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ASSESSMENT OF THE REMAINING SERVICE LIFE OF EXCAVATORS' STRUCTURAL COMPONENTS AT ROȘIA POIENI QUARRY

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Abstract: *This paper presents an integrated analysis of the structural durability of an excavator boom, a critical component subjected to extreme cyclic loads in the harsh mining environment of Roșia Poieni quarry. The study combines a numerical approach based on the Finite Element Method (FEM) with the theoretical principles of fatigue analysis to evaluate the stress state, estimate the remaining service life, and determine the safety factor. The FEM analysis, applied to a hybrid shell-beam model of the Hitachi EX1000 excavator boom, revealed critical stress concentrations in connection and welding zones, confirming these points' vulnerability to fatigue failure. Based on the stress values extracted from the simulation, Wöhler curve (S-N curve), adjusted with specific environmental (corrosion) and reliability factors, was used to estimate the service life. The results indicated a number of cycles to failure of approximately* 3.98×10^4 *and an estimated mean time to failure of 4457.14 hours, which signals a high risk of premature failure. A supplementary evaluation using the Goodman diagram confirmed this risk, calculating a safety factor of 1.49, a value below the recommended standards for dynamic applications. The study concludes that the boom operates in a potentially unsafe regime and proposes a series of practical recommendations to improve its reliability. These include implementing Condition-Based Monitoring (CBM) systems, optimizing the structural design in critical areas, and intensifying anti-corrosion protection programs.*
Keywords: *excavators; quarry; fatigue; durability; finite element method; Wöhler curve; Goodman diagram*

1. Introduction

1.1 Context and justification

The modern mining industry relies heavily on the use of heavy equipment, whose reliability and durability are essential for operational efficiency and personnel safety. In quarry operations, machinery such as hydraulic excavators is subjected to an extreme work regime, characterized by cyclic loads, mechanical shocks, and an abrasive environment [1]. Over time, these conditions lead to material fatigue, causing the progressive degradation of structural components and, ultimately, catastrophic failures. A simple analysis of static strength is not sufficient to guarantee long-term safety, necessitating a more in-depth approach that considers the lifecycle of structures under variable loads [2].

Therefore, evaluating the health of critical components and estimating their Remaining Useful Life (RUL) is imperative. This study focuses on a specific problem encountered in Roșia Poieni quarry, a site known for the hardness of its extracted rock, where the stresses on machinery are particularly severe. The present analysis will focus on the structural integrity of the main boom of a Hitachi EX1000 excavator, a representative model for this type of operation.

1.2 State of research

Research in the field of structural durability has evolved significantly, from the empirical methods initiated by August Wöhler in the 19th century to today's advanced modelling and simulation techniques. The S-N curve method (Stress-Number of cycles), also known as Wöhler curve, remains a fundamental tool for correlating stress amplitude with the number of cycles to failure [3]. However, its application in complex situations requires integrating correction factors that account for geometry, surface finish, and the working environment.

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To evaluate cumulative damage under variable loads, engineering has adopted the Palmgren-Miner linear damage rule, which sums the contributions of each stress cycle to the material's life exhaustion [4].

Currently, these theoretical methods are complemented by numerical analyses, such as the Finite Element Method (FEM), which allows for a precise determination of stress and strain distribution in structures with complex geometries [5]. Numerous studies have used FEM to model excavator components [5, 6], demonstrating its effectiveness in identifying stress concentration zones, which are the points where fatigue cracks initiate. Furthermore, the recent evolution of Condition-Based Monitoring (CBM) technologies opens up new perspectives, enabling the integration of real-time data with predictive models [7-9].

1.3 Study objectives

Through this research, we aim to address the gap between theoretical analyses and operational reality in the quarry. The specific objectives of this paper are:

Identification and characterization of critical components: The first objective is to precisely identify the structural components of large-tonnage hydraulic excavators used in Roșia Poieni quarry that are most susceptible to fatigue failure. This stage is not limited to a simple list of elements but includes a detailed justification of the risks associated with each component, based on the nature of the stresses they are subjected to in the specific working environment. The kinematic role of the main boom, the stick, the digging bucket [10,11], and the welded joints will be analysed, explaining why they represent major points of interest for structural integrity studies.

Analysis of stress and strain state via FEM: The second objective is to perform a detailed structural analysis of the Hitachi EX1000 excavator boom using the Finite Element Method (FEM). This analysis will allow for the determination of the exact distribution of stresses and strains within the structure under a representative working load. The goal is to identify stress concentration zones, which are the initiation points for fatigue micro cracks [12, 13]. The results obtained will serve as the basis for subsequent stages of durability estimation and will provide a precise picture of the component's mechanical behaviour.

Estimation of Remaining Useful Life (RUL): Based on the results of the FEM analysis, we aim to estimate the remaining useful life of the boom. This objective will be achieved by correlating the calculated stresses with the material's experimental data, using Wöhler curve (S-N curve). To ensure a realistic estimation, specific correction factors, such as those for reliability and corrosion, which reflect the quarry's operating conditions, will be integrated [14,15]. Furthermore, the Goodman diagram will be used to calculate the safety factor, providing a quantitative evaluation of the degree of structural risk [16, 17].

Design optimization and recommendations: The final objective is to formulate a set of practical and scientifically-based recommendations aimed at optimizing maintenance and extending the life of the excavators. These proposals will include predictive maintenance strategies (CBM), suggestions for optimizing the structural design in the identified critical areas, and recommendations regarding anti-corrosion protection and Non-Destructive Testing (NDT). Through carrying out these objectives, the paper aims to increase operational safety and reduce operating costs at Roșia Poieni quarry.

2. Materials and methodology

The estimation of the remaining useful life of the structural elements of excavators at Roșia Poieni quarry involves an integrated approach based on correlating the technical specifics of the machinery with real operating conditions and modern methods for evaluating structural durability.

2.1 Presentation of excavators and the working environment

The study was conducted in the operational context of Roșia Poieni copper quarry, a mining site where the dominant rock (andesite and dacite) has a hardness and abrasive nature that subjects machinery to a particularly demanding work regime. The dislodging and loading of material are carried out with high-capacity hydraulic excavators, which are essential for maintaining an intensive and continuous pace. The fleet of excavators analysed includes top models, known for their robustness in mining applications. While the quarry operates several models, including the Liebherr R 974 C Litronic and Liebherr R 9150 B, the detailed numerical analysis in this study was performed exclusively on the Hitachi EX1000 Excavator, a heavy-class tracked machine with an operating weight of approximately 90-100 tons. These are (figure 1, Table 1):

- *Hitachi EX1000 Excavator*: A heavy-class tracked machine with an operating weight of approximately 90-100 tons. It is used for loading large-tonnage dump trucks and for dislodging work in stages. Its breakout force is 709 kN.

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• *Liebherr R 974 C Litronic Excavator*: Known for its reliability in aggressive industrial environments. With an operating weight of approximately 80 tons, it stands out for its high-performance hydraulic system and integrated electronic control (Litronic technology).

• *Liebherr R 9150 B Excavator*: A modern and high-performance machine with increased digging capacity, with an operating weight of 130-140 tons and a bucket capacity of up to 8 m³.

(a)

(b)

(c)

Fig.1. Excavator types used at the Roșia Poieni quarry: (a) Hitachi EX1000 – mining class excavator; Liebherr R 974 C Litronic Excavator; (c) Liebherr R 9150 B Excavator

Table 1. Technical specifications of excavators used at Roșia Poieni quarry

Characteristic	Description
Hitachi EX1000 – mining class excavator	
Operating weight, tons	≈ 90–100
Engine	High-power diesel, water-cooled
Bucket	Backhoe type, with massive cutting teeth, adapted for hard rock
Transmission	Full hydraulic, with massive lifting cylinders
Use	Loading rock blocks into large-tonnage dump trucks
Digging depth, m	4.78
Breakout force, kN	709
Bucket width, m	2.7
Liebherr R 974 C Litronic Excavator	
Operating weight, tons	≈80
Engine power, HP	> 400
Bucket capacity, m³	Between 3.5 and 5
Chassis	Tracked, with hydraulic transmission, adapted to unstable terrain
Cab	Protected, with increased visibility for the operator
Special features	Litronic system for electronic control and real-time monitoring
Liebherr R 9150 B Excavator	
Operating weight, tons	≈130–140
Bucket capacity, m³	≤ 8
Engine, HP	Liebherr V12 diesel, with over 750 HP
Use	Frontal excavation in hard rock, under heavy-duty conditions
Hydraulic cylinders	High-force, redundant lifting system

The Liebherr R 9150 B excavator is one of the most modern and high-performance machines used in large-scale mining operations. This model is part of the heavy-duty range of the German manufacturer Liebherr and is designed to offer maximum productivity in the most demanding operating conditions, such as those encountered at Roșia Poieni quarry.

2.2 Identification of critical components

The heavy hydraulic excavators used at Roșia Poieni quarry (Hitachi EX1000, Liebherr R 974 C, and Liebherr R 9150 B) are exposed to a severe work regime, characterized by repeated load-unload cycles, mechanical shocks, and direct interaction with hard and abrasive rock. In this severe work regime, certain structural components are considered critical and become critical zones from the perspective of mechanical strength and the risk of fatigue or failure.

The identification of these zones is essential for designing inspections, estimating the remaining service life, and preventing structural failures. In the context of the structural evaluation of heavy excavators used in quarries, certain components are considered critical from the perspective of mechanical stresses, operational wear, and the risk of fatigue or crack initiation [18]. These components are recurrently identified as vulnerable zones in periodic technical inspections and maintenance reports. The main critical components are (Figure 2):

• Main boom: This is one of the most stressed structural elements of the machine. It supports the entire weight of the manipulated mass, as well as the shocks generated during the bucket's action on the rock. Furthermore, it is subjected to alternating cyclic tensile and compressive stresses, which makes it prone to structural fatigue. Stress concentration zones are usually in the area where it is attached to the platform and around the articulation of the hydraulic cylinders;

• Stick: This element works in tandem with the main boom and is responsible for the bucket's movement. It is exposed to torsional forces and variable moments during the work cycle. In particular, the articulation area with the bucket and the connection to the main boom are subjected to concentrated forces, which can eventually lead to the appearance of fatigue cracks, especially near welds;

• Excavation bucket: This is the component that comes into direct contact with the excavated material, exposing it to severe abrasive wear and repeated impacts. The side corners, the teeth area, and the welds of the bucket bottom are the most vulnerable. Bucket deterioration not only affects productivity but can also lead to the irregular transmission of forces to the rest of the structure, amplifying the stresses on the booms and articulations;

• Welded joints and HAZ (Heat Affected Zone) areas: In the case of heavy excavators, welds are not just fastening elements but are part of the load-bearing structure. The thermally affected zones (HAZ), especially where materials of different thicknesses meet or where the weld is subjected to constant vibrations, become critical points for crack initiation;

• Undercarriage (track frames and support crossbars): Although it seems like a passive element, the chassis supports not only the machine's total weight but also the dynamic forces transmitted by moving on rough terrain. Critical areas are the rigid corners, transverse welds, and the anchoring points of the mobile components, where cracks or local plastic deformations frequently appear.

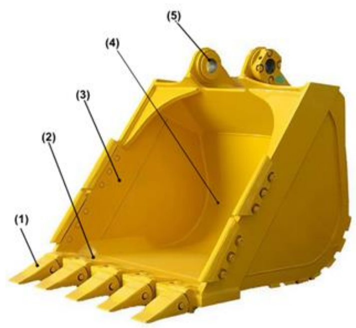

Fig.2. Main components of the excavation bucket: (1) bucket tooth; (2) tooth holder; (3) bucket wall; (4) bucket shell; (5) bucket attachment pin

These components are considered critical not only because of direct mechanical stresses but also because they represent control points for the machine's overall integrity. Any structural defect in these areas can lead to a significant decrease in the equipment's service life, economic losses, and, more seriously, accident risks during operation [19].

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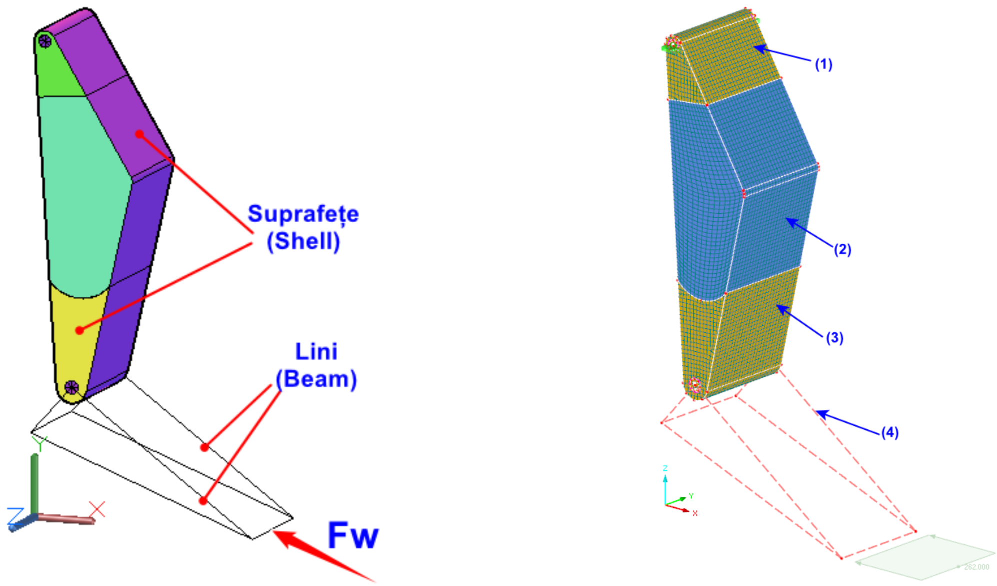
2.3 Numerical analysis methodology (FEM)

Geometric model and discretization

To evaluate the stress state, we used the Finite Element Method (FEM), considered the fastest calculation method for complex structures [10, 11]. Modelling was performed on the boom of the Hitachi EX1000 excavator. The CAD model (figure 3), with a complex geometry, was created in a hybrid form, using:

• Shell elements to represent the thin welded plates of the boom. This choice optimized calculation time while maintaining the accuracy of the analysis;

• Rigid beam elements to simulate the kinematic link and the bucket's action without introducing unnecessary deformations.



(a) (b)

Fig.3. CAD-FEA model of the boom (a) and hybrid CAD-FEA modelling of the boom with highlighted element types: 1 - Discretization with quadrilateral shell elements, 40 mm thickness; 2 - discretization with quadrilateral shell elements, 20 mm thickness; 3 - discretization with quadrilateral shell elements, 40 mm thickness; 4 - rigid elements, bucket modelling

Loading and Boundary Conditions

During the operation of heavy machinery, structural components are subjected to cyclic loads, which vary in time and direction, caused by: hydraulic actuation, self-inertia, contact with the ground or rocks, as well as interaction with other components of the kinematic system. For this reason, a simple static analysis is not sufficient for evaluating long-term structural safety, and an integrated approach that also includes fatigue behaviour is necessary.

During the work cycles, the boom represents one of the most stressed structural elements of the excavator (position 5 on figure 4), being the component that directly transmits the mechanical forces generated by the hydraulic cylinders to the bucket and, implicitly, to the mass of excavated material.

Due to these complex stresses, the boom becomes a critical zone from the perspective of material fatigue and the risk of crack initiation or permanent deformations. For this reason, it is essential to perform a detailed analysis of the stress state in this component, under real operating conditions, to evaluate long-term structural behaviour.

For the structural analysis, the geometric model of the Hitachi EX1000 excavator boom, located in its active working position, in contact with the ground, was used. This position corresponds to the standardized configuration according to SAE J/ISO 6015 [20] for determining the breakout force, thus representing a critical case from a structural point of view. The FEM analysis was performed under a static load, representative of the critical breakout moment. The total breakout force, specified by the manufacturer, is F=709 kN, oriented tangentially to the bucket's working trajectory, in the XY plane. This force is applied over the bucket's width of 2.7 m, transmitting to the structure through the rigid kinematic connection of the bucket to the boom, in the form of a distributed load (q=262 kN/m), according to the relation:

$$q = \frac{F}{l}\text{, kN/m} \tag{1}$$

Fig.4. Critical working position of the boom with the action of the force Fw

The upper attachment points of the boom were considered fixed, simulating its attachment to the main frame of the excavator.

Through this analysis, we aim to identify stress concentration zones, determine the maximum values of mechanical stresses, and estimate the remaining service life based on the fatigue (S-N) curves and operational history. This approach contributes to substantiating predictive maintenance decisions, preventing failures, and optimizing work cycles in the operation of large-tonnage mining machinery [21, 22]. By using the finite element method, stress and strain distributions can be determined in various work scenarios, allowing for the localization of critical points and the evaluation of the influence of various load configurations. These results form the basis for estimating the number of cycles to failure, by correlation with the material's S-N curve, obtained from standard or experimental data.

Furthermore, this analysis can be used as a practical methodology for establishing the optimal locations for strain gauges, with a view to correlating numerical data with experimentally obtained data. Thus, based on the stress and strain distribution obtained in the FEM analysis, the positions where strain sensors should be applied for real-time monitoring of stresses in operation can be selected [10, 11, 16]. By taking data from the strain gauges and evaluating the specific deformations, it is possible to experimentally estimate the number of cycles supported by the structure until a critical fatigue state is reached. This approach then allows for re-plotting the Wöhler curve in a specific real context and correlating it with the actual number of operating hours of the machine [23, 24]. Therefore, the proposed analysis not only has a predictive role but also becomes the basis for an integrated methodology for experimental validation and advanced diagnosis [25,26], applicable in the context of predictive maintenance alongside non-destructive testing for the excavator.

2.4 Fatigue analysis methodology

Foundation of Wöhler curve

In the case of mechanical structures subjected to repeated loads, reliability is deeply linked to fatigue behaviour—that is, how the material reacts to successive cycles of stress below the yield strength. To estimate the service life, Wöhler curve (S-N curve) was used, which correlates alternating stress (σa) with the number of cycles (N) to failure [24]. The design stress was extracted from the FEM analysis results, considering the maximum and minimum stress in a work cycle:

$$\sigma_a = \frac{\sigma_{\max} - \sigma_{\min}}{2}$$
$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2} \tag{2}$$

Palmgren-Miner cumulative damage method

This method was applied to evaluate the cumulative damage, considering cycles at different stress levels.

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} \tag{3}$$

where: D - cumulative damage; n_i - the number of actual cycles at stress level i; N_i - the number of cycles to failure at stress level *i*, obtained from the Wöhler curve. Failure occurs when D=1.

Correction factors

For a realistic estimation, the material's fatigue strength was adjusted with correction factors that account for real operating conditions, according to the equation:

$$\sigma_a = \sigma_e \times C_{load} \times C_{form} \times C_{size} \times C_{surf} \times C_{temp} \times C_{reab} \times C_{Rz} \times C_{cor} \tag{4}$$

where: σ_e - fatigue strength for a standard sample; C_{load}=1 (loading factor); C_{form}=0.699 (form factor); C_{size}=1.0762 (size factor); C_{surf}=0.675 (roughness/surface factor); C_{temp}=1 (temperature factor); C_{reab}=0.753 (reliability factor); C_{Rz}=0.727 (roughness factor); C_{cor}=0.896 (corrosion factor).

In fatigue analysis, Wöhler curve (S-N) is usually established for ideal laboratory samples with a perfectly finished surface and under simple loads. In reality, a structural component like an excavator boom operates under much more complex conditions, which reduce its service life [23,26]. Therefore, these correction factors are applied to obtain a more accurate estimate.

Goodman diagram

To supplement Wöhler curve, Goodman diagram can be used, which is an essential graphical tool for verifying the safety of elements subjected to alternating stresses in the presence of a mean stress. The Goodman diagram correlates the mean stress (σ_m) and the stress amplitude (σ_a) to determine if a combined stress is safe or leads to fatigue. The Goodman line limits the safe operating range for a given material. This diagram is particularly important in applications where there is a static stress component (e.g., self-weight or constant pressure) combined with a variable stress. Using Goodman diagram together with Wöhler curve allows for establishing the service life and an adequate safety margin.

By integrating these two tools—Wöhler curve and Goodman diagram—the durability of the studied element can be evaluated under real operating conditions, and it can be decided whether the boom meets the required reliability criteria [2,24]. To evaluate the fatigue behavior of the excavator boom, three fundamental graphical representations in materials resistance engineering were created: adjusted Wöhler curve, Goodman diagram, and the influence of correction factors on fatigue strength.

3. Results and Discussions

3.1 FEM results analysis

The finite element analysis of the boom provided a detailed picture of the structure's mechanical state under critical load. We extracted two key sets of results: stress distribution and strain distribution.

Stress state

The distribution of equivalent Von Mises stresses (σ_{xy}) in the boom's plane is presented in Figure 5. The colour map clearly shows the stress concentration zones (red and orange marks), located predominantly in the upper corners of the structure and in the intersection zones of the welded panels. This concentration is typical for geometric discontinuities and local stiffness variations. The maximum stress values reach 207 N/mm² in these points, while the median areas of the panels show much lower stress levels (below 200 N/mm²). This distribution suggests that loads are transmitted mainly through the edges and corners of the "stiffened box" type structure.

Strain State

The distribution of strains in the u_x direction (along the force's action axis) is illustrated in Figure 6. A global deformation of approximately 50 mm is observed at the boom's lower extremity. This value, although notable, falls within the expected elastic behaviour of a beam with a variable cross-section. The deformation

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shape is consistent with the force's mode of action, confirming the assembly's good rigidity. However, the high strain gradient in certain areas indicates a "bending-twisting" behaviour, which can lead to long-term fatigue risk.

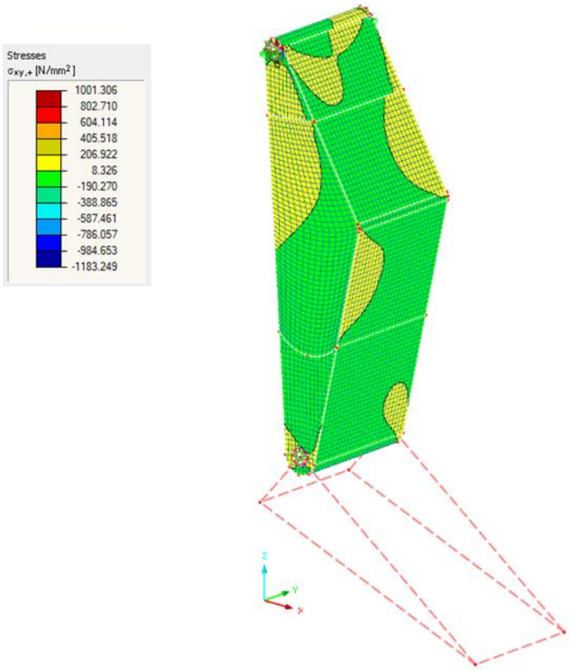

Fig.5. Stress state in the boom

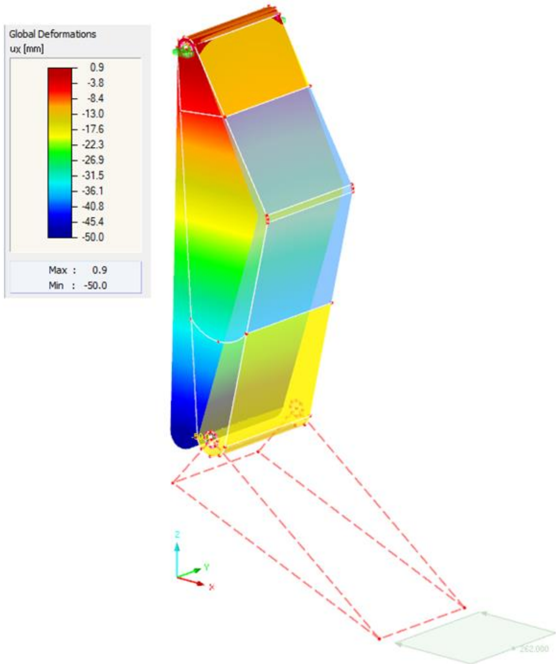

Fig.6. Deformed shape of the boom

3.2 Fatigue durability evaluation

To plot Wöhler curve (S-N curve) for the excavator boom (or for any component subjected to fatigue), the design stress is chosen based on the type of analysis and the evaluation's purpose. To evaluate the long-term structural behaviour, the FEM analysis results were correlated with fatigue resistance principles. The stress σ_a is a fully reversible stress that can reach a maximum value of 207 N/mm² and a minimum value of −190 N/mm². The alternating stress (σ_a) was calculated based on the maximum and minimum stresses in a complete work cycle:

$$\sigma_a = \frac{\sigma_{\max} - \sigma_{\min}}{2} = \frac{207 - (-190)}{2} = 198.5\ N/mm^2$$
$$\sigma_m = \frac{\sigma_{\max} + \sigma_{\min}}{2} = \frac{207 + (-190)}{2} = 8.5\ N/mm^2 \quad (5)$$

Adjusted Wöhler curve for reliability and corrosion factors

Wöhler curve (S-N curve) was adjusted with the correction factors mentioned in Section 2.4.3 to reflect the operating conditions. The resulting graph (Figure 7) represents the relationship between fatigue strength (σ_a) and the number of cycles to failure (N). A critical point corresponding to an alternating stress σ_a=198.5 MPa, considered the current stress value in the analysed structure, is marked on it. From the intersection of this stress with Wöhler curve, an estimated service life of N≈3.98×10^4 cycles were obtained.

This limited number of cycles places the boom in the high-cycle fatigue regime, suggesting a reduced durability. The finding highlights that, under current conditions, the structure could fail prematurely if no geometric optimizations or supplementary protections are implemented. The estimated mean time to failure (MTBF) is 4457.14 hours, which underscores a potentially shorter service life under the current stress conditions.

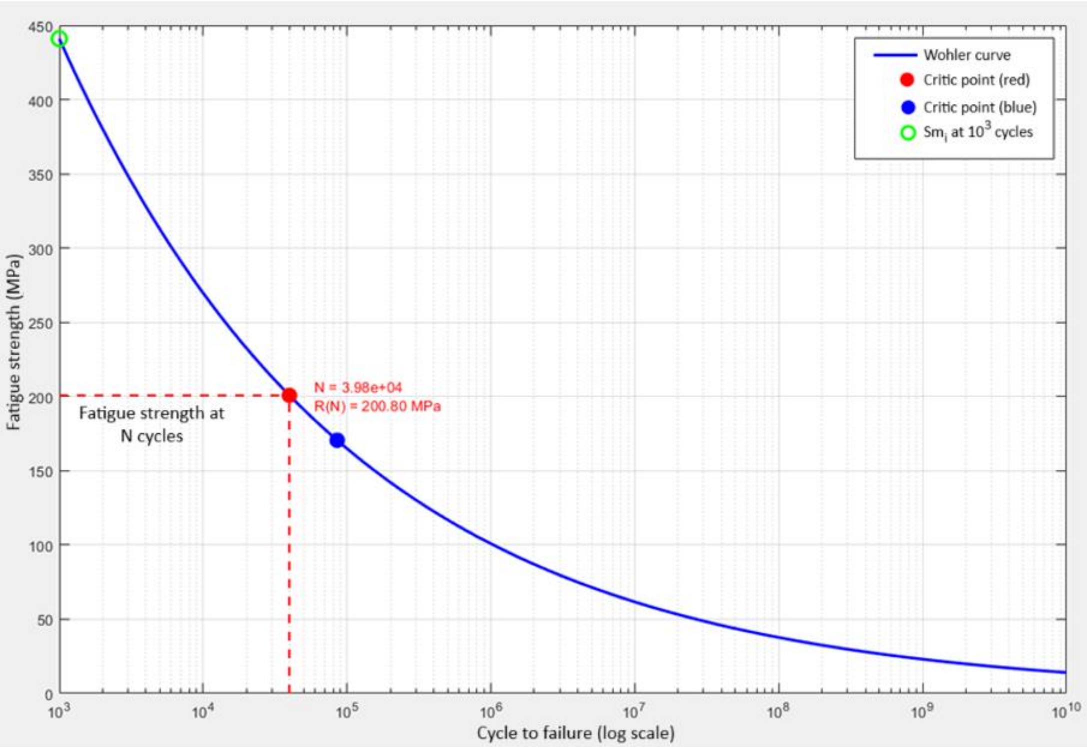

Fig.7. Wöhler curve adjusted for reliability and corrosion factors

Goodman Diagram and Safety Factor Calculation

Using the Goodman diagram, we evaluated the boom's safety under variable load, considering both the mean and alternating stresses (figure 8). The operating point (100 MPa, 150 MPa) was placed on the diagram relative to the critical failure line. The safety factor (SF) was calculated according to the relation:

$$SF = \frac{\sigma_e}{\sigma_a \times \left(1 - \frac{\sigma_m}{R_m}\right)} \quad (6)$$

With the provided values (σ_a=150 MPa, σ_e=180 MPa, σ_m=100 MPa, R_m=510 MPa), the SF is 1.49.

The alternating stress value of 150 MPa was used in this calculation to represent a more typical, repetitive operational load, rather than the extreme stress peaks used for Wöhler curve analysis. This value is close to the minimum admissible limit for dynamic applications (1.5), indicating that the part operates in a potentially unsafe regime and needs re-evaluation.

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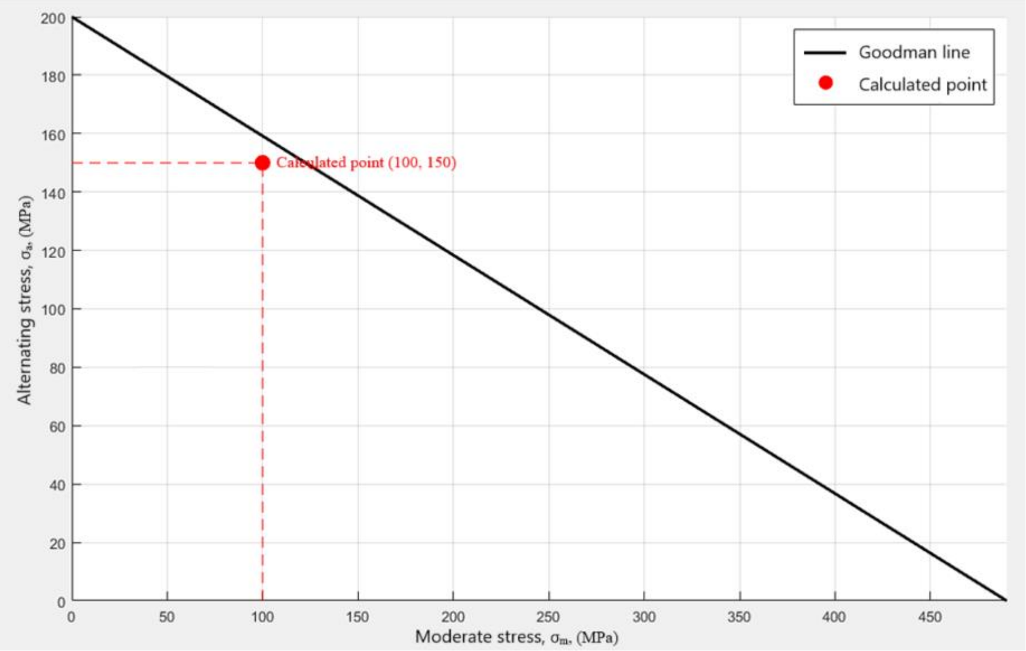

Fig.8. Goodman diagram with safety factor calculation

Influence of environmental factors

The variation of fatigue strength was analysed as a function of reliability (k_{fi}) and corrosion (k_{cor}) factors. The results show a 15-20% decrease in durability due to these factors. This finding underscores the significant importance of anti-corrosion protection and preventive maintenance. The resulting values are k_{fi}=0.924, obtained after 350 hours of operation, and k_{cor}=0.935, determined after 20 years of exposure to a C4 type corrosion environment, according to [27].

4. Conclusions

This study provided a detailed and comprehensive analysis of the structural durability of an excavator boom, using an integrated approach. This combined the theoretical foundation of the Remaining Useful Life (RUL) concept with advanced numerical analysis methods (FEM) and reliability principles (Wöhler curve, Goodman diagram), allowing for a realistic assessment of the risks and service life of critical components.

Main results:

- Risk identification: The FEM analysis confirmed that the Hitachi EX1000 excavator boom is subjected to a critical stress regime, with significant stress concentrations in connection and welding zones.
- Limited service life: The correlation of FEM results with the adjusted Wöhler curve highlighted a limited durability. The estimated number of cycles to failure, approximately 3.98×10^4, places the component in the high cycle fatigue regime, indicating a potentially short service life under current operating conditions.
- Critical Safety Factor: The calculation based on Goodman diagram showed a safety factor of 1.49. This value, which is below the minimum recommended threshold (1.5) for dynamic applications, confirms that the boom operates in a potentially unsafe regime.
- Impact of environmental factors: it was demonstrated that reliability and corrosion factors reduce fatigue strength by 15-20%, emphasizing the major impact of environmental conditions on structural durability.

Recommendations and future perspectives: Based on the results obtained, the following recommendations are necessary to optimize maintenance and increase operational safety:

- Implementation of predictive maintenance (CBM): it is proposed to install state monitoring systems, including strain and vibration sensors, in the critical areas identified by the FEM analysis. This will allow for the early detection of fatigue cracks and the proactive scheduling of repairs, avoiding catastrophic failures;
- Structural design optimization: To increase the safety factor, it is recommended to re-evaluate the boom's design. This could include increasing the material thickness in maximum stress zones or adding supplementary local stiffeners for better stress distribution;
- Rigorous inspection programs: The frequency and rigor of Non-Destructive Testing (NDT), especially with liquid penetrants and ultrasound, must be intensified in welding zones and connection points;

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• Improved anti-corrosion strategies: Given the significant impact of corrosion, it is recommended to use and consistently maintain high-performance industrial painting systems (class C4 or higher) and to promptly recondition affected areas;

• Personnel training: Operating and maintenance personnel must be continuously trained on the importance of adhering to work regimes, early detection of wear signs, and correct application of inspection and repair procedures.

Future research will focus on an analysis based on real dynamic loads, which will provide a more precise prediction of service life, and on integrating real-time data from operating conditions to validate and perfect predictive models. By implementing the proposed recommendations, the operational safety and service life of mining machinery can be significantly increased, directly contributing to reduced costs and optimized production processes in the quarry.

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