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Research Article

Multi-Objective Optimization of Lightweight Inboard Bearing Design for High-Speed Railway Axle

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Abstract:
This research delves into the intricate balance between reducing axle weight and maintaining structural integrity in high-speed rail transportation. Focusing on the critical factor of weight reduction in high-speed axle design, the study employs finite element simulations and standard calculations to systematically explore inboard and outboard bearing wheelsets. Particularly noteworthy is the examination of inboard bearing axles, revealing advantages in mass reduction, deflection, and stress mitigation, with an 8% lower weight than outboard bearing axles. Utilizing multi-objective optimization, the research achieves a remarkable 4% reduction in mass and an associated 4% decrease in stress, resulting in a 12% mass reduction compared to traditional axles. The study also enhances fatigue resistance, demonstrated through radial fatigue reverse factor (FRF) analysis. With a detailed methodology involving ABAQUS modeling, Python scripting, and optimization using the Pointer algorithm in Isight, this research adeptly navigates the trade-off, significantly contributing to the advancement of railway transportation systems.

Keywords: *Optimization, Inboard bearing axle, Outboard bearing axle, Infinite fatigue life, Lightweight design*

1. Introduction

Within the realm of rail transportation, the role of axles is crucial for ensuring both the safety and efficiency of train operations. The design of these axles necessitates a delicate equilibrium between durability and weight, as heavier axles can lead to elevated energy consumption, enhanced riding comfort and stability performance and reduced operational efficiency. Wheelset configurations can be classified into two main types: inboard and outboard bearing wheelsets, as illustrated in Fig. 1. The utilization of inboard bearings within bogies has undergone substantial growth in recent times. The elongated design of an outboard solution offers enhanced design adaptability due to the greater available space encircling the axle. Nevertheless, existing literature highlights that low track force bogies commonly adopt an inboard bearing arrangement, leading to lighter bogie assemblies with reduced structural demands [1]. These bearings present distinct advantages, including diminished total and unsprung mass, as well as lateral force and moments of inertia [2]. Such attributes not only enhance vehicle manoeuvrability along curves but also bolster track compatibility. Additionally, the adoption of inboard bearing axles proves beneficial in addressing specific maintenance challenges tied to conventional wheelsets.

Notably, a substantial proportion of a rail vehicle's overall mass (up to 41%) resides within the railway bogie [3], with the axle accounting for approximately 35% of a standard wheelset's total mass.

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This scenario underscores considerable potential for weight reduction. However, this endeavour is intricate due to the axle is constantly subjected to both combined loads and the stresses caused by cyclic bending fatigue throughout its operational life. The principal challenge involves achieving weight reduction while upholding durability especially for the high-speed train. To address this challenge, the application of multi-objective optimization techniques has emerged as a valuable approach, facilitating the development of lightweight yet resilient axle designs that align with the criteria of enduring fatigue performance. Previous research has concentrated mostly on individual aspects of axle design, such as structural or material strength, vibration resistance, and fatigue performance, and has lacked a complete strategy that considers both weight reduction and durability as complementary objectives [1, 4-6]. This study aims to illuminate the intricate balance between axle weight reduction, structural integrity and satisfy the infinite-life fatigue criterion, thus contributing to the development of high-speed railway transportation systems.

(a) (b)

Fig. 1. Trailer bogie wheelset with (a) inboard bearing axle and (b) outboard bearing axle.

2. Multi-Objective Optimization Methodologies

This study involves an investigation of a railway inboard and outboard bearing axle, employing the commercially available software Abaqus/CAE integrated into an Isight simulation workflow to attain at an optimized design focusing on both durability and weight performance aspects. The schematic representation of the specific optimization workflow procedure is depicted in Fig. 2. Initially, a Python script is used to generate a finite element model, which is subsequently executed in Abaqus/CAE as a pre- and post-processor. A parametric design optimization targeting the inboard bearing wheelset model is carried out using the Isight commercial optimization tool. Isight's integration of the Sim Code module facilitates the organization of input, output, and execution processes within the program [7]. This module operates by accepting a Python script as input, capturing all relevant parameters, and then modifying the code to extract data from the generated file and output it in TXT format. Moreover, an Abaqus module accepts the output file from Sim Code as input, subsequently generating an output database file. Lastly, the fatigue life assessment of the inboard axle is conducted using the commercial Fe-Safe software. This is executed post the extraction of load history data from the optimized finite element model and subsequent comparison with the existing model.

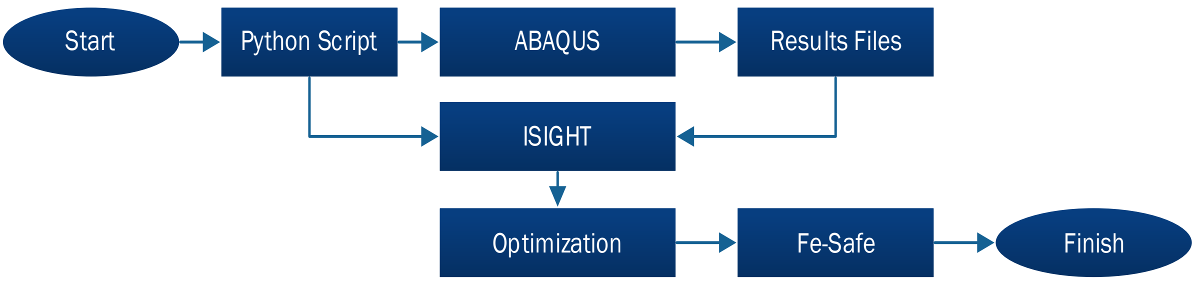
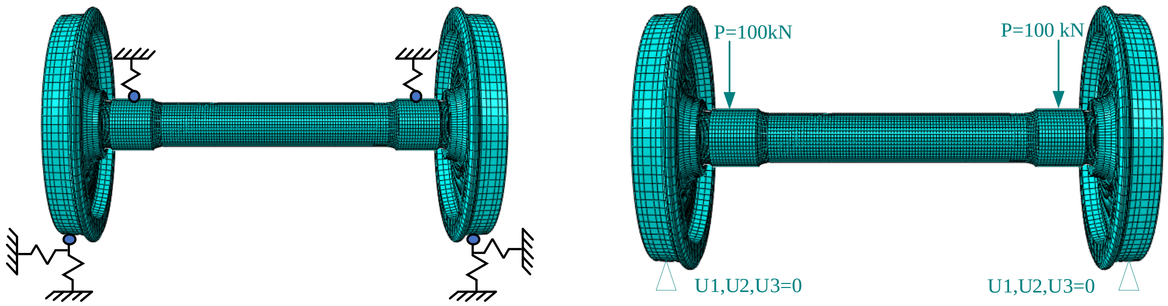


Fig. 2. Structural analysis and optimization process workflows chart

2.1 Finite Element Model

Using Python script, the FE model is implemented in Abaqus/CAE to parameterize the geometric dimensions and automatically apply the contact and boundary conditions as the geometry is modified during the optimization procedure. The wheelset model in this work has two versions: one is an inboard bearing axle model and the other is an outboard bearing axle model. As illustrated in Fig. 3, C3D8R hexahedral solid element type is chosen to ensure convergence and minimize computational cost by carefully meshing the contact of the wheelset. The EA4T steel, which is commonly used in modern railroad axles, is a linear elastic body with a Young's modulus of E=206 GPa and a Poisson's ratio of 0.3.

Master-slave contact type with the user-defined specific radial interference fit technique [8] was used to represent the press fittings. In the context of highly nonlinear contact analyses, the interference is assumed to be 0.2 millimeters [9] and a friction coefficient of 0.1 is chosen as a consistent parameter to strike a balance between efficiency and accuracy. Using this procedure, solely normal contact is established. The behavior in the tangential direction adheres to the conventional Coulomb approach, wherein the maximum permissible shear stresses are associated with the contact pressure arising from the press fit between the contacting parts on the contact surfaces [8].



(a) Step 1- press fitting (b) Step 2- loading step

Fig. 3. Mesh, loading and boundary conditions of FE model.

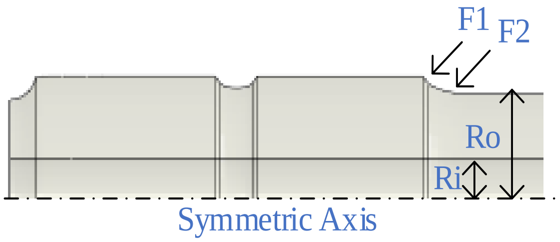
A strategic numerical approach was employed to address the issue, involving a two-step analysis: the first stage encompassing the press fitting, second step followed by loading. To stabilize the wheelset model, spring elements were implemented Fig. 3 (a). Specifically, the axle is confined by two springs exerting forces in directions 1 and 3, while the wheels encounter constraint through springs in three directions. The stiffness of these spring elements was assigned as 1 N/mm, a value devoid of physical meaning and represented the contact and deformation behavior during the press fitting process without introducing excessive stiffness or instability into the simulation. After constructing the residual stress field within the axle owing to press-fitting, necessitating the deactivation of all spring elements. The loading P owing to the bogie and train was applied to the journal bearings' middle plane Fig. 3 (b). Lateral forces and braking forces were neglected in the current case because the vertical axle load is the most critical factor.

2.2 Parametric Design Optimization Algorithm

In the context of optimizing the design of an inboard bearing for railway axle, the primary objective is to minimize the maximum mises stress while simultaneously minimizing the mass. This inherently gives rise to a multi-objective problem, where the ideal design should achieve a balance between minimizing mass and stress while satisfying the infinite life fatigue criterion. To address these challenges, the present research defines the mises stress parameter as an upper limit, set at half of the yield stress, to ensure a safety factor greater than 2. The maximum permissible stresses for hollow axles at transition fillets of EA4T steel is 145 MPa. This constraint formulation captures the safety and functionality aspects of the design while considering stress-induced failure modes. The objective, constraint and design variable are as shown in Table 1. The selected starting design variable ranges for the fillet radii (F1 and F2), inner radius (Ri), and outer radius (Ro) are meticulously chosen to enhance the structural integrity of the railway axle. F1 and F2 play crucial roles in mitigating the highest stress concentrations within the axle. Meanwhile, the axle's overall strength is greatly influenced by its inner (Ri) and outer (Ro) radii of the axle. A stronger axle is usually the result of larger values for Ri and Ro, which reduces the risk of fatigue failure. However, it is critical to find a balance between meeting strength requirements and taking things like weight and cost into account.

For the optimization process, the Pointer Automatic Optimizer is selected due to its ability to effectively handle diverse optimization scenarios. It integrates various algorithms, including an evolutionary algorithm, Nelder and Mead simplex downhill method, sequential quadratic programming (NPQL), a linear solver, and the TABU method [10]. This selection allows the optimizer to adapt to different optimization landscapes. It provides the flexibility to employ a single algorithm or all four simultaneously. Throughout the optimization process, the optimizer continually assesses the performance of each algorithm and dynamically adjusts internal parameters such as step sizes and iterations to achieve optimal results. This capability ensures that the optimization process is efficient and effective in discovering high-quality designs.

Table 1: Objective, constraint, and design variable at initial design (all dimensions in mm)



Optimization – Min {mass, S_mises_max}

Constraint – Max {S_Mises_max < 72.5 MPa (max: permissible stress /2)}

Starting Design Points
F1 = 75.0 [60.0 < x < 90.0]
F2 = 15.0 [12.0 < x < 18.0]
Ri = 30.0 [24.0 < x < 36.0]
Ro = 85.0 [68.0 < x < 102.0]

3. Infinite Fatigue Life Analysis

Railway axles experiencing multiaxial cyclic loading at high rotational speeds tend to reach their high cycle fatigue limit quickly during operation. Traditional fatigue analysis, which establishes a minimum number of cycles to failure, is inadequate for such scenarios. The focus is on determining the possibility of fatigue damage occurring during the component's entire loading history. The absence of damage indicates infinite life potential for the axle.

To address this, the Dang Van is an endurance criterion and employed for high cycle fatigue analysis subject to complex multiaxial stresses. In most cases, fatigue crack initiation takes place at stress concentration zones like fillets and notches. The Dang Van criterion has demonstrated considerable efficacy in assessing infinite fatigue life [11]. This methodology incorporates a multi-scale perspective, establishing a connection between the macroscopic stress derived from finite element analysis (FEA) and the microscopic stress within grain boundaries. Instead of directly calculating fatigue life, a novel approach involves the determination of the fatigue safety factor, denoted as the Fatigue Reverse Factor (FRF), utilizing a simplified pass/fail algorithm. Achieving an infinite life design necessitates ensuring that the FRF surpasses a value of 1 for all elements. To perform a Dang Van analysis, endurance limit stresses and corresponding R values need to be defined (Fig. 4), the endurance stress is 375 MPa for constant amplitude testing at R=0 and the endurance stress is 290 MPa for R=-1 [12].

The Dang Van Criterion can be expressed as

$$\tau = \alpha S = \tau_o \tag{1}$$

Where
τ= local shear stress
S= hydrostatic stress
α, τ_o are material-specific constants at a specific endurance.

The microscopic stress can be expressed as

$$\sigma_{ij}(P,t) = \Sigma_{ij}(P,t) + S_{ij}(P,t) \tag{2}$$

σ_{ij} = microscopic stress tensor
Σ_{ij} = macroscopic stress tensor
S_{ij} = residual stress tensor
P, t are position and time co-ordinates.

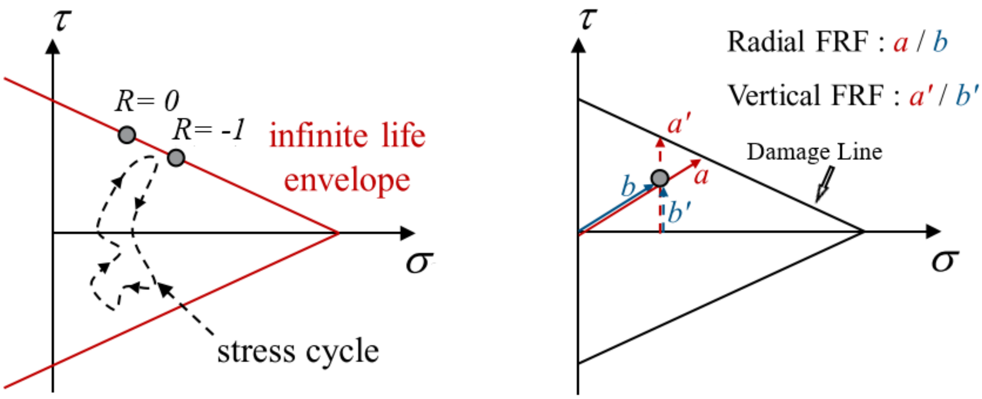


Fig. 4. The Dang Van plot for the endurance limit.

4. Results and Discussion

4.1 Analysis of an Inboard and Outboard Bearing Wheelset FEA Results

Comparing an inboard and outboard bearing wheelset highlight that the inboard bearing configuration results in a lighter wheelset compared to the conventional trailer bogie axle setup. The investigation, comprising both comprehensive finite element (FE) simulations and assessments based on the EN 13103/4 standard for outboard bearing wheelset and the inboard bearing wheelset follows BS 8535 standard calculations [13-15], underscores a remarkable similarity in longitudinal stress distribution patterns between the calculated and FEM results (Fig. 5). The minor 8% divergence observed can be attributed to residual stress originating from the press fitting process. The axle's most prominent bending stress emerges at the stress concentration fillet area, situated farthest from the natural axis.

The location of the highest bending stress within the axle is notable; it occurs at the stress concentration fillet area, farthest from the natural axis as shown in Fig. 5. The utilization of inboard bearings in a wheelset is advantageous from the perspective of axle stress. This is attributed to the mitigation of lateral forces, resulting in a reduction of the bending moment experienced by the axle. Under similar loading conditions, the maximum bending stress encountered by the inboard bearing is notably 38% lower than that experienced by the outboard bearing. An interesting contrast between the two bearing types is observed in their deflection behavior as shown in Fig. 6. The inboard bearing experiences a negative deflection 0.59 mm, while the outboard bearing demonstrates a positive deflection 0.70 mm. This phenomenon can be explained by differences in the load distribution and structural arrangement of the two bearing configurations. The weight of the inboard bearing axle is 8% lower than outboard bearing axle. This distinction can be reasoned by taking into account the varying structural layouts and load dispersion characteristics inherent to the two distinct bearing types.

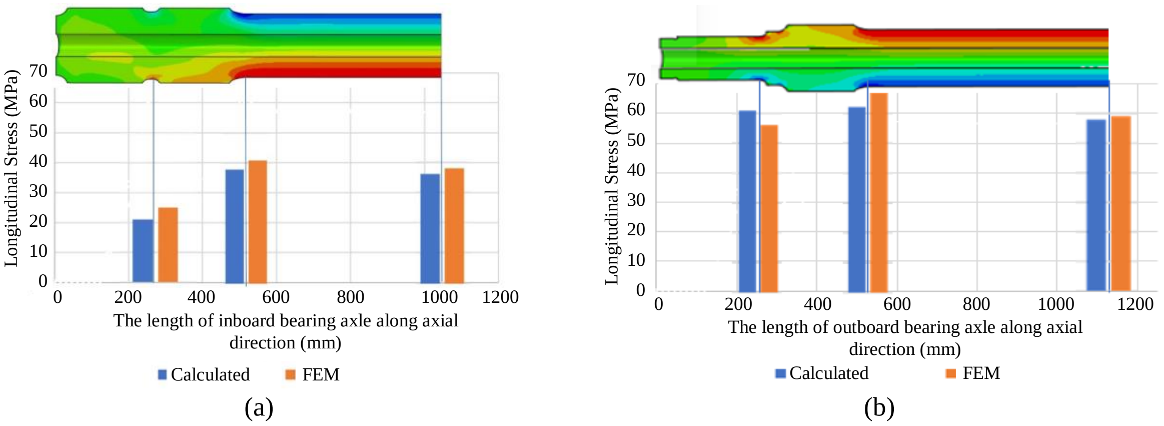


Fig. 5. Comparison of longitudinal stresses of calculated and FEM (a) inboard bearing axle and (b) outboard bearing axle.

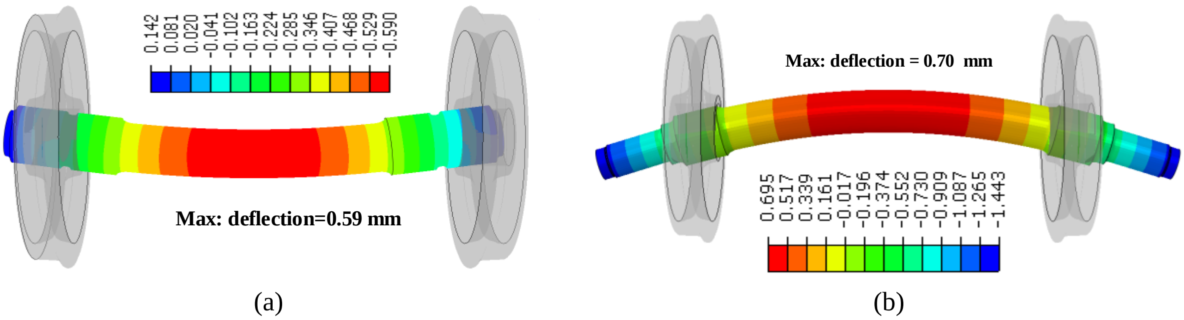


Fig. 6. Comparison the deflection of the axle under the loading (a) for the assembled inside axle boxes (b) for the assembled outside axle boxes.

4.2 Identification of Optimal Design

Fig. 7 shows the Pareto Front of Pareto-Optimal designs generated by plotting the mass objective vs. the S_mises_max objective. The green dot corresponds to the optimal solution composing the Pareto front, blue dots are the possible optimum points while the black plots are the dominated solutions. From Fig. 7, it can be seen that the mass of the wheelset is almost linear and the coefficient of determination R^2 for this linear relationship is calculated to be 0.9115, indicating a strong correlation between the two objectives.

Fig. 8 illustrates a 3D contour graph that depicts the relationship between design feasibility, S_mises-stress, and mass of the wheelset. The contours on the graph serve as insightful indicators of the interaction between these three factors. Points closer to the peak of the contour correspond to regions of higher design feasibility as the contour lines shift towards lower values of design feasibility. Correlation map (Fig. 9) shows the impact of model parameters on target objectives and solid lines represent stronger correlations than dash lines. It can be used to calculate the rank and linear correlation values for every pair of parameters in a model. The inner radius parameter (Ri) and S_mises_max have the strongest inverse linear correction (Rank = -0.978 and Linear coefficient =-0.998) among other parameters.

Fig. 10 illustrates the design variable optimization process history for F1, F2, Ri, and Ro. Graphs show the change of such parameters during the analysis run by run and provide an insight into the convergence of the results. Table 2 presents a comparison between initial and optimum design points, indicating reductions in mass of axle 4% (0.315 to 0.302 tons) and stress 4% (40.39 to 38.82 MPa) achieved through optimization.

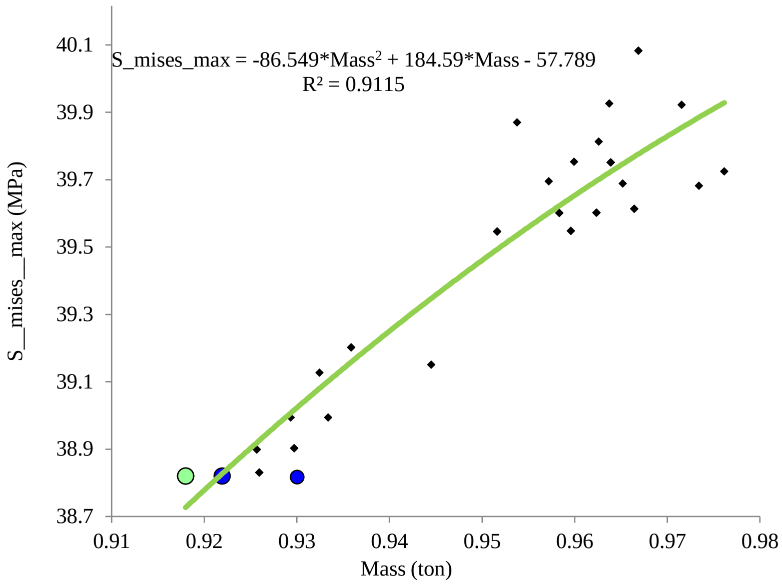


Fig. 7. Pareto plot of S_mises_max vs. mass from optimization.

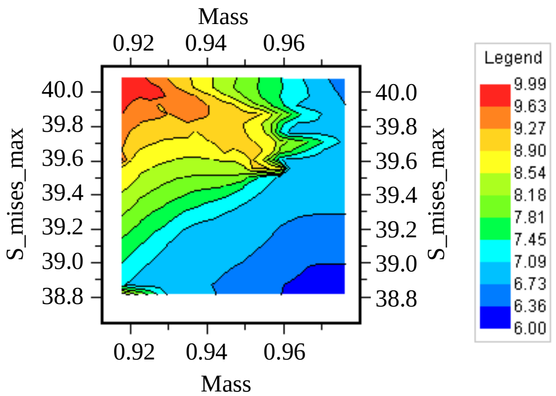


Fig. 8. 3D contour graph of design feasibility vs mass, S_mises_max.

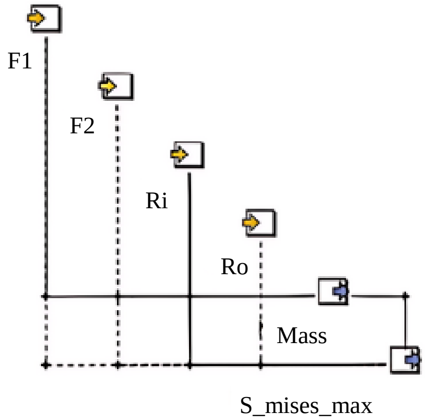


Fig. 9. Correlation map of input and output parameters.

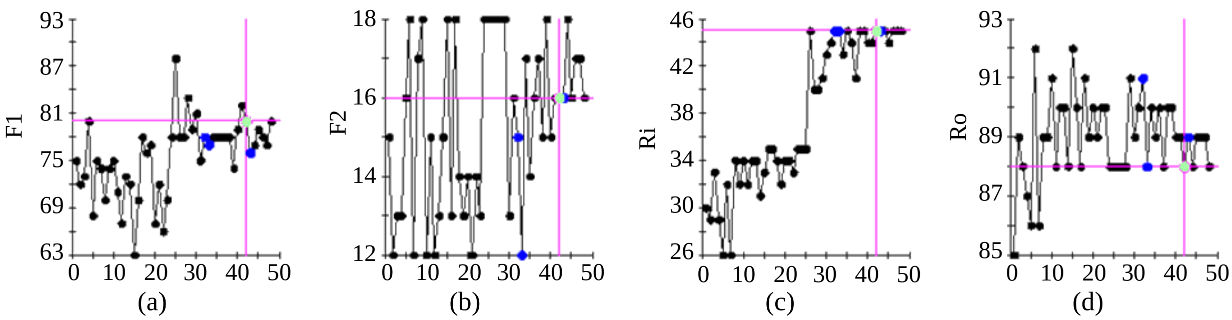


Fig. 10. History of design variable optimization process (a) F1, (b) F2, (c) Ri, (d) Ro.

Table 2: Comparison of the starting design points and optimum design points of inboard bearing axle.

	F1(mm)	F2(mm)	Ri(mm)	Ro(mm)	Mass(ton)	S_mises_max(MPa)
Starting design points	75	15	30	85	0.315	40.39
Optimal design points	80	16	45	88	0.302	38.82

4.3 Assessment of Infinite Life

Fig. 11 presents the results of the radial fatigue reverse factor (FRF) contour analysis before and after an optimization process. The analysis is focused on the inboard bearing axles, particularly their shoulder fillets, with the goal of enhancing their fatigue performance. The key observation is that both of the design points are satisfy the infinite fatigue life condition and the minimum DV Radial FRF value, which was initially 4.59, has increased to 4.64 after the optimization process. This improvement in the FRF indicates that the axles' fatigue resistance under radial loading conditions has been enhanced due to the optimization method applied.

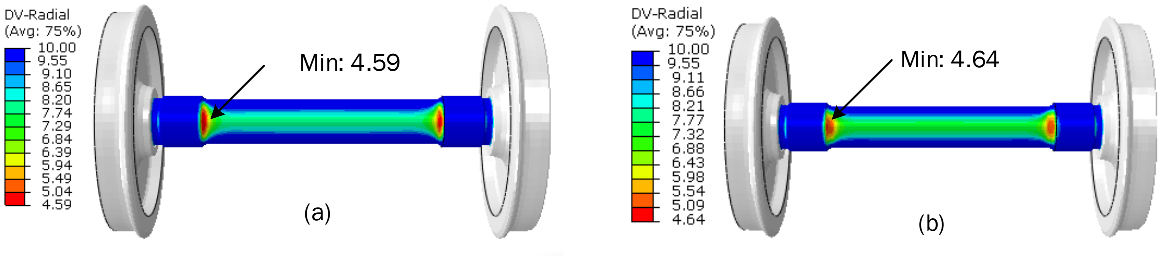


Fig. 11. Radial FRF contour of (a) before optimization and (b) after optimization.

5. Conclusion

This study highlights the intricate interactions between reducing axle weight at high speeds and maintaining structural integrity in rail transportation. Lightweight high-speed train axles are required to reduce aerodynamic forces, enhance performance, and ensure track compatibility and durability. Through comprehensive finite element simulations and assessments based on EN 13103/4 and BS 8535 standard calculations, the study illuminates the distinct characteristics of inboard and outboard bearing wheelsets. Comparative analysis reveals a noteworthy 8% reduction in weight for inboard bearing axles compared to their outboard counterparts, along with a significant 38% decrease in bending stress and 14% decrease in deflection. Evidently, the design of inboard bearing axles emerges as more favourable considering these findings. The subsequent pursuit of multi-objective optimization techniques leads to significant improvements in inboard bearing axle design, as evident in the Pareto front analysis, 3D contour graphs, correlation map and design variable optimization history. Particularly remarkable is the achievement of a 4% mass reduction and a corresponding 4% decrease in stress levels through the optimization process. The research also highlights enhancements in fatigue resistance via radial FRF analysis. By navigating the balance between weight reduction and structural robustness, this study contributes valuable insights to the development of railway transportation systems.

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