

Residual Life Prediction of Railway Axle: A Review

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ABSTRAK

Meskipun dirancang untuk beroperasi selama lebih dari 30 tahun, poros roda kereta api sering mengalami kerusakan selama masa penggunaannya. Kerusakan dapat terjadi akibat pengaruh lingkungan, benturan benda asing, atau ketidaksempurnaan material. Makalah ini memberikan gambaran tentang kerusakan umum yang sering terjadi pada poros roda kereta api dan membahas model perhitungan pertumbuhan retakan kelelahan yang digunakan untuk menganalisis umur sisa, serta parameter yang mempengaruhi kegagalan kelelahan pada poros roda kereta api. Kemudian, studi terkait prediksi umur kelelahan yang telah dilakukan oleh beberapa peneliti telah ditinjau. Studi-studi tersebut menunjukkan bahwa penting mempertimbangkan berbagai variasi data saat melakukan perhitungan untuk menghasilkan hasil yang akurat dan dapat diandalkan.

Kata Kunci: fatigue poros kereta api, Prediksi umur sisa, Perambatan retak

ABSTRACT

Despite being designed to operate for over 30 years, railway axles often experience damage during their service life. Damage can occur as a result of environmental influences, impact from foreign objects, or inherent material imperfections. This paper provides an overview of common damages that frequently occur in railway axles and discusses the fatigue crack growth calculation models used to analyze their remaining life, as well as the parameters that influence fatigue failure in railway axles. Then studies related to fatigue life prediction that has been conducted by several researchers are reviewed. The studies showed that it is important to consider several data variabilities when performing the calculation to produce accurate and reliable results.

Keyword: Railway axle fatigue, Residual life prediction, Crack propagation

1 INTRODUCTION

The railway axles hold a pivotal role in maintaining the safety of railway transportation. Failures in axles can impose significant hazards on human safety, the environment, and can lead to substantial economic losses. The design of railway axles is typically intended for operation over a period exceeding 30 years [1]. This is achieved through the implementation of a nominal stress approach, wherein the applied stress is limited to below the fatigue threshold of the material. The purpose of this approach is to inhibit the growth of fatigue cracks throughout the axle's service life, ensuring its longevity and reliability. However, during its service life, railway axles are often susceptible to damage caused by operational factors such as high loading cycles, varying load amplitudes, corrosive environments, and manufacturing process-related defects.

Several common damages found in railway axles are defects such as inclusions, indentations due to impacts, corrosion pits, scratches, and fretting. Firstly, inclusions are one of the defects commonly found in railway axles, which can occur during the metal manufacturing process. Murakami [2] discovered in his research that the decrease in fatigue strength due to non-metallic inclusions depends on the size and location of these inclusions within the material. Secondly, defects in the form of impact and corrosion can occur during operation. According to statistical data, around 30% of axles on high-speed trains are known to suffer damage due to impacts from Flying Ballast [3]. In the literature, this type of damage caused by impact is also known as foreign object damage (FOD). Zerbst et al., [4] conducted a study on foreign object damage (FOD) caused by flying ballasts of various sizes on axles with processed surfaces at speeds similar to the actual operational condition. The

investigation found that fatigue crack initiation and propagation occurred due to sharp corners and stress concentration caused by FOD. Additionally, coating damage could trigger corrosion, further exacerbating the condition of the axle and increasing the risk of fatigue failure. Lastly, defects such as scratches, indentation marks, and fretting can occur when removing and installing wheels or bearings on the axle. Fretting can cause microcracks to appear on the contact surface due to combined pressure and friction. The fretting mechanism on railway axles has been investigated [5]. Fatigue cracks are initiated at the weakest point located in the vicinity of the wheelset edge [6][7]. At a certain size, these defects can initiate the appearance of fatigue cracks. Defects will become the starting point for fatigue cracks on the axle, where crack growth occurs gradually due to continuous stress and repeated load cycles. If fatigue cracks are not detected, they will continue to grow and potentially lead to failure.



Fig.1 Appearance of damaged railway car [8]

The failure of railway axles due to crack initiation caused by corrosion pits was reported by Odanovic [9], in which the railway car used to transport coal from the mining site to the power plant experienced a broken axle. In Indonesia, the National Transportation Safety Committee [8] investigate the broken railway axle of a coal-carrying freight train. The investigation found that there were scratches caused by hard stamping, which initiated the fatigue cracks. On July 9, 2008, the drive wheel axle of an ICE3 train broke as the train was leaving Cologne Station in Germany, causing the train to derail. As a result of the accident, the ultrasonic testing (UT) interval for the wheel axles on ICE3 trains was significantly shortened. [10].

To detect fatigue cracks early and prevent failures due to crack growth, inspection intervals must be accurately determined. Crack growth calculations are used to assess the remaining technical life of railway axles. For instance, Zhang [11] calculated the remaining life of a hollow shaft on a high-speed train that had surface defects artificially introduced. This fracture mechanics approach estimates the crack growth rate induced by stress in the material and can be implemented numerically using deterministic and/or probabilistic methods, including the latest computer simulations. Section 5 will provide a more detailed discussion.

This paper addresses the crack mechanisms and procedures for predicting the remaining service life of railway wheel axles, with the aim of determining the optimal inspection interval and identifying factors contributing to fatigue failure of railway wheel axles. In conclusion, several valuable notes and recommendations related to the topic are presented.

2 METHOD

The writing of this article involves collecting literature discussing fatigue failure analysis and methods for calculating residual life in railway axle shafts. The process of writing this article follows steps as illustrated in Figure 2.

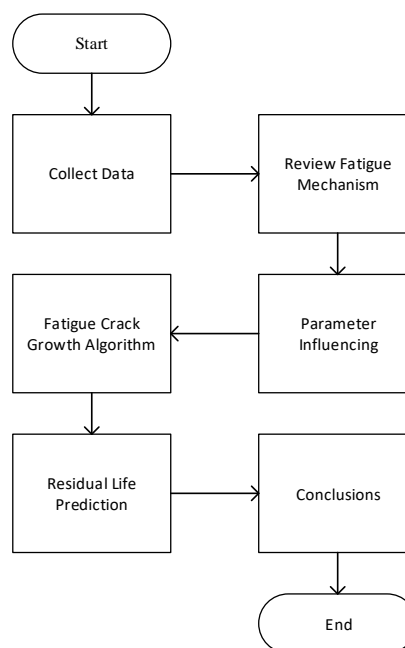


Fig. 2. Methodology

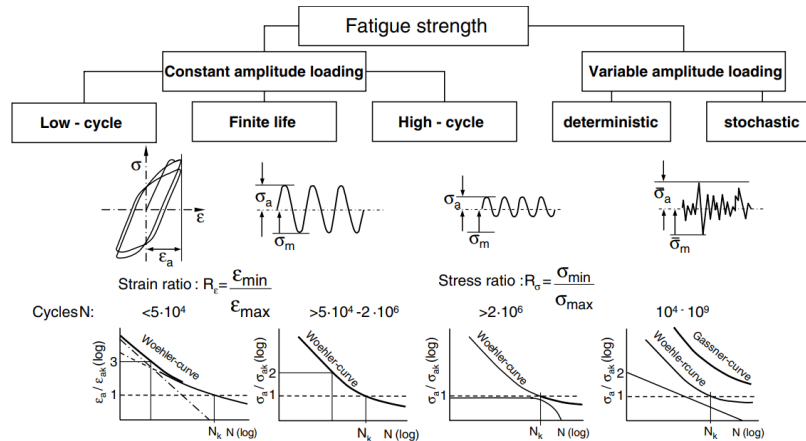


Fig. 3. Regions of fatigue strength; according to [12]

This review article is structured through three main steps. Firstly, the collection of relevant data from various sources, including papers, literature, and international standards related to railway axle fatigue. Secondly, a review of fatigue failure theories encompassing crack propagation factors and methods for calculating the residual life of railway axles. Lastly, summarizing the studies conducted in predicting the remaining life of railway axles.

3 REVIEW FATIGUE MECHANISM

3.1 The Endurance Limit Concept

The concept of "endurance limit" or "fatigue strength" is still widely used in design regulations, assuming that a structural element will not fail as long as this limit is not exceeded [1]. However, recent studies indicate that reduction in fatigue strength as the number of load cycles increases, especially in the high-cycle range exceeding 10^7 cycles. Fatigue strength is divided into several different regions, as shown in Figure 3.

The concept of fatigue limit on the S-N curve is a demarcation point where cracks will not initiate, ensuring that the potential for catastrophic failure due to cracks is eliminated. It's important to remember that the true essence of the fatigue limit lies not in the "absence of" cracks, but rather the arrest of cracks (as explained in section 2.3). Sonsino [12] has introduced an approach to modify the slope of the Wöhler curve ahead of the "endurance limit" knee point to avoid material and component failure. Furthermore, this paper elucidates the correction factors for the gradient of the Wöhler curve across various metallic materials.

3.2 The Crack Propagation Threshold ΔK_{th}

Cracks in a material will not experience significant propagation as long as they are subjected to loads below a certain threshold. This threshold value is known as the crack propagation threshold or threshold stress intensity factor (SIF). The value of the threshold depends on the material properties, environmental conditions, geometry, and R ratio (maximum stress/minimum stress). A general discussion of this issue can be found in [13]; see Figure 4.

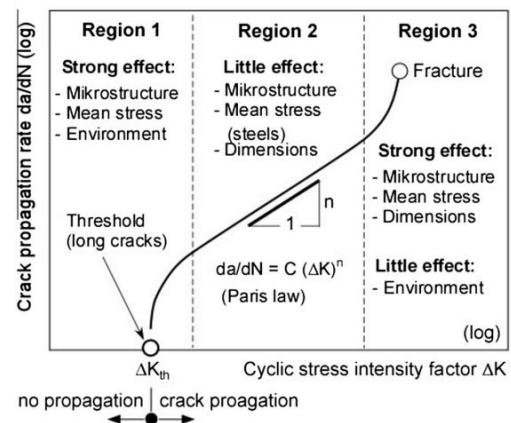


Fig. 4. The $da/dN-\Delta K$ diagram, which is used to depict the propagation of fatigue cracks, is comprised of three distinct regions; according to [13].

Region I in fatigue mechanics refers to the initial stage of crack growth. In this region, there exists what is known as the fatigue crack growth threshold, represented by the symbol ΔK_{th} . Under these conditions, cracks will not propagate as long as the stress intensity factor remains below this threshold. Although other factors may also affect the value of ΔK_{th} , the stress ratio is the most important factor influencing it, based on available data.

Region II represents a region of crack growth where the linear elastic fracture mechanics (LEFM) concept can be employed to analyze this zone. The effect of mean stress in this area is usually the most critical.

Region III is characterized as the crack propagation fatigue zone, where the propagation rate is very high due to the nature of rapid and unstable crack growth, ultimately leading to final failure. Analyzing fatigue crack growth in this region is complex and often overlooked due to the exceedingly rapid crack propagation rate and minor contribution to fatigue life curve.

Bretta et al. [14] carried out a study in which they investigated the crack propagation threshold in high-strength steel specimens used for high-speed train wheel axles. The objective of the experiment was to determine the fatigue threshold for small cracks and to use the findings to analyze the fatigue strength of the full-scale axle.

3.3 Stages of Fatigue Crack Initiation and Propagation

A cycle of a crack comprises five sequential stages : crack initiation, short crack propagation (microstructural and mechanical), long crack propagation, and final crack leading to failure of the structure [15].

3.3.1 Fatigue Crack Initiation

Crack initiation commonly takes place as a result of micro-defects present in the material, like inclusions or surface defects. Under applied loads, these defects create areas of localized stress concentration that exceed the surrounding stress levels, leading to localized plastic deformation in the form of slip bands. Slip bands act as precursors to crack formation and develop during cyclic loading, with dislocation mechanics playing a significant role in the material's fatigue behavior. The response of dislocations is highly dependent on temperature, slip character, and the applied strain amplitude [16].

3.3.2 Propagation of short cracks

The stage of short crack propagation occurs when a crack, formed during the initiation stage, reaches a specific size and exhibits a distinct growth pattern compared to the initial crack. Short cracks are often influenced by the microstructural properties of the material, leading to unique growth mechanisms. The crack propagation rates $da/dN-\Delta K$ curve, observed in

short cracks cannot be adequately explained by Linear Elastic Fracture Mechanics (LEFM). The crack crosses several grains, showing a typical zigzag pattern and potentially resulting in geometrically induced crack closure (geometrically induced crack closure).

At the microstructural level, the propagation of short cracks is influenced by grain boundaries and phases that act as obstacles to slip transmission in adjacent grains. This leads to an unstable growth rate of the cracks. Künkler [17] and Krupp [18] developed numerical models to predict the behavior of microstructurally influenced short crack propagation by employing the principles of elastic-plastic fracture mechanics (EPFM). Other modeling approaches addressing short fatigue cracks affected by grain boundaries can be found in [19].

Although there are various distinct micromechanical modeling approaches to depict the growth of short fatigue cracks, it is not feasible to encapsulate all the aspects and intricacies within a single model. The various modeling approaches display different trends, with some focusing on detailed physical explanations of the crack propagation process using experimental approaches, while others concentrate on developing models for application in real or virtual microstructures closely linked to experimental research through simulations. Therefore, some researchers use the microstructurally short crack (MSC) growth model with the crystal plasticity finite element method (CPFEM) approach [20].

Crack closure phenomena are observed during the mechanical propagation stage of short cracks. These closure effects can be attributed to different mechanisms, including plasticity-induced, roughness-induced, and oxide-induced mechanisms. Detailed discussions on these mechanisms can be found in the cited sources, such as [21] for a concise overview and [22][23][24][25] for in-depth analyses. In a recent study by Paysan [26], simulations were carried out to investigate crack closure mechanisms influenced by plasticity using a three-dimensional finite element method. The 3D finite element EPFM model was employed to accurately capture the three-dimensional aspects of crack closure. Figure 5 presents a visual representation illustrating the diverse mechanisms responsible for crack closure.

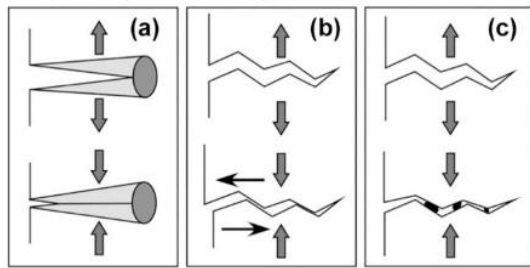


Fig. 5. Crack closure phenomena (a) plasticity-induced ; (b) roughness-induced and (c) oxide-induced; according to [13]

(a) Plasticity-induced

During cyclic loading, as a crack propagates, the material ahead of the crack tip experiences plastic deformation due to the high stress concentration. This plastic deformation induces a region of compressive residual stress in front of the crack tip, opposing the tensile stress responsible for crack growth. As a result, the crack surfaces come into contact and undergo partial closure, leading to a reduction in the effective stress intensity factor. This closure phenomenon effectively retards or even halts the progression of the crack.

(b) Roughness-induced

The surface roughness of a crack significantly retards or arrests crack propagation. This phenomenon is attributed to the existence of plastic deformation regions within the surface asperities of the crack, which generate compressive residual stresses upon contact of the crack surfaces during loading cycles. These compressive residual stresses act in opposition to the tensile stress that drives crack growth.

(c) Oxide-induced

This mechanism is attributed to the formation of an oxide layer on the crack surfaces, resulting in a delay in crack opening and premature closure during cyclic loading.

3.3.3 Long Crack Propagation

The stage of long crack propagation is reached when the crack growth rate becomes stable and is no longer dependent on the crack size. In this stage, crack propagation can be described using the $da/dN-\Delta K$ curve, but it needs to be corrected by considering the crack closure phenomenon, expressed as the $da/dN-\Delta K_{eff}$ curve ($\Delta K_{eff} = K_{max} - K_{op}$). In this curve, ΔK_{eff} represents the effective stress intensity factor that accounts for the effect of crack closure on crack propagation. By considering the crack closure

phenomenon, the $da/dN-\Delta K_{eff}$ curve provides a more accurate estimation of the crack growth rate during the stage of long crack propagation. The value of K_{op} can be determined either through experimental testing on specimens (refer to [22]) or theoretically through finite element analysis [26][27].

Freitas [28] conducted an experimental study to explore the effect of steady torsion on the fatigue crack growth in a shaft under cyclic bending loading, similar to a railway axle. The study demonstrated that the mechanism of long crack propagation in the shaft can be estimated using the Paris-law model, which correlates the data of long crack growth under mixed-mode loading conditions. Additionally, the J-integral approach was employed to predict the growth of short mechanical cracks.

3.3.4 Fracture

The fracture or failure stage occurs when the crack has reached critical dimensions that depend on the geometric factors of the component, material strength, and applied load. At this stage, the component material loses its integrity and can no longer function as intended. The exact criteria for failure may be less significant because during the final stage of fatigue crack propagation, crack growth occurs very rapidly, resulting in minimal differences in remaining life between different definitions.

4 THE RESIDUAL LIFETIME OF A RAILWAY AXLE IS IMPACTED BY VARIOUS PARAMETERS

The estimation of remaining life in railway axles requires consideration of several parameters that influence crack propagation in these axles. In the following section, some of those parameters are presented and discussed, namely material properties, fatigue crack propagation threshold ΔK_{th} , load ratio, press-fit loading, mixed mode loading and sequence loading effect and initial crack geometry.

4.1 Material Properties

The crack propagation threshold is influenced by material properties such as tensile strength, shear strength, and flexural strength. Stronger materials typically exhibit higher crack propagation thresholds due to the increased stress required to initiate crack propagation. The discussion on the influence of railway axle materials on Crack Growth Rate (CGR) curves and stress intensity factor ΔK can be found in [29][30].

These values are determined experimentally using the K reduction test method as described in ASTM E647. Figure 6 shows two characteristic crack growth rate curves of different materials 25CrMo4 and 34CrNiMo6.

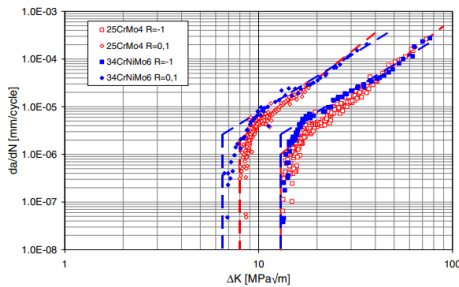


Fig. 6. A comparison of the data regarding the propagation of cracks in 25CrMo4 and 34CrNiMo6 materials is presented at R values of -1 and 0.1; according to [30].

4.2 Fatigue Crack Propagation Threshold ΔK_{th}

In simple terms, ΔK_{th} represents the threshold stress intensity factor that triggers crack propagation. However, in reality, the ΔK_{th} threshold exhibits variability, and the cyclic stress intensity factor ΔK_{th} is dependent on the crack depth. This is illustrated in Figure 7. The $\Delta K_{th,op}$ value increases progressively with the crack extension Δa as the crack initiates propagation, until a point of stability is reached, where the closure effect is no longer dependent on the crack size a or the crack extension Δa .

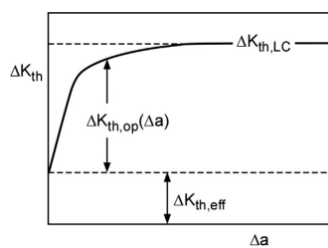


Fig. 7. The schematic diagram illustrates the dependence of the threshold of the stress intensity factor range ΔK_{th} on the crack extension Δa ; according to [31].

In this context, it is important to consider that the influence of cyclic loading on crack propagation depends not only on the load amplitude but also on varying crack depths. However, in the analysis of crack propagation, the threshold value ΔK_{th} can be obtained from the BS7910 and EN standard. Nevertheless, it

should be noted that the implications of using this threshold value may result in a highly conservative approach.

Recently, Cervello [32] reported the results of a research study conducted by the European Association of Railway Wheelset Manufacturers regarding stress concentration values. The study was carried out on full-scale railway axles. In his paper, Cervello compared the latest experimental findings with the existing EN standards.

4.3 Load Ratio

The load acting on a railway axle consists of two types: bending loads and axial loads. Bending loads are caused by the vehicle's mass influenced by gravitational force and exacerbated by dynamic effects such as track irregularities or out-of-round wheels. On the other hand, axial loads are generated from curvature on curved tracks or impacts at crossings or intersections. Furthermore, the axle is subjected to stresses induced by press-fit. Although this does not impact the stress intensity factor ΔK , it does influence the R-ratio ($R = K_{min} / K_{max}$). Figure 8 illustrates the value of K_{max} when the crack position on the axle is located at the 12 o'clock position, while K_{min} is at the 6 o'clock position.

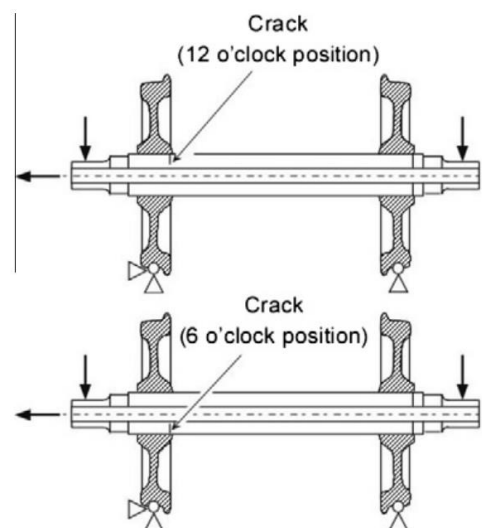


Fig. 8. The bending moments of maximum and minimum magnitude that occur during a single loading cycle; according to [33]

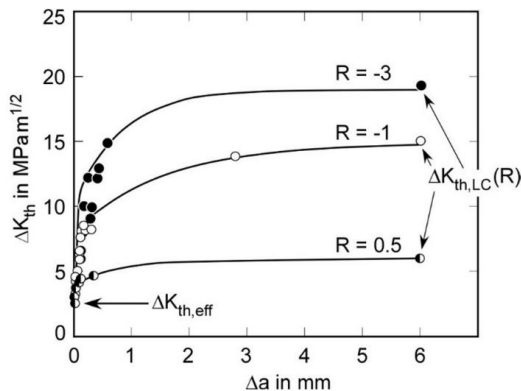


Fig. 9. Example of cyclic R-curves for varying load ratios R; according to [31]

Figure 9 demonstrates the impact of various load ratios ($R = -3, -1, 0.5$) on the behavior of 25CrMo4 steel. It is observed that the threshold stress intensity factor ($\Delta K_{th,LC}$) for long cracks decreases with an increase in the load ratio. This indicates that higher load ratios result in a reduced threshold for crack propagation, highlighting the significance of load ratio considerations in assessing the fatigue performance of the material.

4.4 Press-Fit Loading

The press-fitting process induces a combination of tensile and compressive stresses. During press fitting, the localized load generates compressive forces, resulting in compression in that specific region. However, at adjacent geometric transition surfaces, such as T transitions, the stress distribution can transition to tensile due to the changes in shape and load direction in that area. Madia [34] presents the findings of an investigation into the influence of press-fit on T-position cracks. The results indicate an acceleration in crack propagation, accompanied by a reduction in residual life by approximately thirty percent when compared to analyses that do not consider the press-fit effect.

4.5 Mixed Mode Loading and Sequence Loading Effect

When determining the stress intensity factor, it is typically customary to only consider cracks in mode I. However, in the case of railway axles, where semi-elliptical surface cracks experience compressive loads, mode II and III loading can occur, especially in the T-zone. As a result, when dealing with axles containing cracks in the press-fitted region beneath the wheel seat and at T-transitions, it becomes crucial to account for

the contributions of mode II and III components in the solution. The prediction of the remaining life was found to be 26% greater when the contribution of mixed modes was disregarded [33].

In scenarios involving variable amplitude loading, the variation in stress magnitudes can impact the rate of crack propagation, depending on the sequence of these stress cycles. In situations where there is a high peak load during a period of constant amplitude, the crack growth rate following a tensile overload (OL) is slower compared to the growth rate during the subsequent constant load cycles. This phenomenon occurs when the peak load is tensile in nature. The decelerated crack growth persists for several cycles until the crack growth rate returns to its original behavior. This scenario is depicted in Figure 10.

4.6 Initial Crack Geometry

In their study, Wu et al. [36] documented that foreign object damage (FOD) on railway axles has the potential to initiate crack formation. The damage resulting from FOD on EA4T steel railway axles is predominantly characterized by micro-damage, variations in microstructure, and residual stresses.

The investigation conducted by Madia[34] on hollow shafts based on simulations of semi-elliptical initial crack geometries with length ratios $a/c = 1$ and 0.2 to the same depth ratio $a/t = 0.02$ (shown in Figure 11) revealed a reduction in residual life for both crack length ratios. The crack length ratio $a/c = 0.2$ exhibited a smaller residual life of approximately 20%. The most significant differences were observed during the early stages of crack propagation.

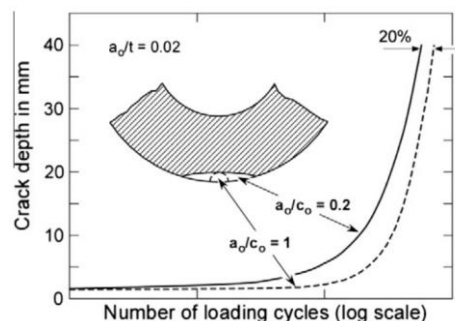


Fig. 11. Crack depth vs. number of loading cycle curves for initial crack geometries $a_0/c_0 = 1$ and 0.2 ; according to [33]

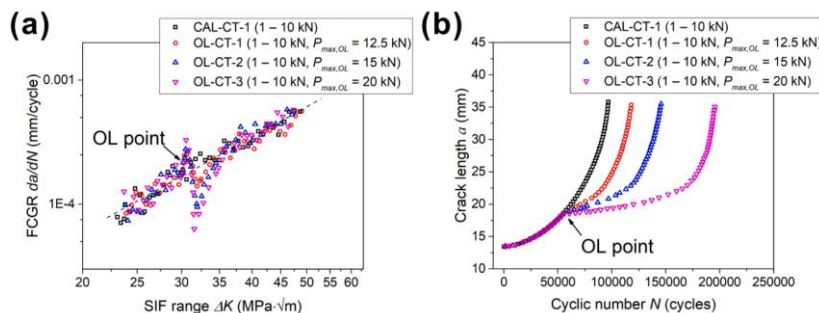


Fig. 10. (a) da/dN vs. ΔK ; (b) a vs. N three OL conditions; according to [35]

5 FATIGUE CRACK GROWTH ALGORITHM

The analysis of fatigue crack growth commonly involves data modeling using a differential equation known as a fatigue crack growth law or model. Integrating this equation produces the a - N curve, showing the relationship between crack length and number of cycles. This curve provides insights into crack propagation behavior and estimates the cycles needed for crack growth from initial to critical size.

The most straightforward approach to model fatigue crack growth in VAL is to disregard the interaction effects of load sequence and determine crack growth on a cycle-by-cycle basis using CAL crack growth laws. A more comprehensive discussion on this matter can be found in reference [37].

6 RESIDUAL LIFE PREDICTION OF RAILWAY AXLE

Residual life prediction refers to estimating the remaining useful life of a component or structure based on the current condition of existing damage or defects, such as cracks, corrosion, or other forms of degradation. This prediction involves analyzing the rate of damage progression and the potential effects of load cycles and environmental factors on structural integrity. The predictions of remaining life provide valuable information for determining the safe remaining operating life of components or structures and for establishing appropriate inspection and maintenance schedules. In the context of fatigue crack propagation analysis for railway axles, a fatigue crack propagation analysis scheme is depicted in Figure 13. A concise overview of the topic can be found in reference [38], while a more comprehensive discussion is available in reference [39].

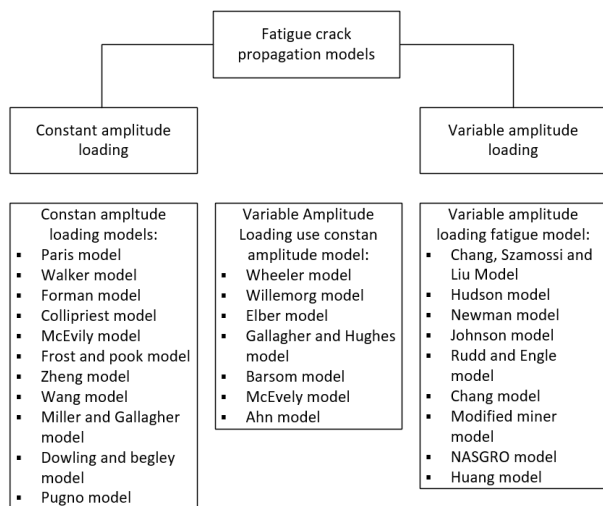


Fig. 12. Fatigue crack growth algorithm

Fatigue crack growth analysis is divided into two categories: Constant Amplitude Load (CAL) and Variable Amplitude Load (VAL). Fatigue crack growth analysis for components subjected to constant amplitude loading is considered easier because it does not require consideration of load history. In contrast, in VAL scenarios, stress with varying magnitudes occurs and influences the crack growth rate depending on the sequence of these stresses. Several fatigue crack growth models are illustrated in Figure 12.

Step 1 establishment the location, shape, and size of the initial crack

To evaluate the remaining service life of railway axles, it is necessary to identify the locations where crack growth can occur. Fatigue cracks are initiated at stress concentration points, which are typically located in the vicinity of the wheel seat due to the effects of press-fit loading, V- and T-notches, or the presence of defects such as inclusions, foreign object damage (FOD), and corrosion in the axle body (see Figure 14).

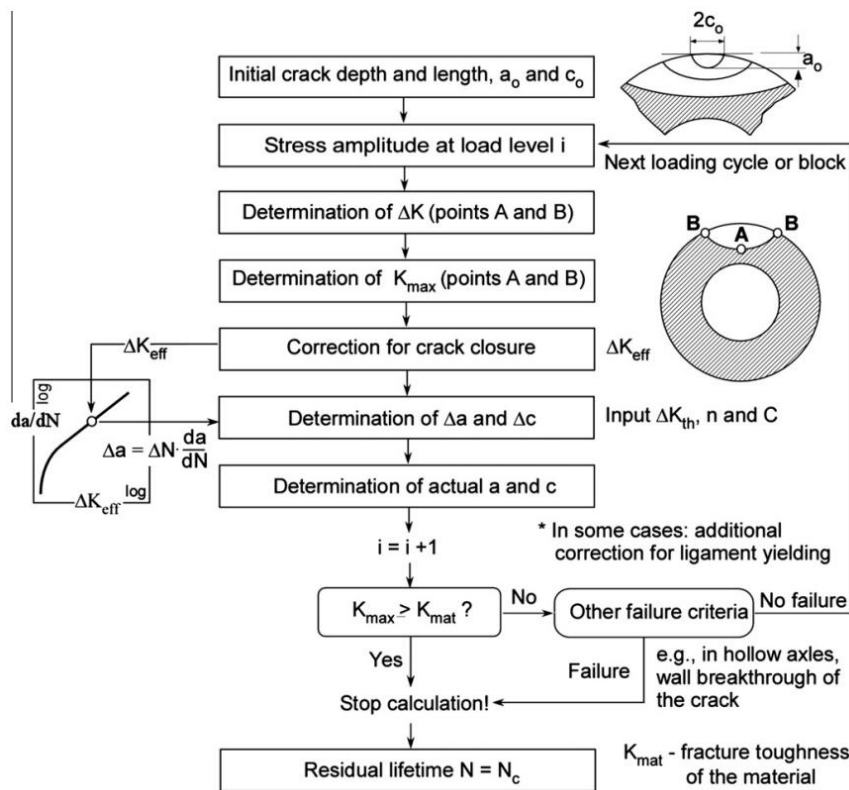


Fig. 13. Scheme of a comprehensive analysis for the propagation of fatigue cracks in a railway axle; according to [1]

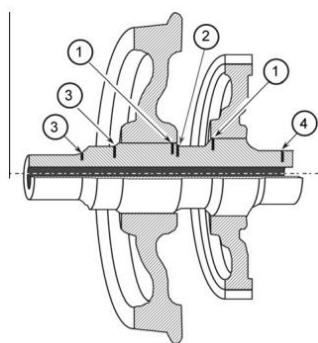


Fig. 14. Typical locations of fatigue cracks in railway axles comprise (1) cracks resulting from press fit underneath the wheel and gear; (2) cracks originating at the geometrical transition of the T notch; (3) cracks arising at the geometrical transitions of the U or V notch; (4) cracks emerging at the shaft, commonly situated at corrosion pits; according to [40]

The analysis of fatigue crack propagation in railway axles is undertaken through consideration of the crack center and surface points (A and B) of the semi-elliptical surface crack, as depicted in Figure 12. This is important because cracks can vary in their depth-to-length ratio during propagation. Failure criteria can be fracture when the maximum stress intensity factor (K

factor) within one load cycle reaches or exceeds the material's fracture toughness, $K_{max} > K_{mat}$. Reference [41] provides solutions for determining stress intensity factors at various locations on railway axles. In the context of damage tolerance analysis, the initial crack size a_0 is an assumed size that corresponds to the detection limit of Non-Destructive Inspection (NDI) techniques.

Step 2 simulation of crack extension

The initial crack can propagate through various mechanisms, such as fatigue, stress corrosion cracking, high-temperature creep, or a combination of these mechanisms. In the case of railway axles, fatigue is generally the predominant mechanism, but it is important to consider the potential contribution of corrosion as well. For semi-elliptical or semi-circular surface cracks, crack propagation needs to be calculated simultaneously in the thickness direction and along the surface.

There are many models used for this approach (see section 4). An advanced and widely used approach is known as the NASGRO model. This model is considered capable of representing crack growth rates in all regions of the crack growth rate diagram (Figure 3). It is important to note that the limitations of many

empirical curves for steel require reference values as fitting parameters. These reference values can be found in standard documents or research papers discussed in this paper. Table 1 presents several studies on residual life prediction of railway axles.

Step 3 determination of the critical crack size

The propagation of cracks in relatively large sizes often exhibits rapid progression, yielding negligible differences in the remaining life of the component. Component failure typically arises when the crack attains a critical size, triggering failure mechanisms such as brittle fracture or unstable crack propagation.

Step 4 determination of the residual lifetime of railway axle

Remaining life refers to the time or number of load cycles required for a crack to propagate from its initial size, a_0 at step 1, to reach a permissible crack size. In addition to the factors influencing the crack propagation rate at step 2, the calculation of remaining life is highly influenced by the choice of initial crack size and shape at step 1. This is a crucial point in determining inspection plans.

Table 1. several studies on residual life prediction of railway axles.

Author	Specimen	Method	Overview
Zhang et al. [11]	EA4T Steel	XFEM simulation NASGRO model BS7910 standard	The researchers conducted experiments on small-sized specimens and then utilized the data from these experiments in the NASGRO crack propagation model to simulate full-sized axles using the eXtended Finite Element Method (XFEM).
Pokorný et al. [42]	EA4T Steel	NASGRO model ASTM E647 code	This study aimed to compare the calculations obtained using the NASGRO model with experimental results concerning the effects of crack closure induced by roughness and oxide on crack closure.
Hu et al [43]	EA4T Steel	TSFA–Variabel Amplitude MBS simulation NASGRO model modified. BS 7910 code	In this research, the NASGRO model was modified using the Variable Amplitude Loading (VAL) approach and the time-stepwise fatigue assessment (TSFA) method to estimate fatigue life.
Mädler et al [10] Rieger et al [44]	EA1N steel EA4T Steel	NASGRO model	The objective of this research is to compare the calculation results using the NASGRO model with experimental data related to the load sequence effect on material fatigue.
Yamamoto et al [45]	SFA640 steel	Paris-law model ASTM E647 code	This research compares the results of experiments conducted on full-scale shafts with CT specimens using the Paris law model.
Luke et al [46]	EA4T steel 34CrNiMo6+Q T Steel	NASGRO model ASTM E647 Code	This study validates the crack growth curves obtained from experiments on M(T) specimens against full-scale shafts using the NASGRO crack growth model.
Li et al [47]	EA4T	Exponential Pit grow model. Hobson short crack model Paris-law model	This study develops a predictive model for the fatigue corrosion life based on the stages of pit growth, short crack, and long crack.
Giannella et al [48]	30NiCrMoV12 steel, solid axle	FEM analysis DBEM NASGRO Model	This study predicts the remaining life based on the NASGRO model using FEM and DBEM simulations, and then compares the results.

7 CONCLUSIONS

The prediction of fatigue crack growth based on fracture mechanics has been reviewed and discussed. It is developed to support the concept of damage tolerance in metallic structures. The prediction models

are divided into two categories based on the type of load: constant or variable amplitude. There are numerous fatigue crack growth models that can represent fatigue rate data, but no single model can capture all cases. Therefore, the selection of an

appropriate model is typically based on the experience and preferences of the analyst.

The assessment methods for crack propagation in railway axles often employ the NASGRO method, as demonstrated in the references cited in this paper (see Table 1). This model is chosen because it is considered to have the capability to account for : first, Three distinct regions in the crack growth diagram: the near-threshold region, the Paris region, and the critical region. Second, Crack closure effect: This phenomenon can significantly influence crack growth behavior and needs to be accounted for in accurate crack growth predictions. Third, Influence of stress ratio on crack growth rate: Different stress ratios can lead to variations in crack growth behavior.

The NASGRO method relies on experimental data for model validation. Several standard codes, such as BS7910 and ASTM E647, provide experimental data related to crack growth. These codes govern the methods for conducting crack growth experiments. While the NASGRO method is widely used, it has limitations in accounting for material variability, loading conditions, and environmental effects, which can affect the accuracy of predictions. Some researchers have addressed this issue by employing probabilistic approaches and statistical data analysis to achieve improved predictions. In conclusion, the selection of crack growth models and calculation methods should be carefully considered, depending on the type of structure and loading conditions involved. Therefore, the strengths and limitations of each model need to be understood in order to generate accurate and reliable calculations.

References

- [1] U. Zerbst *et al.*, "Safe life and damage tolerance aspects of railway axles - A review," *Eng. Fract. Mech.*, vol. 98, no. 1, pp. 214–271, 2013, doi: 10.1016/j.engfracmech.2012.09.029.
- [2] Y. Murakami, "Effect of hardness HV on fatigue limits of materials containing defects, and fatigue limit prediction equations," *Met. Fatigue*, pp. 61–94, 2019, doi: 10.1016/b978-0-12-813876-2.00005-4.
- [3] J. W. Gao, X. Dai, S. P. Zhu, J. W. Zhao, J. A. F. O. Correia, and Q. Wang, "Failure causes and hardening techniques of railway axles – A review from the perspective of structural integrity," *Eng. Fail. Anal.*, vol. 141, 2022, doi: 10.1016/j.engfailanal.2022.106656.
- [4] U. Zerbst, M. Madia, C. Klinger, D. Bettge, and Y. Murakami, "Defects as a root cause of fatigue failure of metallic components. III: Cavities, dents, corrosion pits, scratches," *Eng. Fail. Anal.*, vol. 97, pp. 759–776, 2019, doi: 10.1016/j.engfailanal.2019.01.034.
- [5] J. F. Zheng, J. Luo, J. L. Mo, J. F. Peng, X. S. Jin, and M. H. Zhu, "Fretting wear behaviors of a railway axle steel," *Tribol. Int.*, vol. 43, no. 5–6, pp. 906–911, 2010, doi: 10.1016/j.triboint.2009.12.031.
- [6] E. Schmidová, P. Paščenko, B. Culek, and M. Schmid, "Premature failures of railway axles after repeated pressing," *Eng. Fail. Anal.*, vol. 123, no. January, 2021, doi: 10.1016/j.engfailanal.2021.105253.
- [7] D. Zeng, Y. Zhang, L. Lu, L. Zou, and S. Zhu, "Fretting wear and fatigue in press-fitted railway axle: A simulation study of the influence of stress relief groove," *Int. J. Fatigue*, vol. 118, pp. 225–236, 2019, doi: 10.1016/j.ijfatigue.2018.09.008.
- [8] KNKT, "LAPORAN INVESTIGASI KECELAKAAN PERKERETAAPIAN," 2016.
- [9] Z. Odanovic, M. Ristivojevic, and V. Milosevic-Mitic, "Investigation into the causes of fracture in railway freight car axle," *Eng. Fail. Anal.*, vol. 55, pp. 169–181, 2015, doi: 10.1016/j.engfailanal.2015.05.011.
- [10] K. Mädler, T. Geburtig, and D. Ullrich, "An experimental approach to determining the residual lifetimes of wheelset axles on a full-scale wheel-rail roller test rig," *Int. J. Fatigue*, vol. 86, pp. 58–63, 2016, doi: 10.1016/j.ijfatigue.2015.06.016.
- [11] D. Ji, J. Zhang, K. Yi, Y. Huang, Q. Lu, and H. Zhang, "Surface crack growth simulation and residual life assessment of high-speed train axles based on extended finite element method," *Eng. Fail. Anal.*, vol. 134, 2022, doi: 10.1016/j.engfailanal.2022.106043.
- [12] C. M. Sonsino, "Course of SN-curves especially in the high-cycle fatigue regime with regard to component design and safety," *Int. J. Fatigue*, vol. 29, no. 12, pp. 2246–2258, 2007, doi: 10.1016/j.ijfatigue.2006.11.015.
- [13] U. Zerbst, M. Vormwald, R. Pippan, H. P. Ganser, C. Sarrazin-Baudoux, and M. Madia, "About the fatigue crack propagation threshold of metals as a design criterion - A review," *Eng. Fract. Mech.*, vol. 153, pp. 190–243, 2016, doi:

- 10.1016/j.engfracmech.2015.12.002.
- [14] S. Beretta, A. Ghidini, and F. Lombardo, "Fracture mechanics and scale effects in the fatigue of railway axles," *Eng. Fract. Mech.*, vol. 72, no. 2, pp. 195–208, 2005, doi: 10.1016/j.engfracmech.2003.12.011.
- [15] U. Zerbst, M. Madia, C. Klingner, D. Bettge, and Y. Murakami, "Defects as a root cause of fatigue failure of metallic components. I: Basic aspects," *Eng. Fail. Anal.*, vol. 97, pp. 777–792, 2019, doi: 10.1016/j.engfailanal.2019.01.055.
- [16] M. D. Sangid, "The physics of fatigue crack initiation," *Int. J. Fatigue*, vol. 57, pp. 58–72, 2013, doi: 10.1016/j.ijfatigue.2012.10.009.
- [17] B. Künkler, O. Düber, P. Köster, U. Krupp, C. P. Fritzen, and H. J. Christ, "Modelling of short crack propagation - Transition from stage I to stage II," *Eng. Fract. Mech.*, vol. 75, no. 3–4, pp. 715–725, 2008, doi: 10.1016/j.engfracmech.2007.02.018.
- [18] U. Krupp, O. Düber, H. J. Christ, B. Künkler, P. Köster, and C. P. Fritzen, "Propagation mechanisms of microstructurally short cracks- Factors governing the transition from short- to long-crack behavior," *Mater. Sci. Eng. A*, vol. 462, no. 1–2, pp. 174–177, 2007, doi: 10.1016/j.msea.2006.03.159.
- [19] H. J. Christ, C. P. Fritzen, and P. Köster, "Micromechanical modeling of short fatigue cracks," *Curr. Opin. Solid State Mater. Sci.*, vol. 18, no. 4, pp. 205–211, 2014, doi: 10.1016/j.cossms.2014.05.001.
- [20] W. D. Musinski and D. L. McDowell, "Simulating the effect of grain boundaries on microstructurally small fatigue crack growth from a focused ion beam notch through a three-dimensional array of grains," *Acta Mater.*, vol. 112, pp. 20–39, 2016, doi: 10.1016/j.actamat.2016.04.006.
- [21] R. Pippa and A. Hohenwarter, "Fatigue crack closure: a review of the physical phenomena," *Fatigue Fract. Eng. Mater. Struct.*, vol. 40, no. 4, pp. 471–495, 2017, doi: 10.1111/ffe.12578.
- [22] E. Salvati, H. Zhang, K. S. Fong, X. Song, and A. M. Korsunsky, "Separating plasticity-induced closure and residual stress contributions to fatigue crack retardation following an overload," *J. Mech. Phys. Solids*, vol. 98, pp. 222–235, 2017, doi: 10.1016/j.jmps.2016.10.001.
- [23] A. K. Vasudevan and D. Kujawski, "Roughness induced crack Closure : A review of key points," *Theor. Appl. Fract. Mech.*, vol. 125, no. April, p. 103897, 2023, doi: 10.1016/j.tafmec.2023.103897.
- [24] N. Gates and A. Fatemi, "Friction and roughness induced closure effects on shear-mode crack growth and branching mechanisms," *Int. J. Fatigue*, vol. 92, pp. 442–458, 2016, doi: 10.1016/j.ijfatigue.2016.01.023.
- [25] J. Maierhofer, D. Simunek, H. P. Gänser, and R. Pippa, "Oxide induced crack closure in the near threshold regime: The effect of oxide debris release," *Int. J. Fatigue*, vol. 117, pp. 21–26, 2018, doi: 10.1016/j.ijfatigue.2018.07.021.
- [26] F. Paysan and E. Breitbarth, "Towards three dimensional aspects of plasticity-induced crack closure: A finite element simulation," *Int. J. Fatigue*, vol. 163, 2022, doi: 10.1016/j.ijfatigue.2022.107092.
- [27] K. Solanki, S. R. Daniewicz, and J. C. Newman, "Finite element analysis of plasticity-induced fatigue crack closure: An overview," *Eng. Fract. Mech.*, vol. 71, no. 2, pp. 149–171, 2004, doi: 10.1016/S0013-7944(03)00099-7.
- [28] M. de Freitas, L. Reis, M. D. Fonte, and B. Li, "Effect of steady torsion on fatigue crack initiation and propagation under rotating bending: Multiaxial fatigue and mixed-mode cracking," *Eng. Fract. Mech.*, vol. 78, no. 5, pp. 826–835, 2011, doi: 10.1016/j.engfracmech.2009.12.012.
- [29] V. Giannella, "Stochastic approach to fatigue crack-growth simulation for a railway axle under input data variability," *Int. J. Fatigue*, vol. 144, 2021, doi: 10.1016/j.ijfatigue.2020.106044.
- [30] M. Luke, I. Varfolomeev, K. Lütkepohl, and A. Esderts, "Fracture mechanics assessment of railway axles: Experimental characterization and computation," *Eng. Fail. Anal.*, vol. 17, no. 3, pp. 617–623, 2010, doi: 10.1016/j.engfailanal.2009.04.008.
- [31] J. Maierhofer, S. Kolitsch, R. Pippa, H. P. Gänser, M. Madia, and U. Zerbst, "The cyclic R-curve – Determination, problems, limitations and application," *Eng. Fract. Mech.*, vol. 198, pp. 45–64, 2018, doi: 10.1016/j.engfracmech.2017.09.032.
- [32] S. Cervello, "Fatigue properties of railway axles: New results of full-scale specimens from Euraxles project," *Int. J. Fatigue*, vol. 86, pp. 2–12, 2016, doi: 10.1016/j.ijfatigue.2015.11.028.

- [33] U. Zerbst, M. Schödel, and H. T. Beier, "Parameters affecting the damage tolerance behaviour of railway axles," *Eng. Fract. Mech.*, vol. 78, no. 5, pp. 793–809, 2011, doi: 10.1016/j.engfracmech.2010.03.013.
- [34] M. Madia, S. Beretta, and U. Zerbst, "An investigation on the influence of rotary bending and press fitting on stress intensity factors and fatigue crack growth in railway axles," *Eng. Fract. Mech.*, vol. 75, no. 8, pp. 1906–1920, 2008, doi: 10.1016/j.engfracmech.2007.08.015.
- [35] H. Liang, R. Zhan, D. Wang, C. Deng, X. Xu, and B. Guo, "Effect of crack-tip deformation on fatigue crack growth: A comparative study under overload/underload conditions," *Theor. Appl. Fract. Mech.*, vol. 118, 2022, doi: 10.1016/j.tafmec.2022.103268.
- [36] S. C. Wu, Y. Luo, Z. Shen, L. C. Zhou, W. H. Zhang, and G. Z. Kang, "Collaborative crack initiation mechanism of 25CrMo4 alloy steels subjected to foreign object damages," *Eng. Fract. Mech.*, vol. 225, 2020, doi: 10.1016/j.engfracmech.2019.106844.
- [37] S. M. Beden, S. Abdullah, and A. K. Ariffin, *Review of fatigue crack propagation models for metallic components*, vol. 28, no. 3. 2009.
- [38] U. Zerbst, K. Mädler, and H. Hintze, "Fracture mechanics in railway applications - An overview," *Eng. Fract. Mech.*, vol. 72, no. 2, pp. 163–194, 2005, doi: 10.1016/j.engfracmech.2003.11.010.
- [39] U. Zerbst, M. Vormwald, C. Andersch, K. Mädler, and M. Pfuff, "The development of a damage tolerance concept for railway components and its demonstration for a railway axle," *Eng. Fract. Mech.*, vol. 72, no. 2, pp. 209–239, 2005, doi: 10.1016/j.engfracmech.2003.11.011.
- [40] U. Zerbst, C. Klinger, and D. Klingbeil, "Structural assessment of railway axles - A critical review," *Eng. Fail. Anal.*, vol. 35, pp. 54–65, 2013, doi: 10.1016/j.engfailanal.2012.11.007.
- [41] M. Madia, S. Beretta, M. Schödel, U. Zerbst, M. Luke, and I. Varfolomeev, "Stress intensity factor solutions for cracks in railway axles," *Eng. Fract. Mech.*, vol. 78, no. 5, pp. 764–792, 2011, doi: 10.1016/j.engfracmech.2010.03.019.
- [42] P. Pokorný, T. Vojtek, L. Náhlík, and P. Hutař, "Crack closure in near-threshold fatigue crack propagation in railway axle steel EA4T," *Eng. Fract. Mech.*, vol. 185, pp. 2–19, 2017, doi: 10.1016/j.engfracmech.2017.02.013.
- [43] F. Hu, S. Wu, X. Xin, F. Guo, and Z. Ren, "Determination of the critical defect and fatigue life of high-speed railway axles under variable amplitude loads," *Int. J. Fatigue*, vol. 168, 2023, doi: 10.1016/j.ijfatigue.2022.107446.
- [44] M. Rieger *et al.*, "Fatigue crack growth in full-scale railway axles – Influence of secondary stresses and load sequence effects," *Int. J. Fatigue*, vol. 132, 2020, doi: 10.1016/j.ijfatigue.2019.105360.
- [45] M. Yamamoto, K. Makino, and H. Ishiduka, "Comparison of crack growth behaviour between full-scale railway axle and scaled specimen," *Int. J. Fatigue*, vol. 92, pp. 159–165, 2016, doi: 10.1016/j.ijfatigue.2016.07.001.
- [46] M. Luke, I. Varfolomeev, K. Lütkepohl, and A. Esderts, "Fatigue crack growth in railway axles: Assessment concept and validation tests," *Eng. Fract. Mech.*, vol. 78, no. 5, pp. 714–730, 2011, doi: 10.1016/j.engfracmech.2010.11.024.
- [47] H. Li, J. Zhang, S. Wu, H. Zhang, and Y. Fu, "Corrosion fatigue mechanism and life prediction of railway axle EA4T steel exposed to artificial rainwater," *Eng. Fail. Anal.*, vol. 138, 2022, doi: 10.1016/j.engfailanal.2022.106319.
- [48] V. Giannella, R. Sepe, A. Borrelli, G. De Michele, and E. Armentani, "Numerical investigation on the fracture failure of a railway axle," *Eng. Fail. Anal.*, vol. 129, 2021, doi: 10.1016/j.engfailanal.2021.105680.