to cyclic mechanical loading are investigated by metallography, micro hardness mapping and advanced scanning electron microscopy.

The C-profiles were made of steel S390. Metallographic samples are prepared from a region of basic material as well as from the zone of intensive plastic deformation in the joint vicinity. Unloaded samples and samples after cyclic loading are analysed.

Metallographic and microhardness analysis are applied on the specified samples. Analysis will reveal local structural and mechanical properties of the basic material and deformation influenced zones. Changes and local properties of the studied material due to clinching technology is investigated.

Advanced scanning microscopy analysis leads to the analysis of phases and their influence on global behaviour of the studied material. SEM analysis is also used for identification of crack initiation places and mechanisms as well as crack propagation mechanism.

Fig. 2. Clinch joint after fatigue loading

CONCLUSION

The study of the material structure will be used for a deeper analysis of the fatigue behavior of clinch joints and will contribute to a more reliable assessment of structures manufactured using this modern technology.

ACKNOWLEDGMET

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QUANTITATIVE TECHNIQUES
FOR ASSESSING FATIGUE DAMAGE AFTER FAILURE

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Key words: Fractography; Failure analysis; Damage mechanics; FRASTA; Entire Fracture Surface Method.

1. ABSTRACT

A significant quantity of the fatigue life studies and a considerable number of fracture investigations have been carried out to measure changes associated with the damage process. However, there are currently no set rules for the fractographical assessment of fatigue damage, and efforts are being made to find suitable techniques or alter current ones. Consequently, this study looks at two efficient post-failure techniques for identifying and quantifying damage. Fracture surface topography analysis, or FRASTA, has been used to solve a variety of failure problems. This quantified fractographic approach was first used in the early 1980s and has since been improved upon in tandem with developments in computing and measurement methods. To understand the behavior of a material under stress, especially in fatigue scenarios, the second methodology is known as the "entire fracture surface method" in material science. This method involves analyzing the entire surface of a fracture, or the broken surface parameters. This approach aids in forecasting fatigue life and comprehending fatigue phenomena.

2. METHODS

Fracture surface topography analysis (FRASTA)

Under the FRASTA method [1, 2], data on the topography of two failure surfaces is sent into a computer, and then by varying the separation between these surfaces, the locations of gaps and overlaps are identified. The failure is examined and the failure procedure is rebuilt using this information. Two types of results from this investigation are shown in Fig. 1. The FAPP graphic shows black areas that indicate the overlap of the crack surfaces and white areas that show a separation between them. Most often a gap between the crack surfaces to be a sign of a crack. FAPP is useful for identifying the sites of cracks and analyzing the FAPP series, which aids in understanding the direction of crack advancement, the shape of the crack tip, and the development of neighboring microcracks. The relationship between crack initiation and advancement and the material's microstructure can also be better understood by aligning the FAPP with microscopic photographs of the damaged surfaces at the same magnification and overlaying them. The cross-section (XSP), a diagram cut perpendicular to the failure surface, is the second result. You have complete control over the cut's angle. Both the angle and the extent of crack tip opening may be accurately determined by XSP. Furthermore, it is feasible to see the amount of plastic deformation required before each area fails in the areas colored in black. This makes it easier to estimate the effort required for failure at each cross-section.

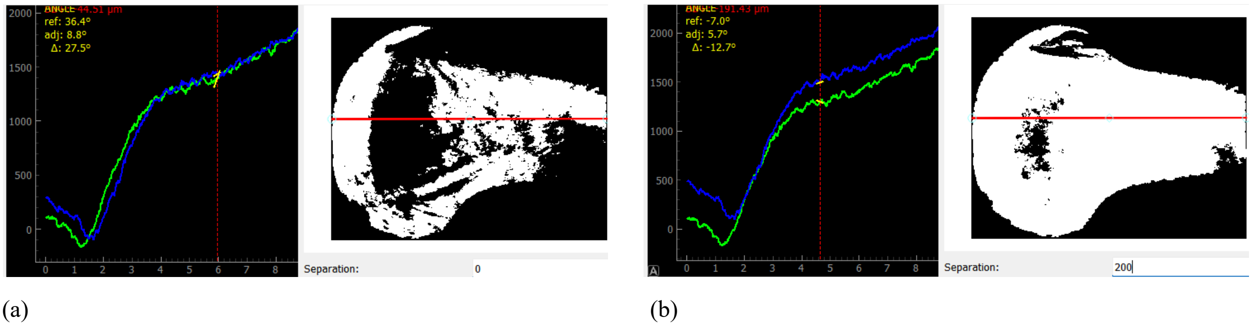

Fig. 1. XSP and FAPP obtained by matching conjugate topographs, with separation: (a) 0 µm, (b) 200 µm

Entire fracture surface method

This method focuses on the surface morphology, roughness, and other characteristics of the fracture to understand the failure mechanisms and predict fatigue life. Unlike methods that focus on specific areas, the entire fracture surface method examines the entire fracture surface for analysis (see Fig. 2).

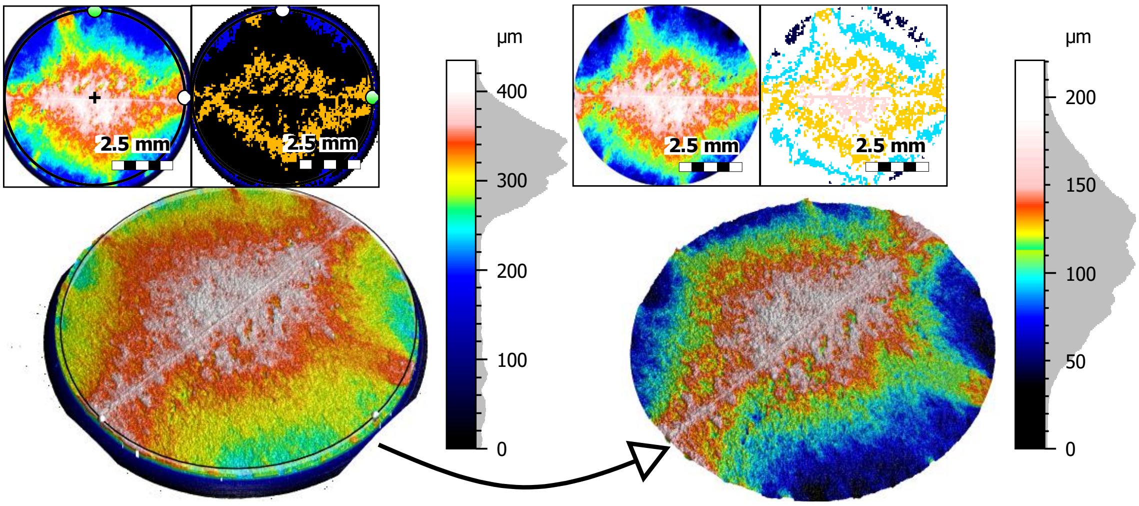

Fig. 2. Data processing for entire fracture surface method

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PROBABILISTIC DAMAGE TOLERANT ASSESSMENT OF CRACKED STRUCTURES UNDER SIZE EFFECT

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Key words: Probabilistic damage tolerant assessment, Weakest-link theory, Size effect, Crack size, Residual fatigue life model

Aero-engine turbine disks and other hot-end components, as the core parts of major equipment, are strategic focal points for the sustainable development of future industries. Their structural integrity and safety reliability are crucial foundations for guaranteeing the long-term service of hot-end structures. In this study, focusing on cracked structures of the FGH96 turbine disk, the simulated specimens and round-bar specimens of different sizes with an artificial defect were designed. Combining in-situ and direct current potential drop (DCPD) technologies, the study on fatigue crack initiation and propagation tests at 600°C was conducted on the materials and structures of turbine disks, specifically including crack growth behavior, failure mechanisms, and probabilistic life models. First, the initial fatigue crack was pre-produced and the crack growth rate was monitored using the DCPD technique, while the critical crack size at fracture was measured using optical microscopy. Subsequently, the uncertainty quantification study was performed on the initial and critical crack sizes. Considering the evolution of crack size, a novel failure assessment diagram was proposed to evaluate the critical crack size, then, developing a damage tolerance assessment diagram. Fracture morphology and failure assessment diagram results indicated that the crack tip was in a plastic state, leading to the inapplicability of traditional elastic crack growth models. Therefore, a residual life prediction framework accounting for crack tip plasticity was proposed. Additionally, it was found that the stress intensity factor of the specimen at fracture was related to geometric dimensions. Finally, integrating initial crack size, critical crack size, and geometric dimensions, a probabilistic life prediction model based on the weakest link theory was proposed. This work introduces a novel approach to probabilistic damage tolerance assessment for components with defects, providing significant engineering insights.

AIR BLAST TNT EQUIVALENCE FOR EXPLOSIVE WITH AND WITHOUT ALUMINIUM POWDER

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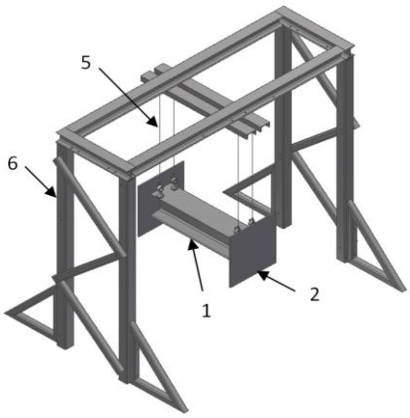
Key words: TNT equivalent, ConWep, blast wave, LS-Dyna

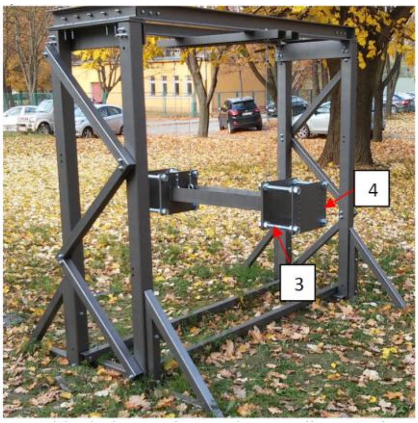
The addition of aluminum powder to the explosive reduces the maximum value of the pressure impulse while significantly increasing the duration of the pressure impulse coming from the detonation of the explosive [1–3].

The purpose of the conducted research was to determine and compare TNT equivalents of charges made of HMX explosive without and with the addition of aluminum powder. TNT equivalent is used in many cases when studying the effects of a blast wave impulse on a structure [4, 5].

Experimental tests were carried out using: fabricated explosive charges without and with aluminum powder, a ballistic pendulum and high-speed cameras (Figs. 1 and 2) [6, 7].



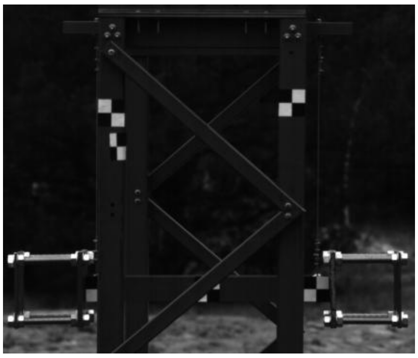
a)



b)

Fig. 1. Diagram of the test setup (a); test rig (b); (1) double T-bar, (2) steel plate, (3) distancing element (4) steel, removable plate, (5) rope, (6) frame [7]

a)



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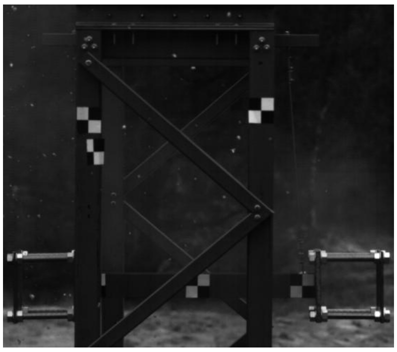

Fig. 2. Test rig during the experimental tests; a) initial position, b) tilt during the test [7]

Based on these, the effects of the pressure wave on a structure were determined in the form of the time course of the pendulum's tilt. The course of the phenomenon was then reflected using an explicit implementation of the finite element method in the Ls-Dyna Ansys program [8]. In the case of numerical analyses, the ConWep algorithm [9] was used, which allows the use of TNT equivalent for the analysis of the pressure wave's effect on the structure. By trial and error, the values of the equivalent were chosen to represent the experimental course of the pendulum tilt as accurately as possible.

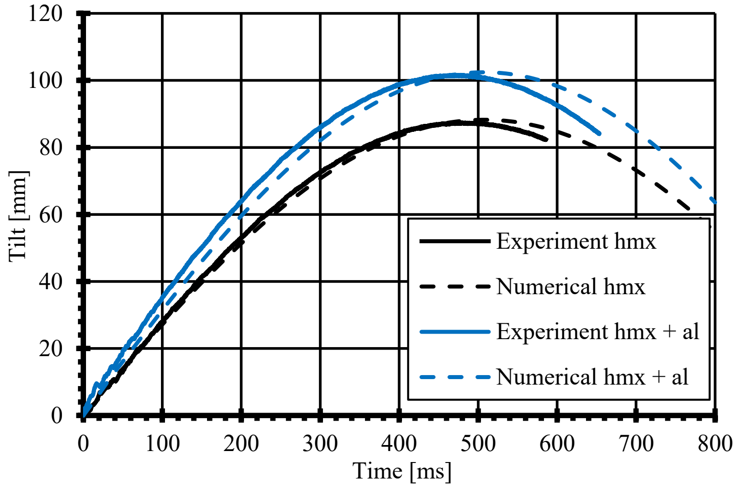

Fig. 3. Comparison of experimental results and numerical analyses for HMX without and with the addition of aluminum powder

In both analyzed cases, a very high agreement was obtained between experimental results and numerical analyses. The value of the TNT equivalent in the case of a load with aluminum powder was 20% higher, than without the addition (Fig. 3).

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DAMAGE TOLERANCE OF INDUCTION-HARDENED S38C RAILWAY AXLES SUBJECTED WITH FOREIGN OBJECT DAMAGE AT LOW TEMPERATURE

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The safety of high-speed railway axles is threatened by defects, including inclusions, corrosion pits, fretting damage and foreign object impact damage. Temperature is an important factor influencing the damage mechanism and the subsequent fatigue behavior of railway axles. Previous work mainly focuses on the damage tolerance of railway axles with impact damage at room temperature, while giving less consideration on low temperature. To illustrate the influence of low temperature on the formation of impact damage on induction-hardened S38C railway axles, specimens were kept at –40°C and then shot by projectiles made of tungsten steel at varying velocities. The micro-macro morphologies of impact damage were observed by optical microscope and scanning electronic microscope. The fatigue behavior of damaged specimens was evaluated by four-point bending fatigue test.

José A.F.O. Correia

José A.F.O. Correia was born in 1984 in Peso da Régua, Portugal, and is currently a Professor and a Researcher at the CONSTRUCT institute, Faculty of Engineering, University of Porto (FEUP, Portugal). Between March 2018 and February 2024, he was a Guest Professor at the Delft University of Technology (Netherlands). Additionally, he was an Invited Professor at the University of Porto (2018–2019) and at the University of Coimbra (2016/09–2021/08), and he was an Associate Professor by invitation at UTAD (2022/03–2023/02).

In 2007, José A.F.O. Correia obtained a Graduation in Civil Engineering (5 academic years) from UTAD. In 2009, he obtained an MSc. in Civil Engineering (Structural Mechanics) from UTAD. He has a Specialization in Steel and Composite Construction from the University of Coimbra (2010). In 2015, He got a Ph.D. Degree in Civil Engineering from the University of Porto. In 2024, He obtained the Habilitation in Civil Engineering – Fatigue and Structural Integrity from the University of Porto. He also obtained an MSc. in Mechanical Engineering, specializing in Solid Mechanics, from UFF.

Since 2019, Doctor José A.F.O. Correia has been included in the world's top 2% scientists list, as ranked by Stanford University. José A.F.O. Correia is co-author of more than 234 journal papers in the most relevant scientific journals, 200 proceedings in conferences, 18 book chapters, and also co-author/co-editor of 22 books (15 completed; 7 ongoing). He also edited more than 21 issues of scientific journals as a Guest Editor. On the Scopus platform, he is (co)author of 378 documents in the most relevant scientific journals, and has an h-index of 50.

He was/is a supervisor of doctoral and master's students in the areas of Civil and Mechanical Engineering – 24 Ph.D. (13 completed) and 51 MSc. (47 completed).

He was/is the (co)coordinator at FEUP of 7 R&D projects (e.g., FADEST, FiberBridge, SOS-WindEnergy, Hyperloop-Verne, PT-Chinese Project, NEXUS, SuRe3-OW-GH2, Green4Bridges) and consulting services (university extension).

APPLICATION FOR PREDICTION OF CRACK PATH AND FRACTURE PARAMETERS IN CTS SPECIMENS UNDER MIXED-MODE I+II

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Key words: CTS, machine learning, fracture, fatigue crack growth

1. BACKGROUND

Mixed-mode fracture behavior of metal materials like steel is often assessed with Compact Tension Shear Specimen proposed by Richard [1]. This specimen enables testing fracture behavior under fatigue loading with different mixicity ratio, which can be regulated by changing the loading angle. This approach is commonly used, but also have its own challenges. To properly asses the results researchers have to find the stress intensity factors for mode I and mode II for the points on the growing crack. However analytical solutions provided by Richard are only valid for the starting geometry (with initial straight crack). Therefore, numerical calculations has to be provided (commonly used solution here is finite element analysis). This, however, can be time-consuming process. In the present times, one of the possible solutions to this type of the challenges is to use machine learning approaches. As shown in [2] it is possible to use mixed numerial – machine learning approach to predict mechanical quantities.

2. MACHINE LEARNING APPROACH FOR CRACK PATH PREDICTION

In the conference, results of the work on prediction of crack path in CTS specimen will be presented. As an effect a tool was prepared, that is able to generate the chart of the crack propagation for given size of the

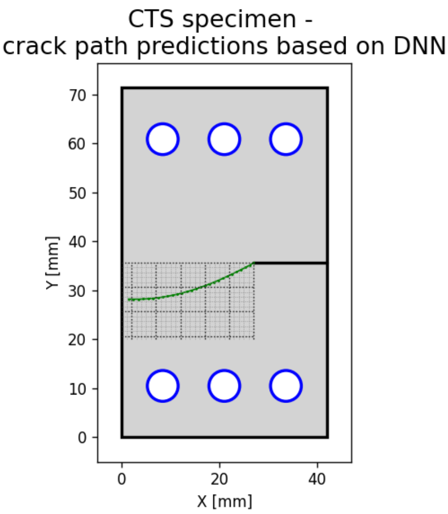

Fig. 1. Exemplary crack path generated by the app (green line)

specimen, loading angle, position of the crack and other parameters. Path prediction can be based on one of the three models – based on XGBoost, DNN or TabNet. It is also possible to determine fracture parameters for any point in the specimen (which is possible point on the crack path for some starting conditions).

Exemplary crack path generated by the app is presented in Fig. 1 for loading angle 60°.

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ASSESSMENT OF THE FRACTURE TOUGHNESS OF STEAM PIPE MATERIAL BASED ON NUMERICAL SIMULATIONS

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Keywords: steam pipeline, numerical analysis, fracture toughness, J-integral, stress and strain distributions in front of the crack tip, stress triaxiality factor

1. INTRODUCTION

Assessing the current condition of the material of engineering structures is an important task faced by engineers involved in strength analysis. It is a complex assignment due to the complex nature of the effects of various factors on the material of the structure. In the case of district heating pipelines, these can be thermal interactions, conditions of long-term mechanical loading and the operating environment leading to the development of corrosion and hydrogen damage [1, 2]. An important aspect is that the presence of defects is not assumed at the development and implementation stage of a structure. However, for operational reasons, the formation and development of cracks in the structure under consideration cannot be ruled out, which can have a determining effect on its ability to carry loads [3]. In such cases, the implementation of fracture mechanics procedures is an essential part of the strength assessment, in order to avoid dangerous consequences as a result of failure [4]. The development of computer techniques makes it possible to carry out strength analysis of structures on the basis of the results of numerical simulations using FEM. It is then possible to determine the characteristic quantities of mechanical fields (stresses, strains, stress triaxiality factor) before the crack front, and on their basis to formulate conclusions about the condition of the material and the strength of the structure [5, 6]. This paper presents the assumptions of the proposed procedure for assessing the strength of steel for energy pipelines, with emphasis on the implementation in the procedure of simulations using FEM.

2. MATERIAL AND EXPERIMENTAL STUDIES

The strength analysis was carried out on energy pipeline material made of 15CrMoV5-10 steel (13HMF). This is the material in its initial state (designation 13HMF_i) and after more than 22 years of operation (designation 13HMF_o). Specimens were taken from the pipelines for laboratory testing and microstructure analyses were performed. Uniaxial tensile tests were carried out to determine the strength and plasticity characteristics. After operation, the pipeline material showed an approximately 20% lower tensile strength level, with similar values of strain at fracture in relation to the initial material. The nominal and true tensile curves are shown in Fig. 1.

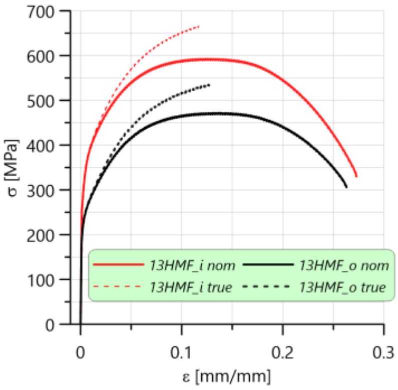

Fig. 1. Nominal and true tensile diagrams of tested steel

3. NUMERICAL SIMULATIONS

The strength assessment of the pipeline steel exposed to heat was based on the results of numerical simulations. To this end, numerical models of specimens identical to those used in laboratory tests were developed in Abaqus: a cylindrical uniaxially tensile specimen and a three-point bending SENB (Fig. 2a). The use of a tensile specimen in the calculations will allow the true stress-strain material relationship to be properly prepared. By simulating the numerical loading of a specimen model with a crack, the distributions of stress, strain and stress triaxiality factor in front of the crack tip were determined. The J-integral values were numerically calculated and compared with the laboratory test results (Fig. 2b). These quantities were used to formulate an assessment of the condition of the material of the pipeline.

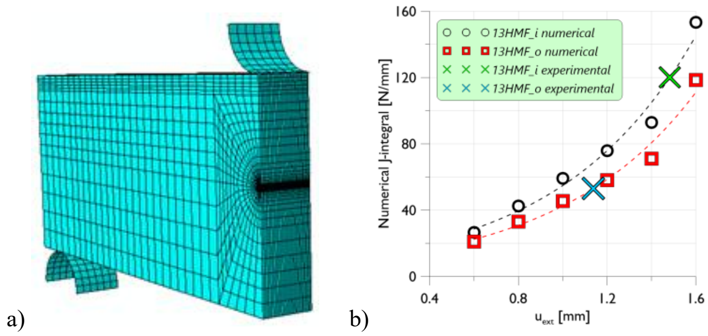

Fig. 2. FEM numerical calculation: a) SENB specimen model, b) determined values of the J-integral

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MECHANICAL BEHAVIOUR PREDICTION OF THE HYBRID COMPOSITE REBARS FOR CONCRETE STRUCTURES BASED ON MICROMECHANICAL APPROACH

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Key words: composite structure, rebars, micromechanics, hybrid

1. INTRODUCTION

Composites are one of the modern materials, which alter conventional metal structure in various applications. Fiber Reinforced Polymers (FRP) are characterized in mechanisms other than isotropic structures such as fiber breakage, delamination or matrix cracking. Hybridization of the reinforcement in the composite structure provides to achieve additional positive effect of various fibers application, which cannot be estimated by common Rules of Mixture. Composite rebars are one of the modern application, where FRP materials are a substitute for steel reinforcement. Prediction of the ultimate tensile strength in the unidirectional FRP structure and verifying various hybrid configuration mechanical behavior is crucial during design of the optimized structure. Currently, the Representative Volume Element (RVE) [1, 2] and analytical models [3, 4] were developed to establish impact of the fiber distribution, voids inclusion or reinforcement hybridization on the mechanical parameters such as strength, stiffness or pseudo-ductility effect.

2. RESULTS AND DISCUSSION

Analytical models were chosen to estimate the mechanical behavior of the composite rebars. According to Vanegas-Jaramillo assumption, failure in the on-axis tensile loading is achieved when the fiber crack

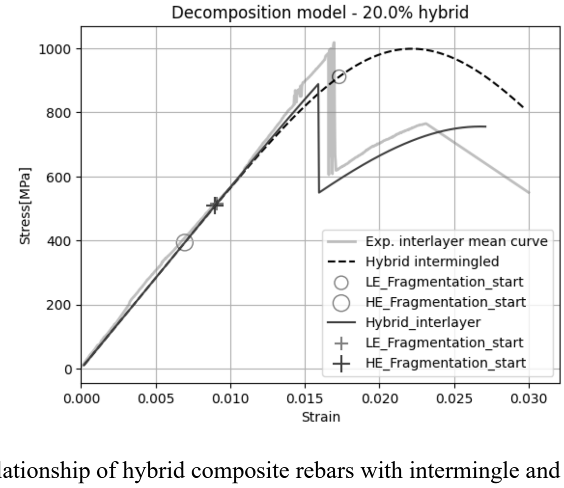

Fig. 1. Stress–strain relationship of hybrid composite rebars with intermingle and interlayer hybridization. Analytical prediction of the low-elongation (carbon) and high-elongation (glass) fibres initial fragmentation process is highlighted for each type of material

density obtain critical level. Based on the Weibull distribution of fiber parameters taken from the single fiber tests, mechanical properties of the polymer and the interfacial strength of the matrix-reinforcement connection, the Neumester's fragmentation model, also referred to as the Critical Number of Breaks (CNB) model, were developed[5]. Mechanical behavior of the profiles with various content of the glass and carbon fibers were designated. Comparison of the stress-strain relation between intermingled and interlayer hybrid reinforced distribution were established. According to the analytical outcome, the optimized hybrid content were chosen and the hybrid composite rebar were manufactured using pultrusion process. The predicted results were compared with the analytical estimation using Digital Image Correlation technique. Moreover, analysis of the damage mechanism estimated from the analytical approach were compared with the events registered using Acoustic Emission system.

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NUMERICAL-EXPERIMENTAL ANALYSIS OF THE EFFECT OF A STRESS CONCENTRATOR ON THE STRENGTH OF CFRP MATERIAL

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Key words: stress concentrator, carbon fibers, mechanics of composite materials

1. INTRODUCTION

With the increasing use of carbon fiber reinforced polymers (CFRP) in engineering structures such as pressure vessels, wind turbine blades, and aircraft fuselages, interest in modeling their mechanical response under various loading conditions has been steadily growing. Polymers, including CFRP, enable the aerospace industry to optimize structural design in terms of weight, stiffness, and strength. In the aerospace industry, the assembly of aircraft requires drilling in fiber-reinforced materials to connect consecutive components. This process is particularly challenging due to the initial damage induced during drilling, as well as the fact that the hole itself becomes a site of stress concentration. The presented results concern the numerical analysis of filament-wound structures made of continuous carbon fiber reinforced polymer (CFRP). Due to the wide application of such structures in aerospace and other engineering fields, it is essential to develop a model capable of reliably describing their mechanical behavior in the presence of stress concentrators. The proposed solution is a numerical model with progressive damage, with particular emphasis on incorporating the delamination mechanism.

2. CONCLUSIONS

Based on the conducted analyses (static tension and compression experiments), the following conclusions were drawn:

1. The numerical model with material shear nonlinearity and progressive damage, which includes the matrix tension and compressive failure, and shear failure accurately describes the mechanical response of the CFRP structure under tensile loading.
2. In the case of compressive loading, which is the most challenging for composite materials, the model overestimates the strength. This fact might be explained due to the lack of implementation of defects and the delamination mechanism, which is not covered by progressive damage model.
3. An alternative approach is a 3D model with an interlayer, which would allow the progressive damage model to be extended by incorporating an additional failure mechanism, namely delamination. However, in this case the numerical analysis requires more computational power.

ACKNOWLEDGMENT

The presented research results were obtained within the framework of the research task entitled "Analysis of fatigue strength (HCF) and damage mechanisms of filament-wound CFRP structures in the presence of stress concentrators", funded by the pro-quality subsidy for the development of the research potential of the Faculty of Mechanical Engineering, Wrocław University of Science and Technology, in 2025.

FATIGUE LIFE PREDICTION OF NOTCHED SPECIMENS UNDER SIZE EFFECT USING CP-FFT: APPLICATION TO NI-BASED SUPERALLOY GH4169

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Key words: crystal plasticity, FFT, size effect, notch fatigue, life prediction, probabilistic

Fatigue behavior of Ni-based superalloy GH4169 is significantly influenced by the microstructural characteristics and notch effect. In this study, a microstructure sensitive multiscale modelling framework is developed to investigate the size effect on the fatigue behavior of Ni-based superalloy GH4169 notched components. By integrating crystal plasticity theory with FFT-based computational homogenization framework, the proposed approach captures the grain-level mechanical response under cyclic loading. Specifically, fatigue life prediction is performed using the FIP extracted from RVE accounting for local stress concentration effect. Moreover, to reduce the sensitivity of FIP to discretization effect, a non-local averaging approach is introduced. To explore the probabilistic dispersion of fatigue failure, FIPs obtained from multiple microstructural realizations are analyzed using Gumbel distribution and statistical assessments are conducted to evaluate fatigue life distribution. Finally, the predicted results are compared with experimental data, demonstrating the reliability of the proposed methodology in predicting the notch and size effects from probabilistic aspect.

CLOSURE OF COLLINEAR CRACKS IN BENDING OF MULTILAYER PLATE WITH SYMMETRICAL STRUCTURE

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Key words: multilayer plate, closable crack, collinear defects, bending, 2D statement

ABSTRACT

The problem of contact interaction of crack faces of in a set of collinear through cuts during bending of thin multilayer plates with symmetrical structure is considered in a two-dimensional formulation. Based on the rigid normal hypothesis, the incomplete through-thickness crack closure is investigated in framework of model of contact along a line and interpreted as the joining of crack faces at the outer surface of the plate [1, 2].

A boundary value problem corresponding to such a model is formulated for a pair of biharmonic equations of plane stressed state and Kirchhoff's theories of layered plate in domains with cuts.

An analytical solution of singular integral equations is constructed for a system of two collinear cracks. The influence of material inhomogeneity and mutual arrangement of defects on the magnitude of the forces and moment intensity factors and on the distribution of contact reaction on the closed crack faces is analyzed. In particular, the values of the ultimate bending loads for contact cracks are compared in two cases of stiffness distribution, when the core of the plate is stiffer and more ductile than its periphery.

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EQUILIBRIUM OF PLATE WITH CYCLIC-SYMMETRICAL SYSTEM OF RADIAL CRACKS HEALED NEAR TIPS

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Key words: plate, radial cracks, partial healing, fracture

ABSTRACT

The express methodology for assessing the strength of a body with a partially healed crack is used for modeling the renovation of damaged structures. We adopted the hypothesis that the elastic properties of the body with a partially healed crack are preserved. However, the specific surface energy of separation of surfaces is different from that in a solid body. Thus, we came to the problem of mechanics of crack in a homogeneous in terms of elastic properties and heterogeneous in terms of crack resistance [1].

The consequence of healing of damage plate with cyclic-symmetrical systems of radial through crack is studied for cases of uniform all-round tensile and bending load. The crack closure effect in plate under bending is considered using the model of contact along a line [2, 3]. In numerical form, quantitative estimates of healing efficiency are established depending on three parameters: degree of filling of cracks, crack resistance of the newly formed interface, number of defects. In particular, the results of healing of internal and external defects vertices are compared.

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The main research fields are:

1. Fatigue and fracture of traditional and innovative materials.
2. Based on energy approaches for fatigue and fracture design.
3. Bio-inspired design of complex multifunctional structures.
4. Data-driven methods applied to advanced design of complex, customized structures.

FATIGUE CRACK GROWTH RATE DESCRIPTION IN LONG TERM-OPERATED BRIDGE STEEL

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Key words: puddle iron, degradation, fatigue crack, crack growth rate

ABSTRACT

All over the world, including in Poland and Portugal, there are exist steel structures that are 100 or more years old. In particular, the construction of railway lines in the 19th and 20th centuries contributed to thousands of steel structures for bridges and viaducts being constructed. Knowledge of materials used in the past and their properties, after many years of use, is now necessary to determine the usefulness of the constructed structures. The authors of the abstract intend to present their own experience in this field. Among other things, they want to present the results of experimental research involving a 100-year-old bridge from the point of view of fatigue-related crack growth in puddle iron. The paper presents the results of tests on historic bridge steel from structures operated in Poland and Portugal. One of the most important issues related to the safety assessment of this type of bridge is the assessment of resistance to fatigue crack propagation. The paper presents the results of tests – fatigue crack kinetics curves determined in accordance with ASTM E647. In addition, a comparative analysis and assessment of the impact of microstructural degradation processes on fatigue life was performed. Furthermore, for selected cases, the issue of R-factor influence was discussed, i.e. an analysis was performed using original mathematical models as well as the concept of effective ΔK, which takes into account the effect of fatigue crack closure. An important aspect from a serviceability point of view is also the procedure of extending the fatigue life of cracked bridge steel components. The authors conducted experimental tests using various techniques to arrest crack growth (stop hole, CFRP strips in various combinations). As a result, the advantages and disadvantages of each of these solutions were compared and discussed.

ASSESSMENT OF THE EFFECT OF FIRE TEMPERATURES ON S235 STEEL USING ACOUSTIC EMISSION METHOD, NUMERICAL ANALYSIS AND METALLOGRAPHIC TEST

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Key words: steel S235, acoustic emission, numerical modeling

This paper discusses the results of tensile tests performed on smooth S235 steel samples stored at ambient temperature and exposed to fire temperatures (700°C, 900°C, and 1100°C for 40 and 80 minutes). Acoustic emission (AE) measurements were taken during loading, along with force and deformation. The recorded AE events were analyzed individually and classified using a k-means algorithm. Analysis of the obtained results allowed the identification of acoustic emission signals characterizing various processes occurring during the operation of the steel material under load. The tests revealed significant differences compared to the material stored at ambient temperature and exposed to temperatures corresponding to fire conditions. A numerical model was developed based on the laboratory test results. The microstructure of the tested materials was also observed. The analyses conducted allowed for a reliable assessment of the feasibility of using the acoustic emission method for load monitoring and post-fire assessment of the condition of S235 steel. It was found that the acoustic emission method, due to differences at low loads, can be an effective technique for diagnosing the condition of steel after exposure to fire temperatures.

GCYCLEFAT: INSIGHTS INTO ULTRA-HIGH-CYCLE FATIGUE BEHAVIOR OF ENGINEERING ALLOYS

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Key words: Giga-cycle fatigue, additive manufacturing, S690 steel, AL alloys, IN625, testing, modelling

ABSTRACT

The GCYCLEFAT project addressed the emerging challenge of predicting fatigue behavior in engineering alloys subjected to loading cycles beyond 10^7, within the Giga-Cycle Fatigue (GCF) regime. In this domain, traditional fatigue models lose reliability, as crack initiation frequently shifts from the surface to internal defects, making microstructural features – such as defect type and density – critical to fatigue life prediction. Nevertheless this feature could be considered material dependent. Therefore, several metallic alloys were investigated, representing distinct manufacturing routes and defect populations: a hot-rolled structural steel (S690), a spring steel (51CrV4), a lightweight cast Al–Si alloy, and an additively manufactured alloy (DED IN625). High-frequency ultrasonic fatigue testing (20 kHz) was the core methodology, supported by low-frequency baseline tests to evaluate frequency effects, modelled numerically with thermal–mechanical simulations to capture self-heating during cycling.

For structural steel, both uniaxial and multiaxial fatigue tests were conducted, including cruciform specimens and notched geometries, under constant and block loading. The cast aluminium alloy, often used in thin-walled transport structures, was tested using specially designed planar specimens compatible with thin-section extraction. For the AMed material, known for high internal porosity, UHCF testing focused on constant amplitude loading and microstructure-fatigue life correlations.

The project delivered robust insights into frequency effects, thermal damage modelling, and multiaxial fatigue. GCYCLEFAT provided testing methodologies in the giga-cycle fatigue regimes, and enhanced fatigue design frameworks for long-life structural applications and contributes to safe, cost-effective engineering solutions.

ACKNOWLEDGEMENTS

This research was funded by FEDER and National Funds (FCT), through the GCYCLEFAT project entitled "Giga-Cycle Fatigue Behaviour of Engineering Metallic Alloy", reference PTDC/EME-EME/7678/2020.

FREQUENCY EFFECT IN MULTIAXIAL FATIGUE BEHAVIOUR OF A STRUCTURAL STEEL FOR OFFSHORE WIND TURBINE SUPPORT SYSTEMS

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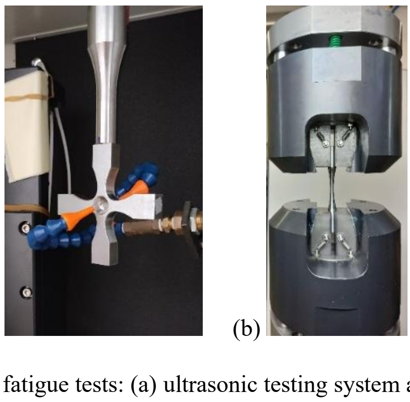
Key words: frequency effect, multiaxial fatigue, structural steel

ABSTRACT

Fatigue analysis is fundamental to ensure structural integrity of support systems of offshore wind turbines, since wind, waves, working loads, among others, are usually cyclic and lead to cumulative damage [1]. In order to perform a fatigue analysis of offshore structures, the methodologies and recommendations described in design standards such as DNV (Det Norske Veritas) [2], CSS (China Classification Society) [3], and ABS (American Bureau of Shipping) [4] are usually followed. However, these design standards do not take into account multiaxial stress states [5].

Moreover, very high cycle fatigue regime (VHCF) has been gaining interest due to sustainability goals to extend service lives of structures, such as offshore wind turbines. The assessment of this regime imply higher frequencies of testing to reduce the testing time require to characterize the region beyond 10 millions of cycles [6]. As consequence, ultrasonic fatigue testing systems are commonly used to assess this regime, since they can achieve a frequency of testing usually around 20 kHz.

However, this new technology brings challenges such as specimen's design, overheating and frequency effect. The last topic mentioned is particularly relevant since it can compromise the validity of experimental data estimated at higher frequencies. Moreover, frequency effect is influenced by material characteristics, resulting into different effects on experimental data. Some authors tried to address this topic by proposing analytical models, which can include and correct this effect for certain materials [7]. Nonetheless, the frequency effect in multiaxial fatigue data is not well described in literature.



(a) (b)

Fig. 1. Setups of multiaxial fatigue tests: (a) ultrasonic testing system and cruciform specimen, (b) electromechanical testing system and hourglass specimen

Therefore, in this work, frequency effect in multiaxial fatigue behaviour of S690 steel is analyzed to include it in experimental fatigue data. Thus, experimental tests were performed at different frequencies of testing and under multiaxial loading conditions. In Figures 1a and 1b are illustrated experimental setups of multiaxial fatigue tests performed with an ultrasonic testing system and cruciform specimens [8], and with an electromechanical testing system and hourglass specimens, respectively. The results estimated are compared with other works from literature of experimental tests performed at uniaxial loading conditions [9, 10].

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APPLICATION OF MULTI-OBJECTIVE OPTIMIZATION TO IMPROVE THE RELIABILITY AND STABILITY OF STRUCTURE

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Key words: safety, reliability, multi-objective optimization, comfort, stability

1. INTRODUCTION

Electric kick scooters' popularity is constantly growing in the Europe. It is anticipated that sales of this type of solution will grow by approximately 25% per annum [1]. Conversely, these vehicles possess characteristics that impede their dissemination and utilisation for purposes other than their intended function as the final stage of a journey. These include, for example, their weight and size, which make them difficult to transport using traditional means of transport, their low range [2], and their limited ability to handle uneven terrain.

Bearing this in mind, the Leonardo project (microvehicle fOr staNd-alone and shaReD mObility) developed an electric micro-vehicle that combined the features of a unicycle and a scooter. The main goal was to design a vehicle with a large front wheel suitable for rough surfaces [3] and achieve greater torque and range, while keeping the total weight below 10 kg. Reducing the weight of the entire solution to under 10 kg was an especially challenging task. To achieve this, the suspension elements were completely eliminated. A board took over the role of the shock absorber, providing adequate comfort while ensuring an appropriate level of durability.

The following section of the paper outlines methods for determining operational loads and conducting multivariate optimisation analyses. These analyses allow for weight reduction and ensure that the structure meets functional requirements [4].

2. EXPERIMENTAL TESTS

The first part of the project involved modifying a commercial electric scooter to allow boards of different stiffness and thickness to be mounted on it. Next, a measurement system and a test track were developed to ensure the same conditions were maintained each time. The track consisted of a loop containing typical urban obstacles, as well as areas featuring distinct transverse obstacles. One of the main objectives of the experimental research was to determine the forces acting on the rider. To this end, shoes fitted with strain gauges were prepared (Fig. 1).

Consequently, the maximum and average forces acting on the driver when overcoming obstacles were determined. Following the execution of appropriate calculations, a logarithmic characteristic was obtained, thereby demonstrating the maximum and average forces as a function of the stiffness of the board.

Fig. 1. Views of the right instrumented shoe from below (left figure) and side (right figure)

Furthermore, information pertaining to the driver's subjective feelings was collected. On the basis of the evidence presented, the following conclusions were drawn: 1. A less rigid chassis has been shown to provide a superior driving experience on roads with minor surface irregularities; 2. It is evident that a more rigid chassis provides enhanced stability, thereby reducing the requirement for weight distribution while driving.

2. NUMERICAL OPTIMIZATION

In the second part of the study, a numerical model was developed that replicates the actual structure, while allowing for parametric changes in the stiffness and thickness of the board. Subsequently, two load variants were prepared: symmetrical and asymmetrical. The objective of the optimisation process was to obtain the minimum thickness of the board that results in desired stiffness of the optimal case, as determined by experimental testing, and maintain the tension stress below the allowable value. In the subsequent phase, two optimisations were executed employing distinct algorithms: genetic and RSM (Response Surface Methodology). A comparative analysis of the outcomes obtained from these optimisations was then conducted.

The result of the work carried out is the development of a method for optimising the design of an electric scooter board. The genetic algorithm that was utilised in this study has been demonstrated to be a more efficacious approach, enabling a substantial reduction in the weight of the structure and the reproduction of stiffness.

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LATERAL-TORSIONAL BUCKLING CAPACITY OF BEAMS WITH WEB OPENINGS OR VARYING CROSS-SECTIONS

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Key words: lateral-torsional buckling, elastic critical moment, patch-corroded beams, castellated beams, cellular beams

1. INTRODUCTION

Steel beams with web openings, such as castellated and cellular beams, are widely used in bridges, stadiums, and industrial structures due to their reduced weight, increased stiffness, and material efficiency. However, these beams are particularly vulnerable to lateral-torsional buckling (LTB) because of their increased depth and reduced torsional stiffness. Thickness reduction due to uniform corrosion also increases the susceptibility of LTB in patched corroded beams, which can be categorized as "beams with varying cross-sections". Conventional design codes (e.g., Eurocode 3 [1]) provide accurate solutions for beams with uniform cross-sections, but they lack explicit analytical expressions for beams with varying cross-sections (VCS) or with web openings. Current semi-empirical approaches (1T and 2T methods) are either overly conservative or uncertain in their application. Thus, a reliable analytical framework is required to predict LTB capacity in such members.

2. OBJECTIVES AND METHODOLOGY

The paper proposes a new analytical formula for the elastic critical buckling moment ($M_{cr,vcs}$) of beams with VCS or web openings, derived using the energy method (Rayleigh–Ritz approach). The method accounts for bending about the minor axis, Saint-Venant torsion, and warping torsion energies, equating total strain energy with the external work of applied loads. The derived closed-form expressions for simply supported and fixed beams subjected to equal end moments were obtained as shown in Eqs. (1) and (2).

$$M_{cr,vcs} = \frac{\pi}{L^2}\sqrt{\alpha E I_z \left(\beta G I_T + \gamma E I_w \frac{\pi^2}{L^2}\right)}, \tag{1}$$

$$M_{cr,vcs} = \frac{2\pi}{L^2}\sqrt{\alpha' E I_z \left(\beta' G I_T + 4\gamma' E I_w \frac{\pi^2}{L^2}\right)}, \tag{2}$$

where: E is modulus of elasticity, G is shear modulus and L is length of the beam. The I_z, I_T and I_w are second moment area about z–z axis (i.e., minor axis), torsional constant and warping constants of the original cross section of the beam respectively. The parameters α, α', β, β', γ and γ' depend on alterations in length location and the associated cross-sectional properties. The method was further generalized for beams under distributed loading via moment-modification factors. Using the derived $M_{cr,vcs}$, the non-dimensional slenderness was computed, leading to design buckling resistances consistent with Eurocode 3.

3. VALIDATION

The proposed formula was validated against, (i) Experimental tests on castellated and cellular beams [2, 3], covering different web opening shapes (hexagonal, circular, Angelina) and, (ii). Finite element (FE) simulations of beams with web openings and patch-corroded beams, carried out using ANSYS Workbench. Results show very good agreement between the analytical predictions, experimental capacities, and FE simulations as shown in Fig. 1. The method accurately captured LTB capacities across a wide slenderness range. In the case of lateral-distortional buckling, the proposed formula provided conservative predictions, as expected.

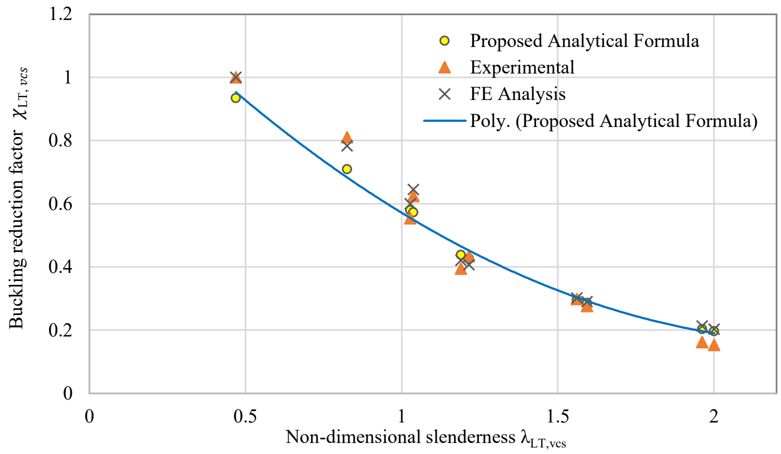

Fig. 1. Buckling reduction factor versus non-dimensional slenderness

4. DISCUSSIONS AND CONCLUSIONS

For castellated and cellular beams, the analytical predictions of lateral-torsional buckling (LTB) capacities matched experimental results within engineering accuracy, outperforming existing semi-empirical methods. For patch-corroded beams, the analytical approach also closely captured nonlinear finite element (FE) buckling capacities, demonstrating robustness in modeling corrosion-induced varying cross-sections (VCS). Importantly, the framework bridges a gap in Eurocode 3 by providing explicit analytical expressions for the critical buckling moment (M_{cr}) of beams with both VCS and web openings.

An analytical framework for predicting the LTB capacity of beams with web openings and VCS has therefore been established. The main contributions are:

1. Derivation of explicit closed-form equations for the elastic critical buckling moment of beams with VCS using the energy method.
2. Extension of the approach to a wide range of loading and boundary conditions through modification factors.
3. Validation against more than ten full-scale experimental beams and twenty-four FE-simulated corroded beams, with strong agreement observed.

The proposed method provides a reliable and efficient alternative to experimental and numerical approaches, offering a rational basis for future design code development. Future work should focus on extending the methodology to unsymmetrical cross-sections and composite members.

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NUMERICAL AND ANALYTICAL ANALYSIS OF ROUGHNESS EFFECTS IN PLA FDM PARTS: COMPARISON BETWEEN AS-PRINTED AND POST-MACHINED SURFACES

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Keywords : surface roughness, milling process, 3D surface measurements, local stress state, stress concentrators

ABSTRACT

Additive manufacturing, particularly Fused Deposition Modeling (FDM), has profoundly impacted the production of polymer parts due to its flexibility and cost-effectiveness. However, a significant limitation of FDM printed parts is their elevated surface roughness, which can negatively affect their mechanical performance, fatigue resistance, and dimensional accuracy. This roughness has the potential to initiate crack formation at the surface under the action of external forces. Polylactic acid (PLA) composite parts exhibit visible surface irregularities, which may result from the layer-by-layer deposition process or the use of inappropriate printing parameters. Post-processing treatments are often necessary to ensure the desired quality and surface integrity of the final product.

This research aims to analytically and numerically investigate the impact of surface roughness on the mechanical behavior of FDM printed PLA parts. To this end, the study will compare as-printed surfaces with milled surfaces.

The study emphasizes the importance of incorporating real surface roughness data into Finite Element Method (FEM) simulations to more accurately predict the mechanical behavior of the parts. The study also addresses the implementation of post-processing techniques to improve the functional performance of FDM printed parts, especially for critical applications.

Accurately representing the actual topography of a surface in a numerical model is essential for many engineering and scientific applications, especially those involving surface interactions, stress concentrations, wear, fatigue, and fluid dynamics. Numerical simulations of real surface topographies are necessary to realistically represent the behavior of parts under boundary conditions in mechanical problems.

Surface roughness was measured using an AltiSurf 520 three-dimensional surface measurement system to obtain necessary roughness parameters and surface profile details, which were then reproduced in CAD models. Geometric models that incorporated the measured surface profiles were used to create different CAD configurations for both as-printed and milled parts. Numerical simulations evaluate stress distribution and identify potential crack initiation zones, highlighting differences induced by surface quality.

Milling has been demonstrated to reduce surface roughness, thus improving the mechanical behavior of the parts. This is a critical factor in engineering applications, particularly those concerned with ensuring structural integrity. At the same time, it has been observed that the milling process introduces local level defects and increases surface roughness by forming burrs when inadequate milling parameters are used.

Based on the results of previous research [1–5] and the impact it has on defining surface quality, this paper considers cutting speed to be the most important milling parameter. The main problem with milling PLA is the formation of burrs, which significantly impacts the integrity of the milled surface. This problem

can arise from various causes, such as high cutting speeds, excessive cutting depths, inadequate feeding rates, or the utilization of low infill ratios during the 3D printing process.

Based on the results obtained, it can be concluded that using a high cutting speed (100 m/min) in the milling process significantly improves the surface quality of printed PLA parts. Milling with high cutting speeds improves surface roughness and eliminates burr formation. The results also indicate that the high feed rate increases the rate of chip removal. This facilitated heat dissipation and reduced surface damage.

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The main research fields are:

1. Maintenance modeling and optimization of technical systems.
2. Reliability and resilience assessment of industrial systems.
3. Supply chain resilience and logistics modeling.

BEYOND RELIABILITY: FROM PREDICTION TO RESILIENCE – HOW RESILIENCE-BASED MAINTENANCE AND AI TRANSFORM SAFETY OF COMPLEX STRUCTURES

The lecture explores a paradigm shift in the safety and maintenance of complex industrial systems, moving beyond traditional reliability and prediction methods towards resilience-based approaches. The presented concept, Resilience-Based Maintenance (RBM), integrates AI-driven decision support with system-level resilience engineering to anticipate, absorb, and adapt to disruptions under uncertainty. Drawing from recent research in industrial systems and Maintenance 5.0, the talk highlights how AI, digital twins, and human-centric design principles can enhance proactive risk management, reduce downtime, and improve operational continuity. The presentation bridges theory and practice, offering examples from mining and manufacturing sectors, and demonstrates how resilience metrics complement reliability indicators in safeguarding critical infrastructure.

COMPOSITE ADHESIVE TO PREVENT CAVITATION DAMAGE IN CYLINDER LINERS OF LOCOMOTIVE DIESEL ENGINES

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Key words: adhesive composite, cavitation, cylinder liner, locomotive diesel engine, surface coating

The cylinder liners used in locomotive diesel engines are subject to significant mechanical stress due to long-term operation under conditions of high pressure, temperature, and vibration. To meet power requirements for high torque and long-term durability in these challenging operating conditions, turbulence increases in the coolant passage channels on the outer surface of the cylinder liners where the flow direction changes or the channel geometry narrows. Local pressure drops in these areas can cause the liquid to fall below its vaporization pressure, leading to the formation of microscopic vapor bubbles. These bubbles that form in the regions where the flow reaches high pressure again suddenly collapse (implosion) and create very high temperature and pressure pulses locally [1], [2]. This impact effect causes deformations, microcracks, pitting, and material wear on the surface of the cylinder liner over time. The cavitation process that occurs in this way also significantly shortens the working life of the engine components. It also reduces the material life, reduces engine efficiency, and increases maintenance costs. Therefore, it is necessary to understand the working mechanics of locomotive diesel engines, which are characterized by high combustion pressures and fast piston movements, in detail and to evaluate suitable surface repair materials to prevent these effects.

The effectiveness of repair materials is directly related to their resistance to the challenging hydrodynamic conditions frequently encountered in engine operating environments. Research has shown that surface repair composites with certain formulations can provide high resistance to cavitation erosion. These materials have been specifically developed to protect the liners against corrosive effects by supporting the protective effect of coolants on wet-type cylinder liners in heavy-duty locomotive diesel engines [3]. In addition, the hardness and mechanical strength of composite materials are important properties for increasing wear resistance [4]. Studies have shown that it provides both basic protection and significantly reduces wear caused by cavitation wear [5]. By strengthening the structural integrity of cylinder liners, such composite surface coating processes reduce the severity of cavitation-induced damage and the frequency of repairs, while extending their operational life. In addition, high-frequency vibrations in locomotive diesel engines can cause alternating stresses that increase the risk of cavitation damage to the liners. Therefore, damping solutions in engine design and operational stages are considered as an effective measure to protect the integrity of the cylinder liner and reduce cavitation-related erosive processes [6].

In technical engineering applications, the durability of epoxy-based adhesive composites is of critical importance, especially in terms of strength, creep and fatigue behavior under long-term loading. A study was conducted to evaluate the durability of Belzona, Unirep and Chester Metal adhesive composites. The study emphasized that Belzona filler composites provided higher creep and fatigue strength under both static and dynamic loading conditions, while epoxy composites such as Unirep and Chester Metal, which are unfilled or have different filler types, showed lower mechanical strength and life in the long term. It has been emphasized that such materials used in the repair of technical structures may show strength losses of up to 50% over time and that this situation must be considered for safe design [7]. In parallel, in other studies, both short-term and long-term mechanical performances of the adhesive composite called Belzona (which has many series) were examined; it was revealed that Belzona 1111 and 1812 products reinforced with fillers have higher static strength and longer fatigue strength compared to unmodified epoxy adhesives. It has been stated that the static load capacity of these adhesive joints can be at 60°C and have a working life of at least 500 hours [8]. It is seen that the adhesive composites in question can also be applied in technical parts exposed to high mechanical stresses, such as the repair of damages on the surface of cylinder liners. These findings show that in engineering applications, not only strength values but also behaviors such as creep and fatigue should be taken into consideration in the selection of adhesives, and advanced analysis methods are a valuable tool in this process.

As a result, the creep and fatigue behavior of adhesives used in these areas containing cylinder liners in locomotive diesel engines is extremely critical, given that these liners operate under both thermal cycles and cyclic dynamic heavy loads. It is seen that Belzona and Chester Metal Super composite adhesive products can offer an alternative solution in filling the gaps on metal surfaces, closing cavitation holes, and forming a protective layer in such surface repair applications. According to the technical data sheets of the examined products [9], [10]; In industrial applications under different mechanical and environmental conditions, Chester Metal products provide long-lasting protection in cylinder liners with their ceramic-based structure offering superior resistance to high temperatures and abrasion, while Belzona products are preferred in the effective repair of damages on cylinder liner surfaces with their cavitation resistance and strong adhesion properties against mechanical loads thanks to their silicon steel-added epoxy composite. The appropriate application of surface repair adhesives to reduce cavitation damage in locomotive diesel engines can be an economical and environmentally friendly solution compared to the production of new cylinder liners. Such repair methods aim to increase engine performance, reduce maintenance times, and create sustainable engineering solutions. This multifaceted approach aims to improve engine reliability and performance, minimize maintenance costs, and unplanned downtime due to engine failures.

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