Proceedings of the Seventh International Conference on
Railway Technology: Research, Development and Maintenance
Edited by: J. Pombo
Civil-Comp Conferences, Volume 15, Paper 22.3
Civil-Comp Press, Edinburgh, United Kingdom, 2026
ISSN: 2753-3239, doi: 10.4203/ccc.15.22.3
©Civil-Comp Ltd, Edinburgh, UK, 2026

Fatigue Performance of Drilled Railway Rails: Integrated Experimental Testing and Finite Element Analysis

J. Sainz-Aja[1], P. San Roman[1], J. A. Casado[1], I. Carrascal[1], D. Ferreño[1], R. Moreno[2], D. Peribañez[2], H. Vega[2] and S. Diego[1]

[1]University of Cantabria, Spain
[2]Metro Madrid, Spain

Abstract

This work presents a comprehensive assessment of the fatigue response of railway rails incorporating lubrication holes, combining experimental testing with advanced numerical modelling. Laboratory fatigue tests were performed on rail specimens subjected to three-point bending to reproduce critical stress conditions.

A finite element strategy was developed using ANSYS, consisting of two complementary models. The first model replicates the experimental setup and was calibrated against the obtained fatigue data to accurately capture the material and structural response. Building on this validation, a second model representing a rail track segment with multiple supports was implemented to analyse more realistic service conditions.

The numerical simulations were employed to investigate the effect of key parameters, including wheel load position, hole diameter, and hole location, on stress distribution and fatigue initiation. The results reveal a strong dependence of fatigue performance on geometric configuration and loading conditions, particularly in the vicinity of the drilled hole.

Overall, the study provides useful insights into the structural implications of introducing lubrication holes in rails and supports the development of improved design and maintenance strategies aimed at enhancing fatigue life in railway infrastructure.

Keywords: fatigue, lubrication holes, S-N curve, finite element modeling (FEM), fatigue rail, structural integrity.

1 Introduction

Railway systems are widely recognised as a key component of sustainable mobility, in particularly in urban environments where high transport demand requires efficient and reliable solutions [1]. Metro networks, in particular, operate under demanding service conditions, characterised by frequent train passages, reduced curve radii, and elevated contact forces between wheel and rail [2]. These factors result in severe mechanical loading scenarios that accelerate degradation processes such as wear and fatigue, ultimately affecting both safety and maintenance costs. Ensuring the durability of rail infrastructure under such conditions is therefore a critical challenge for operators and engineers.

To alleviate friction-related issues and mitigate wear in curved tracks, lubrication strategies are commonly adopted in metro systems [3]. One widely implemented approach consists of introducing lubrication holes in the rail head, allowing lubricant to be delivered directly to the wheel–rail contact interface. Although this solution has demonstrated clear benefits in terms of noise reduction and wear control, it also modifies the local geometry of the rail [4]. The presence of such discontinuities may induce stress concentration effects, which can compromise the structural integrity of the component by promoting fatigue damage under cyclic loading.

Fatigue mechanisms in railway rails are governed by the initiation and subsequent propagation of cracks driven by repeated load cycles. These processes are influenced by multiple factors, including contact stress conditions, material characteristics, residual stresses, and environmental effects [2], [5]. The introduction of geometric features such as drilled holes further intensifies the local stress field, increasing the likelihood of crack initiation.

In this context, a rigorous understanding how design parameters—such as hole size and location—affect fatigue behaviour is essential for ensuring safe operation [6], [7]. Numerical techniques, particularly finite element modelling, have proven to be powerful tools for analysing these complex interactions, enabling detailed evaluation of stress distributions and supporting fatigue life predictions through approaches such as S–N methodologies [6], [8], [9], [10], [11].

In this framework, the present study investigates the fatigue performance of railway rails incorporating lubrication holes through a combined experimental and numerical approach. Fatigue tests are first conducted on representative rail specimens subjected to cyclic bending in order to establish reference S–N data. A corresponding finite element model is then developed and calibrated against the experimental results. Building upon this validation, a more comprehensive model representing a rail track segment is implemented to simulate realistic loading conditions, including the effect of a moving wheel load. A parametric analysis is performed to examine the influence of hole geometry and positioning on fatigue life. The outcomes of this work contribute to a better understanding of the structural implications of lubrication systems and provide guidance for the design of safer and more durable railway components.

2 Methods

An experimental programme was conducted to quantify the fatigue behaviour of railway rails containing lubrication holes under controlled conditions. The testing strategy was specifically designed to reproduce a stress state representative of the most demanding service scenarios at the hole location. The resulting data provide a reliable reference for the calibration and subsequent validation of the numerical modelling approach.

2.1. Experimental setup

The experimental study was performed using full-scale rail segments corresponding to the UIC 54 (54E1) profile, manufactured in R260 steel. Each specimen measured 800 mm in length and included a single drilled hole located at the centre of the rail head. The hole diameter was set to 8.5 mm, in line with typical configurations used in lubricated railway tracks (see Figure 1). All samples were in as-received condition, without prior service exposure or visible damage.

To ensure that the critical stress condition was achieved during testing, the rails were mounted in an inverted position, placing the head region under tension during bending. The drilled hole was positioned at midspan and directly aligned with the load application point, thereby maximising the stress concentration at this location.

Figure 1: Full scale tested rails.

2.2. Fatigue tests

Cyclic loading tests were carried out using a servo-hydraulic testing system operating under force control. The loading configuration consisted of a three-point bending setup, with a support span of 700 mm and load applied at the centre of the specimen. Prior to testing, local machining was performed at the contact regions to guarantee uniform load transfer and avoid unintended local effects.

The fatigue loading was applied with constant amplitude cycles and a stress ratio of $R = 0.1$, ensuring that the upper fibre of the rail remained under tensile stress throughout the test. A loading frequency of 5 Hz was adopted for all specimens. Each test included an initial phase of 10^5 cycles, followed by continued cycling at the same load level until either failure occurred or a maximum threshold of 3×10^6 cycles was reached.

For each test, the total number of cycles to failure was recorded and used to derive the corresponding S–N relationship. After failure, the fracture surfaces were examined in order to identify the crack initiation site and propagation characteristics, with particular focus on the region surrounding the drilled hole.

2.3. Finite Element Modeling

A numerical strategy was implemented using finite element analysis to investigate the fatigue behaviour of rails with lubrication holes. Two complementary models were developed. The first one reproduces the laboratory testing conditions and was used for calibration purposes, while the second represents a rail track segment subjected to more realistic loading configurations. Both models were constructed to ensure consistency in terms of material properties, fatigue parameters, and modelling assumptions.

Calibrated model based on experimental configuration

The first model was designed to replicate the three-point bending tests performed on the rail specimens (see Figure 2). The geometry corresponds to a UIC 54 rail segment with a central hole located in the rail head, matching the dimensions of the tested samples. Boundary conditions and load application were defined to reproduce the experimental setup, including support spacing and central loading.

A three-dimensional discretisation was adopted using tetrahedral elements. Special attention was given to the region surrounding the hole, where a refined mesh was introduced to accurately capture local stress gradients. The remaining domain was meshed more coarsely to maintain computational efficiency. The material behaviour was assumed to be linear elastic, using representative mechanical properties for R260 rail steel.

The analysis procedure consisted of two stages. First, a static simulation was carried out to verify that the model correctly reproduced the expected bending response. Subsequently, fatigue life was evaluated using a stress-life (S–N) approach, incorporating mean stress effects through an appropriate correction model. The fatigue parameters were adjusted iteratively to achieve agreement between numerical predictions and the experimental S–N data. Fatigue life was assessed at the internal surface of the hole, identified as the most critical region for crack initiation.

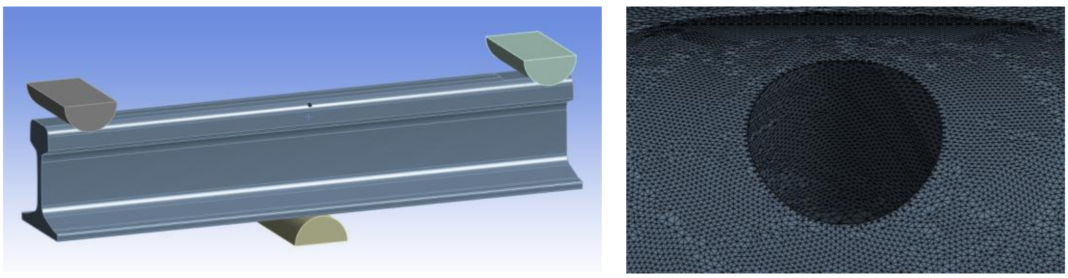

Figure 2: Calibrated model based on experimental configuration.

Full-track model for parametric analysis

A second model was developed to represent a rail segment under more realistic service conditions (see Figure 3). This model includes multiple spans supported at regular intervals, simulating a continuous track system. The rail geometry is consistent with the UIC 54 profile, and the supports were idealised as rigid constraints spaced according to typical track layouts.

Within this framework, a single lubrication hole was introduced in the rail head, and its geometric characteristics were varied parametrically. Different hole diameters and positions along the span were considered to evaluate their influence on fatigue performance. In addition, a moving load representing the passage of a railway wheel was applied at multiple locations along the rail to identify the most critical loading scenario.

The mesh strategy followed the same criteria as in the calibrated model, with local refinement in regions of high stress concentration, particularly around the hole and beneath the applied load. Linear elastic material behaviour was assumed, and the same fatigue methodology was employed to ensure consistency between models.

For each configuration, the stress distribution was first obtained through static analysis. Fatigue life was then computed using the S–N approach, and the minimum number of cycles to failure associated with the most unfavourable load position was extracted. This procedure allowed the construction of representative fatigue curves for each structural configuration and enabled a direct comparison of the influence of hole geometry and location.

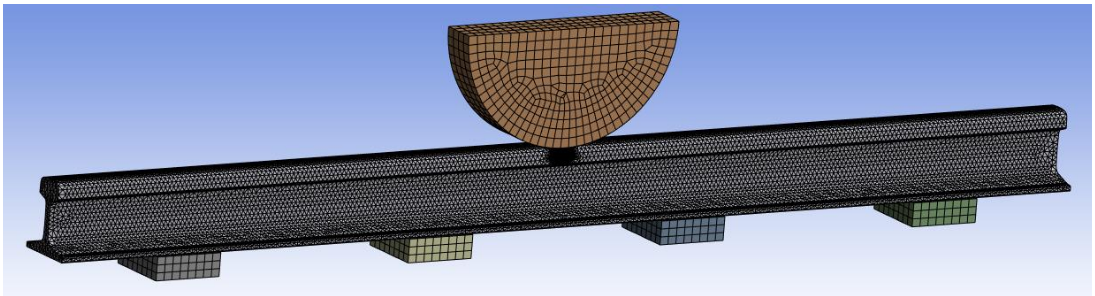

Figure 3: Full-track model for parametric analysis.

3 Results

The following section presents the outcomes of the experimental campaign carried out on rail specimens with lubrication holes. The results focus on the fatigue life obtained under cyclic loading conditions and the corresponding S–N relationship derived from the tests. In addition, post-failure observations are discussed to identify the dominant damage mechanisms and the typical location of crack initiation. These findings provide the reference framework for the subsequent validation of the numerical models.

3.1. Experimental results

The fatigue response of the drilled rail specimens was characterised through constant-amplitude cyclic tests under the loading conditions described previously. For each load level, the number of cycles to failure was recorded, allowing the construction of an experimental S–N relationship representative of the studied configuration. The obtained results (Table 1) show the expected trend of decreasing fatigue life with increasing stress amplitude, with failure occurring within a wide range of cycles depending on the applied load.

Lab test	Max. stress [MPa]	Stress amplitude [MPa]	Number of cycles
CAR-3	258	232	125.450
CAR-4	235	212	244.000
CAR-5	214	193	316.412
CAR-6	193	174	586.313
CAR-7	171	154	>3.000.000

Table 1: Number of cycles to failure recorded for each applied load level.

At lower stress levels, some specimens reached the predefined run-out limit without failure, indicating the presence of a fatigue endurance threshold under the tested conditions. Conversely, higher stress amplitudes led to significantly reduced fatigue lives, confirming the strong sensitivity of the system to the applied load magnitude. Overall, the experimental data provide a consistent basis for describing the fatigue behaviour of rails containing lubrication holes.

Post-test inspection of the specimens revealed a clear and repeatable failure pattern (see Figure 4). In all cases, crack initiation occurred at the internal surface of the drilled hole, where stress concentration is highest. From this location, cracks propagated progressively across the rail head until final fracture. The fracture surfaces exhibited features characteristic of fatigue damage, including a well-defined crack initiation region and a subsequent propagation zone.

These observations confirm that the presence of the lubrication hole governs the fatigue response of the component, acting as the critical site for damage initiation. The experimental results therefore validate the relevance of focusing the numerical analysis on this region and provide a reliable reference for the calibration and assessment of the finite element models.

Figure 4: Full-track model for parametric analysis.

3.2. Experimental VS. numerical S-N curve (model 1)

The predictive capability of the reduced finite element model was assessed by comparing its fatigue life estimations with the experimental S–N data obtained from the laboratory tests. Both datasets were analysed under equivalent loading conditions, with fatigue life evaluated at the hole surface, identified as the critical location for crack initiation.

The comparison (see Figure 5) shows a strong correlation between numerical predictions and experimental results across the full range of stress levels considered. The finite element model accurately captures the slope and position of the S–N curve, indicating that the adopted modelling assumptions and fatigue parameters provide a reliable representation of the physical behaviour.

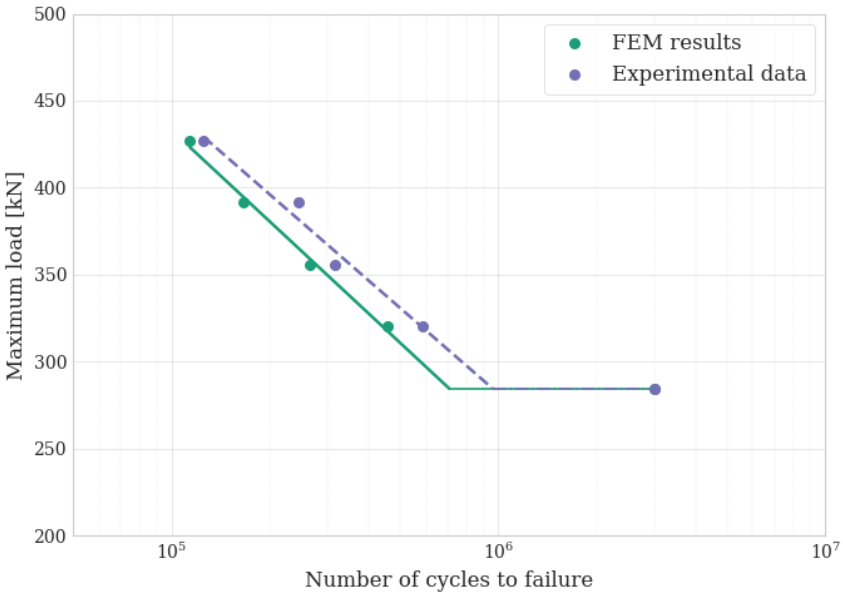

Figure 5: Full-track model for parametric analysis.

Minor deviations observed at specific load levels can be attributed to inherent variability in fatigue testing and to simplifications in the numerical model, such as the assumption of linear elastic material behaviour. Nevertheless, these differences remain within acceptable limits for engineering applications.

Overall, the level of agreement achieved confirms that the calibrated model can be confidently used to predict fatigue life in rails with lubrication holes. This validation step supports its application to more complex scenarios, including the full-track simulations and parametric analyses presented in the following sections.

3.3. Parametric study

The validated finite element framework was subsequently applied to investigate the influence of key geometric parameters on the fatigue performance of railway rails with lubrication holes. The analysis focused on two main variables: hole diameter and hole position along the rail span. For each configuration, a moving load was simulated along the rail to determine the most critical loading condition, defined as the one leading to the minimum fatigue life.

Influence of hole diameter

The influence of hole size was evaluated by comparing fatigue life predictions for different diameters while maintaining the same boundary conditions and loading scenarios. The results show a clear and consistent trend: increasing the hole diameter leads to a reduction in fatigue life across all configurations (see figure 6).

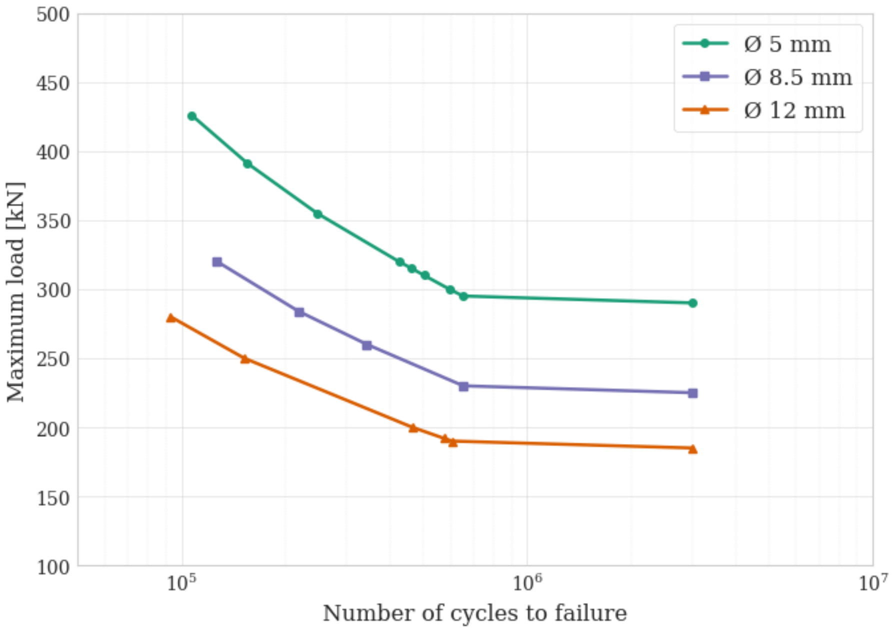

Figure 6: S–N curves obtained for different hole diameters (5 mm, 8.5 mm, and 12 mm) with the hole lo-cated at midspan.

This behaviour is directly related to the amplification of stress concentration at the hole edge as the diameter increases. Larger discontinuities generate higher local stresses, which accelerate crack initiation and reduce the number of cycles to failure.

The effect becomes more pronounced at higher stress levels, where the differences between configurations are significantly magnified.

These findings highlight the importance of controlling hole size in practical applications, as even moderate increases in diameter can lead to a noticeable decrease in fatigue resistance.

Influence of hole position

The position of the lubrication hole along the rail span was also found to have a significant impact on fatigue performance. Among the configurations analysed, the midspan location consistently resulted in the lowest fatigue life, corresponding to the region of maximum bending moment under vertical loading (see Figure 7).

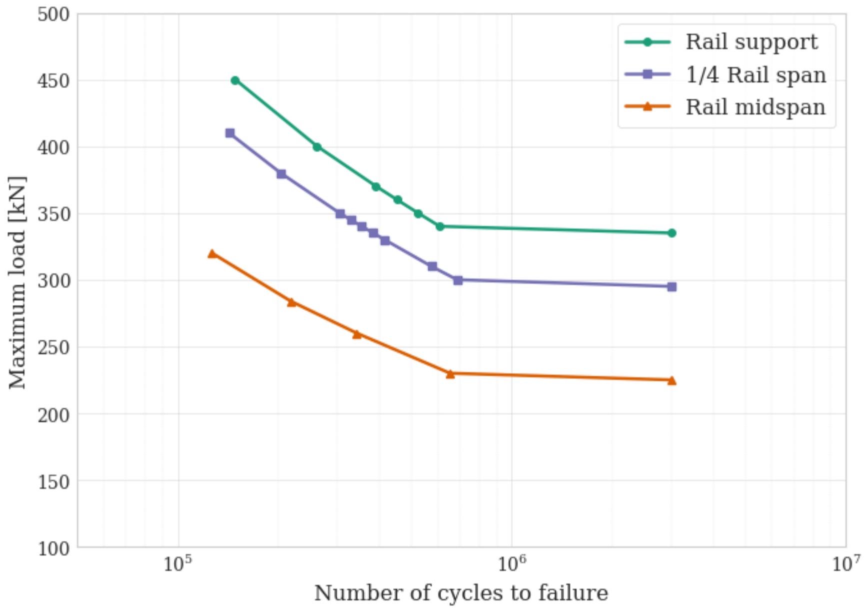

Figure 7: S–N curves obtained for different hole diameters (5 mm, 8.5 mm, and 12 mm) with the hole lo-cated at midspan.

Relocating the hole away from this critical region led to a progressive improvement in fatigue life. Positions closer to the supports exhibited more favourable behaviour, as the local stress levels are reduced due to the lower bending moment. This trend was observed consistently for all hole diameters considered.

The results demonstrate that, in addition to geometric size, the relative placement of the hole with respect to the structural system plays a key role in determining fatigue performance. From a design perspective, avoiding the central span region can significantly enhance the durability of the rail component.

4 Conclusions and Contributions

This study has investigated the fatigue behaviour of railway rails incorporating lubrication holes through a combined experimental and numerical approach. The main findings can be summarised as follows:

- The finite element model developed to reproduce the laboratory testing conditions provides accurate fatigue life predictions, showing strong agreement with the experimental S–N data. This confirms the suitability of the adopted modelling strategy for analysing drilled rail configurations.
- The presence of the lubrication hole governs the fatigue response of the rail, acting as the primary site for crack initiation due to the associated stress concentration.
- Hole diameter has a significant influence on fatigue performance. An increase in diameter leads to a systematic reduction in fatigue life, highlighting the need to carefully control this parameter in practical applications.
- Hole position along the rail span is also a critical factor. Locations near midspan result in the most severe fatigue conditions, whereas positions closer to the supports lead to improved fatigue performance.
- The numerical framework, once validated, enables the evaluation of realistic loading scenarios, including the identification of worst-case conditions through the simulation of moving loads. This provides a valuable tool for assessing design alternatives beyond experimental limitations.

Overall, the results contribute to a better understanding of the structural implications of introducing lubrication holes in railway rails and provide useful guidance for optimising their design in terms of fatigue resistance and operational safety.

Acknowledgements

The author gratefully acknowledges the financial support provided by the Ramón y Cajal Programme, funded by the Ministerio de Ciencia e Innovación and the Agencia Estatal de Investigación.

References

[1] D. Liu, J. Wang, L. Xu, H. Zhang, and X. Tan, 'Comparison of energy consumption and carbon emissions of high-speed rail with other transportation modes from life cycle perspective: A case of Beijing-Shanghai', *Research in Transportation Business and Management*, vol. 59, Mar. 2025, doi: 10.1016/j.rtbm.2024.101278.

[2] S. Wang *et al.*, 'Analysis of the causes of severe side wear of the high rail on metro curves by numerical simulation and field investigation', *Proc. Inst. Mech. Eng. F J. Rail Rapid Transit*, vol. 238, Aug. 2023, doi: 10.1177/09544097231193274.

[3] W. J. Wang, R. Lewis, M. Evans, and Q. Y. Liu, 'Influence of Different Application of Lubricants on Wear and Pre-existing Rolling Contact Fatigue Cracks of Rail Materials', *Tribol. Lett.*, vol. 65, Mar. 2017, doi: 10.1007/s11249-017-0841-9.

[4] M. Milanese, F. Iacobazzi, M. Stark, and A. Risi, ‘Development of common rail lube oil injector for large two-stroke marine diesel engines’, *International Journal of Engine Research*, vol. 23, p. 146808742110080, Apr. 2021, doi: 10.1177/14680874211008005.

[5] J. Ringsberg and B. L. Josefson, *Assessment of uncertainties in life prediction of fatigue crack propagation in welded rails*, vol. 8. 2009.

[6] J. Sainz-Aja *et al.*, ‘Fatigue Life Assessment of Railway Rails with Lubrication Holes: Experimental Validation and Finite Element Modelling’, *Metals (Basel).*, vol. 15, no. 9, Sep. 2025, doi: 10.3390/met15090992.

[7] Y. C. Park, C. An, H. B. Sim, M. Kim, and J. K. Hong, ‘Failure Analysis of Fatigue Cracking in the Tension Clamp of a Rail Fastening System’, *International Journal of Steel Structures*, vol. 19, no. 5, pp. 1570–1577, Oct. 2019, doi: 10.1007/s13296-019-00231-5.

[8] H. C. Eden, J. E. Garnham, and C. L. Davis, ‘Influential microstructural changes on rolling contact fatigue crack initiation in pearlitic rail steels’, *Materials Science and Technology*, vol. 21, no. 6, pp. 623–629, Jun. 2005, doi: 10.1179/174328405X43207.

[9] G. P. Pucillo, A. Carrabs, S. Cuomo, A. Elliott, and M. Meo, ‘Cold expansion of rail-end-bolt holes: Finite element predictions and experimental validation by DIC and strain gauges’, *Int. J. Fatigue*, vol. 149, Aug. 2021, doi: 10.1016/j.ijfatigue.2021.106275.

[10] X. Xu, L. Xie, S. Zhou, J. An, Y. Huang, and D. Li, ‘Fatigue Crack Propagation Behavior and Life Prediction of Welded Joints of SMA490BW Steel for Bogies’, *Processes*, vol. 11, no. 7, Jul. 2023, doi: 10.3390/pr11071984.

[11] D. Ferreño *et al.*, ‘Experimental and finite element fatigue assessment of the spring clip of the SKL-1 railway fastening system’, *Eng. Struct.*, vol. 188, pp. 553–563, Jun. 2019, doi: 10.1016/j.engstruct.2019.03.053.