Topology Optimization of Draw Gear Support for Railway

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Abstract— **The growing global scarcity of raw materials, combined with the rising economic costs of manufacturing, has increasingly directed research and industrial efforts toward the development of innovative products designed with improved material efficiency. These efforts typically focus on minimizing material consumption, adopting more cost-effective and energy-efficient production technologies, and reducing reliance on manual labor through automation. Such strategies not only contribute to lowering the overall production cost of components but also support improvements in operational efficiency, for instance by enabling even slight increases in the payload capacity of railway freight transport. Nevertheless, optimization of this kind must not come at the expense of safety. On the contrary, the requirements imposed on newly manufactured components in the railway sector have become progressively more stringent, reflecting both regulatory demands and the expectations of operational reliability. In the present study, a draw gear support designed in accordance with EN 15566 was investigated. A topology optimization procedure was carried out to reduce the mass of the component, followed by a stress–strain analysis and a fatigue assessment to evaluate its structural performance and durability.**

Keywords— **Topology optimization, FEM, Fatigue, Drawbar, Railway wagons.**

I. Introduction

In the design of new products, priority is given to ensuring compliance with current technical, functional, and economic requirements in order to guarantee reliable operation throughout the product's service life. Growing market competition requires continuous product optimization to improve performance and lower production and operating costs [1]. This process typically includes the refinement of structural geometry, the selection of advanced materials, and the adaptation of manufacturing technologies to achieve higher efficiency.

These benefits extend not only to the optimized product itself but also to other products of the manufacturer with similar parameters. In this way, transportation costs are reduced for the customer, while additional discounts can be realized for bulk purchases.

In recent years, topology optimization has been increasingly applied. By removing material from weakly loaded areas, a significant reduction in weight can be achieved. However, this approach results in complex geometries, which introduce technological limitations during manufacturing. Despite these challenges, the automotive industry has demonstrated that a 10% mass reduction can lead to a 6–8% decrease in fuel consumption [2].

With the development of metal additive manufacturing technologies, such as Selective Laser Melting (SLM) and Direct Energy Deposition (DED), it has become possible to produce geometries that cannot be manufactured by conventional methods [3]. However, the industrial application of these methods remains constrained by high production costs and the generation of residual stress in the manufactured components.

Residual stresses are recognized as one of the most critical challenges in metal additive manufacturing, as they originate from repeated thermal cycling and non-uniform cooling during processing [4]. These stresses can lead to distortions, crack initiation, and loss of dimensional accuracy. In addition, complex geometries often contain stress concentrators that increase the likelihood of local failures [5]. To address these issues, integrated topology optimization techniques and computational modeling approaches have been proposed [6]. Furthermore, post-processing treatments—such as annealing, quenching, or mechanical finishing—are applied in combination with numerical simulations of the internal microstructure. Through these methods, the risk of deformation and microcrack formation in the manufactured component can be assessed and predicted [7].

Therefore, in engineering practice, a balance must be established: the complex geometries generated through topology optimization should be adapted to conventional manufacturing methods such as casting. This approach enables both economic efficiency and technological feasibility to be achieved simultaneously. A representative example can be found in shipbuilding, where the application of topology optimization to a container ship hatch cover resulted in a mass reduction of 2,49 tons, yielding direct material cost savings of $3635 per component [8].

In many countries, the use of automatic couplers has been widely adopted. According to [9], their adoption exceeds 80–85% in North and South America and in Australia. In Africa, the adoption rate is above 50%, while in Asia it approaches 80%. In Europe, however, screw couplers remain the most common solution, despite the ERA technical report recommending a transition to digital automatic couplers (DAC) [10] and the availability of modern patents and research on this subject [11], [12] and [13].

The loads that occur during operation are significant, and the requirements for railway vehicles are defined in numerous regulatory documents, such as UIC leaflets, European standards, and TSI specifications [14], [15], [16] [17]. Various studies have investigated defects in different elements of the coupling system, often based on actual

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failures observed in service [18], [19], [20] and [21], while [22] presents statistical data on the most frequent types of failures. These findings confirm the severe loading conditions to which coupling systems are subjected. Studies on longitudinal dynamics [23], [24], [25] and [26] demonstrate that the design of such components requires special consideration due to the dynamic nature and amplitude of service loads, which expose the components to cyclic loading and fatigue. In the present study, the focus is placed on the support of the coupling device, which is widely used in railway vehicles across the European Union.

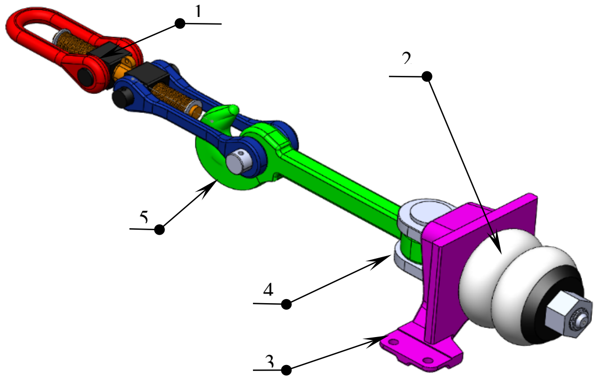

Fig. 1. Standardized draw gear: 1 – screw coupling, 2 – polymer energy absorber, 3 – DG support, 4 – draw bar, 5 – draw hook.

In [27], the support of the draw gear, positioned at location 3 in Fig. 1, was investigated using a newly designed configuration. The results from that publication have been adopted as key parameters for the present work.

II. Load cases and evaluation criteria.

The component under investigation is designed to withstand a minimum breaking force of 1500 kN and to operate for 30 years in compliance with [16]. A detailed analysis can be found in [27], while TABLE I presents the cycle counts for different load cases, which are applied to assess the probability of fatigue assessment.

TABLE I
Condition of dynamic test for all parts except screw coupling [16]

Lifecycle in years	Range of forces to be applied		
	1000kN	ΔF1 = 200kN	ΔF2 = 675kN
	1200kN	ΔF1 = 240kN	ΔF2 = 810kN
	1500kN	ΔF1 = 300kN	ΔF2 = 1015kN
		***N_1* in cycles**	***N_2* in cycles**
20	all	10^6	$1,45x10^3$
30	all	$1,5x10^6$	$2,15x10^3$

The load cases required for the static and dynamic assessment of the component are summarized in TABLE II.

TABLE II
Load cases for support plate for load of 1,5MN

Load case	Force magnitude	Evaluation criteria
1	1500kN	Minimum braking force of 1500kN
2	1125kN	Accumulation damage <1
3	1015kN	Accumulation damage <1
4	300kN	Accumulation damage <1

The most used criterion for evaluating similar type of component is the safety factor, which is also widely applied to other elements of railway rolling stock [28]. It is defined as the ratio between allowable stress and calculated stress, as expressed in (1).

$$S \geq \frac{\sigma_{lim}}{\sigma_c}, \qquad (1)$$

where:
S – safety factor,
σ_c – calculated stress,
σ_{lim} – permissible stress;

In this study, the yield limit is not taken as a strict criterion; instead, the component is assessed based on the requirement for a minimum breaking force, as specified in TABLE II. Therefore, the evaluation is performed by considering fatigue accumulation and by extending the computational model into the plastic region. Fatigue damage is determined using Miner's rule, as applied in [29], and is calculated according to (2).

$$D = \frac{n_1}{N_1} + \frac{n_2}{N_2} + \cdots + \frac{n_k}{N_k} = \sum_{i=1}^{k} \frac{n_i}{N_i} \leq 0 \qquad (2)$$

where:
D – accumulated fatigue in the considered node,
n_i – applied number of cycles for investigated load cases,
N_i – endurance number of cycles according to S-N;

III. Methodology for optimization.

Based on the performed analysis, a methodology for applying topology optimization has been developed. The methodology combines several approaches for structural optimization:

– Classical approach – based on stress analysis of the investigated component. This method is widely used in the design of mechanical engineering products, as it enables the identification of specific zones in the structure, such as stress concentrators, over-dimensioned regions, and elements that do not contribute to the load-bearing capacity.
– Topology optimization – capable of generating complex geometries by performing iterative stress analysis on the elements of the computational model and eliminating non-stressed elements. This process results in advanced geometrical forms that may require specialized manufacturing methods.

By combining the two methods, it becomes possible to identify zones where topology optimization cannot be effectively applied, particularly in regions with high stress concentrations. The proposed methodology includes the following steps:

- Creation of a computational model and execution of a verification calculation. The probability of fatigue occurrence in the material is assessed using the methodology in [27].
- Analysis of the stress state of the investigated object, including the identification of weakly stressed zones and stress concentrators.
- Development of a geometry focused on removing

material from low-stress zones and introducing material to counteract stress concentrators.
- Verification of the new geometry, including fatigue assessment and analysis of results according to [27].
- Application of topology optimization.
- Analysis and processing of the optimized geometry, followed by verification calculations and fatigue assessment according to [27].
- Refinement of the geometry, taking into account the selected manufacturing method.
- Final verification of the component and analysis of the results.

IV. APPLICATION OF THE DEVELOPED METHODOLOGY.

In the present work, the first step of the proposed methodology was carried out in detail in [27]. The most significant results are summarized in the comparison provided below.

A. Application of optimization based of Stress distribution approach.

As part of the application of the methodology, the first step involved the stress-state analysis of the finite element model of the draw gear support, the detailed investigation of which is presented in [27]. For the stress analysis, the most unfavorable loading case was selected, corresponding to the maximum applied force, namely LC1 from TABLE III. Fig. 2illustrates the distribution of stress at a loading time of 1 s, where the applied force reaches 1500 kN.

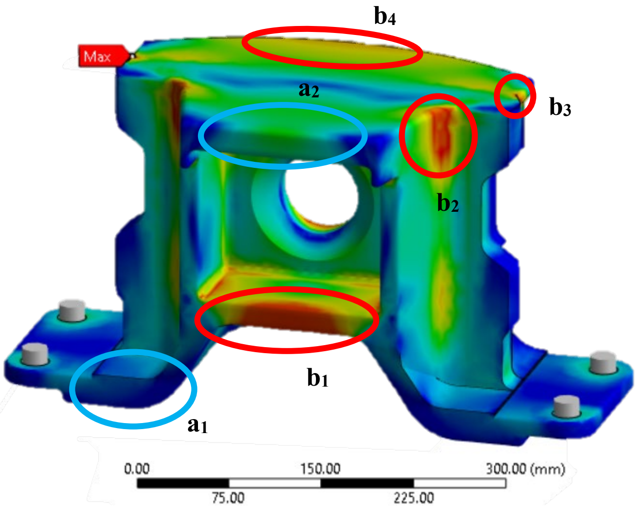

Fig. 2. Stress zone of a new design drawbar support. a – oversize zone, b – stress concentrators.

The stress analysis identified several distinct regions of interest in the geometry of the draw gear support. Some of these regions, highlighted in blue, indicate oversizing, meaning that the material dimensions there are larger than necessary to safely sustain the applied loads. The most prominent example of this condition is located of the lower part, referred to as zone a1, where the stress levels remain below 60 MPa. Such low stresses suggest that the thickness of the material in this area could be reduced without compromising the structural integrity of the component.

Another area of interest is zone a2, where the stresses reach values of approximately 200 MPa in the central region of the overhanging section. However, toward the two ends, located near the closing box of the drawbar of the draw gear, the stress levels drop significantly to around 50 MPa. This uneven distribution indicates that the geometry in its current form is not fully optimized for load transfer. The central portion contributes more effectively to carrying the applied forces, while the ends carry very little load.

From these observations, two important conclusions can be drawn. First, the thickness of the material in both zones a1 and a2 is greater than required to withstand the design loads. Second, the extended geometry at the top, which resembles an overhang, does not contribute significantly to the load-carrying capacity of the structure and can be considered unnecessary from a functional perspective. These findings highlight opportunities for reducing excess material, which is in line with the objectives of the proposed optimization methodology.

The zones highlighted in red represent areas of stress concentration. In zone **b$_1$**, the maximum stresses reach values close to 350 MPa. Although this indicates a critical region, the stress field shows a gradual dissipation, which makes it possible to consider reducing the thickness of the material in this area without negatively affecting the strength of the component.

A similar phenomenon is observed in zone **b$_3$**, where the stress levels are lower compared to **b$_1$**. For this region, a more decisive modification was introduced. Originally, a horizontal web was positioned above zone **b$_3$**, with the purpose of lowering the stresses in the neighboring zone **b$_2$**. However, the analysis demonstrated that the web was not efficient in fulfilling this role and added unnecessary weight to the structure. For this reason, the web was completely removed. To compensate for its removal and to control the stress concentration in zone **b$_2$**, reinforcing ribs were introduced around the radius of this area. These ribs are more effective in redistributing stress and in reducing the risk of fatigue cracks developing over time

Based on the conducted analysis, several constructive modifications were introduced, resulting in a weight reduction of approximately 11%. Fig. 3 illustrates the optimized geometry obtained after the application of the classical optimization approach, which relies on stress-state analysis. The implemented modifications include removal of the rib in the upper part of zone **b$_4$**; reduction of the wall thickness of the drawbar housing of the draw gear; increase of the height of the base plate; cut-outs in the upper section; and the addition of stiffening ribs in zone **b$_2$**.

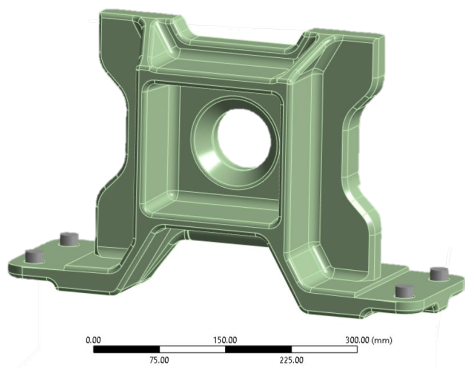

Fig. 3. Optimization design of STRESS DISTRIBUTION APPROACH

After the proposed design modifications were implemented, the new component was subjected to detailed verification. The purpose of this step was to ensure that the modified geometry provides the necessary structural capacity and resistance to fatigue. In addition, the verification was used to examine how the modifications influence the stress distribution. To achieve this, the methodology presented in [27] was applied, which made it possible to directly compare the new design drawgear support with the original design. The results of this assessment, which illustrate the impact of the modifications and their benefits, are presented in Fig. 4.

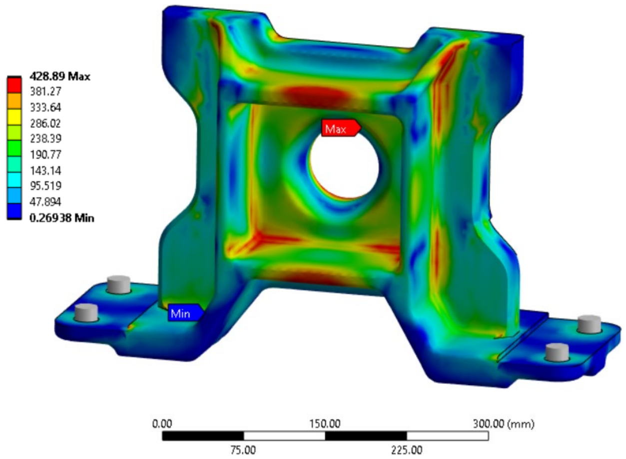

Fig. 4. Stress results of Optimization design structure by STRESS DISTRIBUTION APPROACH

The presented results correspond to loading case LC1, which represents the most critical condition with the maximum applied force. A significant reduction of the dark-blue regions, representing stresses up to 50 MPa, can be observed. This change indicates that stresses are now distributed more uniformly compared to the previous design.

In zone **a$_2$**, the loading level is greater than in the original geometry, and the stresses are distributed more evenly. This leads to more effective use of the material. In zone **b$_2$**, where a stress concentrator was previously identified, the stress field now covers a larger area. This means that the localized character of the concentration has been eliminated, reducing the risk of crack initiation in this critical region.

A fatigue assessment was then carried out using Miner's rule, following the methodology in [27] [29] The obtained damage value is significantly lower than 1, which confirms that the revised component is not expected to fail due to fatigue within the required service life.

In summary, the results demonstrate that local stress concentrators have been removed, and the stresses are more uniformly distributed throughout the structure. The fatigue analysis also shows that the accumulated damage remains far below the critical threshold. This indicates that the component can operate reliably over a 30-year service period. These improvements establish a strong foundation for the next stage of the study, which involves the application of topology optimization to further enhance weight efficiency

B. Application of Topology optimization.

When applying topology optimization, several adjustments to the model are required. These adjustments include the removal of nonlinear contacts from the finite element model, since such contacts cannot be used in combination with topology optimization. In order to comply with the requirements of the TSI, European standards, and UIC leaflets [16], [14], [15] and [17] it is also necessary to specify the zones where material removal is not permitted. These zones typically include functional areas such as connection interfaces, fastening holes, and surfaces intended for assembly. Some of these restricted zones are illustrated in Fig. 5.

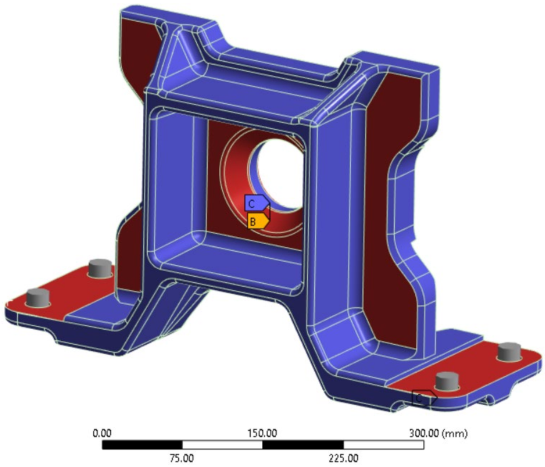

Fig. 5. Restricted region for optimization according to normative legislation.

The restricted zones include the mounting holes located symmetrically on both sides, the supports through which the load is transmitted to the wagon frame, the openings and chamfers associated with the drawbar of the coupling device, and the platform on which the energy-absorbing unit is seated. In this way, it is ensured that no material is removed from these critical regions and that the optimized component remains fully compatible with operational requirements. The optimization target was defined as a 30% mass reduction, and Density Based Optimization was applied.

The optimized version of the component obtained after the application of topology optimization is shown in Fig. 6. The transparent contour represents the geometry obtained through the application of the classical stress distribution approach, while the discretized region corresponds to the geometry optimized using topology optimization.

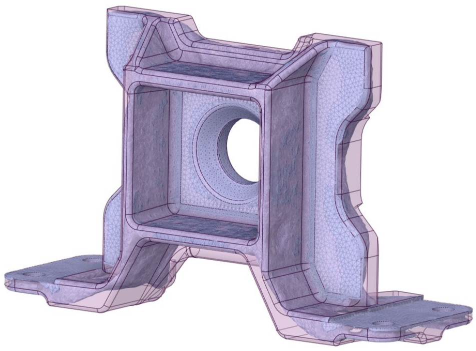

Fig. 6. Comparation of geometry of drawgear support.

Before proceeding with the verification calculations of the component and the evaluation of accumulated fatigue, the optimized geometry must be prepared. Using appropriate tools in *SpaceClaim™*, the geometry was smoothed and multiple “craters,” which typically appear after the optimization process, were removed. Due to the high complexity of the geometry, a non-conventional meshing strategy was required; therefore, a Cartesian mesh was applied. After completing these steps, the finite element model was solved, and a fatigue assessment was performed. The results obtained for loading case LC1 are shown in Fig. 7. It is noteworthy that the maximum stresses are approximately 100 MPa higher compared with those obtained using the optimization based on the stress distribution approach.

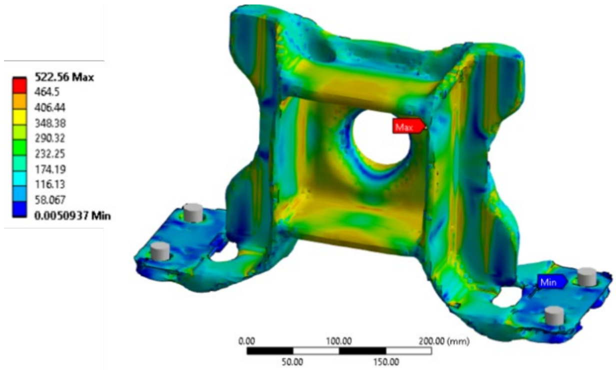

Fig. 7. Results of calculation model after appalling topology optimization – LC 1

The fatigue assessment revealed significant differences in the number of cycles that the component can withstand under different loading cases.

C. Adaptation of optimized geometry to manufacturing technology.

The geometry obtained in the previous step can meet the modern requirements of the regulatory documents [14] [15], [16] and [17],, but it must be adapted to a suitable manufacturing process, as discussed in [9]. For a one-off component, which is not intended for series production, metal additive manufacturing, such as that considered in [3], [4], [5] and [6] could be an appropriate choice. In the present case, however, this approach is not applicable, since the component is designed for mass production and, due to the nature of the loads to which it is subjected, it would be vulnerable to residual stresses generated during the additive manufacturing process.

For this reason, attention was focused on developing a casting, taking the optimized geometry as a basis and modifying it to include technological fillets, chamfers, draft angles, machining allowances, and other features necessary for the production of the final component. The results for the most unfavorable loading case are shown in Fig. 8, where the maximum stresses reach 448 MPa, and the critical stress zone remains unchanged compared to the results obtained after the application of topology optimization.

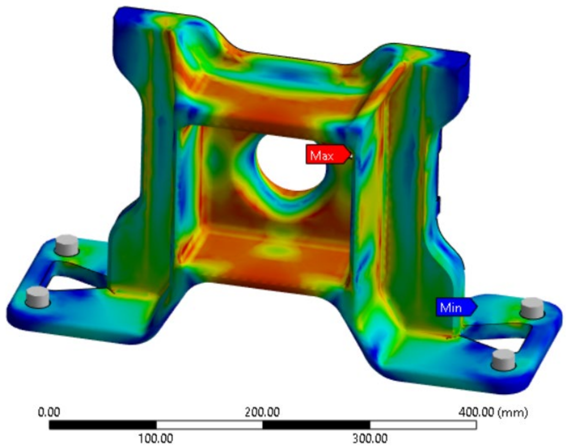

Fig. 8 Results of calculation manufacturing adapted optimized design structure – LC 1

V. Comparison of results

As part of the study, four alternative designs of the component were developed, each with different mass and production cost. Fig. 9 presents a comparison between the first variant and the optimized geometry adapted for manufacturing by casting, showing the stress state under the most unfavorable loading case.

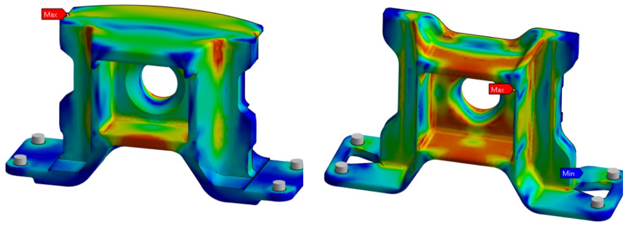

Fig. 9. Comparation of stress distribution between new design structure and final optimized design structure.

A clear reduction of the blue and green regions is observed, accompanied by a more uniform distribution of stresses throughout the component. The outcomes of the methodology are summarized in TABLE III, which lists the maximum stresses under all loading conditions, the calculated fatigue damage, the number of design changes, and additional relevant data.

TABLE III
Comparison of the results in different computational model.

Design product	New design product	Stress distributio n approach	Topology optimizatio n	Topology optimizatio n /casting
Max Strass [MPa]	434.5	428.89	523.57	448.7
Iteration process	6	1	1	2
Accumulate d damage	0,01	0,03	2,08	0,12
Mmanufact uring method	Casting	Casting	additive manufactur ing	Casting
Total weigh [kg]	40.54	36,13	25.44	28.78

The results presented in TABLE IIIshow increased cycle counts for LC1 and LC2, where the evaluation was performed for 2150 cycles, while the test program specifies only one cycle for each case. The outcomes of the topology optimization indicate that under such conditions the accumulated fatigue damage significantly exceeds 1. However, when the cycle counts for the first two load cases are reduced to the values specified in the test program, the damage value decreases to within acceptable limits, reaching 0.17.

Although the mass of the topology-optimized variant is the lowest at 25.44 kg, its geometry is too complex to be manufactured as a casting

VI. Conclusions and Recommendations

In conclusion, it should be noted that a methodology for weight reduction of newly developed components has been proposed. This methodology is characterized by its ability to eliminate imperfections in the initial designs that prevent further optimization.

The methodology was applied to a newly developed support of a draw gear. The results show that the mass of the investigated component was reduced by approximately 29%. Verification analyses were performed at each step of the methodology, considering more than ten variants of the support. The analysis of the results demonstrates that, despite the occurrence of localized plastic deformations, the accumulated fatigue damage does not lead to failure of the component and complies with the requirements of EN-15566.

For further development of the study, it is advisable to simulate the casting process using appropriate techniques such as CFD. To fully validate the optimization methodology, it is necessary to produce a prototype and perform experimental testing. During such tests, stresses could be measured at critical points of the structure to confirm the accuracy of the numerical predictions.

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References

[1] B. Martin, B. Luca, G. Angelo and H. Richard, "Informing additive manufacturing technology adoption: total cost and the impact of capacity utilisation," *International Journal of Production Research,* vol. 22, no. 23, pp. 6957-6970, 2017.

[2] P. C. Gibson, M. Stephen, Z. Philani, M. Whisper and S. Andreas, "Comparative analysis of topology optimization versus material substitution:Is there a best method for vehicle weight reduction?," *Procedia CIRP,* vol. 128, pp. 132-137, 2024.

[3] C. Yunhui, J. C. Samuel, M. C. David, M. Sebastian, A. H. Simon, M. F. Danielle, C. Thomas, C. A. Robert, V. M. Oxana, J. B. Gavin, A. J. Martyn, L. A. L. Chu and D. L. Peter, "Correlative Synchrotron X-ray Imaging and Diffraction of Directed Energy Deposition Additive Manufacturing," *Acta Materialia,* vol. 209, p. 116777, 2021.

[4] B. Nabin, P. J. Muhammad, R. Nithin and S. R. Chandra, "A Review of the Residual Stress Generation in Metal Additive Manufacturing: Analysis of Cause, Measurement, Effects, and Prevention," *Micromachines MDPI,* vol. 14, no. 7, p. 1480, 2023.

[5] B. Peiying, J. Ali, X. Kewei, Y. Fangxia, Z. Nan and S. Yun, "A Review of the Evolution of Residual Stresses in Additive Manufacturing During Selective Laser Melting Technology," *Materials MDPI,* vol. 18, no. 8, p. 1707, 2025.

[6] K. B. Sina, K. Abdullah, S. C. Omer, L. M. Peyman, O. Soner, O. Akin, K. Adnan and K. Bahattin, "Minimizing thermally induced residual stresses in metal additive manufacturing through peridynamics topology optimization," *Engineering with Computers,* vol. 41, pp. 2505-2531, 2025.

[7] G. Nicolò, H. Daijun, Y. Dewen, C. Fan and Y. Wentao, "Crystal plasticity model of residual stress in additive manufacturing using the element elimination and reactivation method," *Computational Mechanics,* vol. 69, p. 825–845, 2022. [8] J. K. Author, "Title of paper," to be published.

[8] F. Y. Ahmet and K. Mehmet, "Topology Optimization-Driven Design of Container Ship Hatch Cover for Lightweight Performance and Cost Efficiency," Journal of Offshore Mechanics and Arctic Engineering," *Journal of Offshore Mechanics and Arctic Engineering,* vol. 147, no. 4, p. 041701, 2025.

[9] Bundesministerium für Digitales und Verkehr (BMDV), "Development of a concept for the EU-wide migration to a digital automatic coupling system (DAC) for rail freight transportation," Federal Ministry of Transport and Digital Infrastructure (BMDV), Berlin, 2020.

[10] ERA, "Digital automatic couplers (DAC): Technical Document.," European Union Agency for Railways (ERA), Valenciennes, 2022J.

[11] M. Schüler, "DRAW AND BUFFER GEAR FOR A RAILWAY COUPLING, AND RAIWAY CAUPLING". International Patent WA 2022/223394 A1, 27 October 2022.

[12] W. Simon, C. Colin and S. Maksym, "A review on design and testing methodologies of modern freight train draft gear system," *Railway Engineering Science,* pp. 127-151, 7 June 2021.

[13] Y. Om Prakash and V. Nalinaksh S., "The influence of AAR coupler features on estimation of in-train forces," *Railway Engineering Science,* pp. 233-251, 18 February 2023.

[14] leafled UIC 520, Wagons, coaches and vans - Draw gear - Standardisation, 2003.

[15] Leaflets UIC 826, Technical provisions for the supply of screw couplings for tractive and trailing stock, UIC, 2004.

[16] БДС EN-15566:2022 Railway applications - Railway Rolling stock - Draw gear and screw coupling, European Committee for Standardization, 2022.

[17] COMMISSION, "concerning the technical specification of interoperability relating to the subsystem 'rolling stock - freight wagons' of the trans - European conventional rail system," *Official Journal of the European Union,* 2006.

[18] C. Anghel, D. I., F. N., B. N. and B. R., "The analysis of a damaged component from the connection system of the wagons," *Engineering Failure Analysis,* pp. 93-107, 05 December 2012.

[19] V. P. M., J. ,. G. D., R. N. and J. F. F., "Experimental and numerical research on the failure of railway vehicles coupling links," *Engineering Failure Analysis,* p. 105497, 21 May 2021

[20] N. František, J. Michal, P. Michal, T. Libor, F. Stanislava and B. Otakar, "Investigation of the brittle fracture of the locomotive draw hook," *Engineering Failure Analysis,* pp. 305-312, 05 July 2019.

[21] U. Robert, N. František, N. Pavol and P. Peter, "The investigation of the fatigue failure of passenger carriage drawhook," *Engineering Failure Analysis,* pp. 609-616, 21 June 2019.

[22] V. P. Marija, T. Jovan, Z. S. and M. Nebojša, "Analysis of coupling system failures on freight trains," *ACTA TECHNICA JAURINENSIS,* vol. 16, no. 1, pp. 11-17, 2023.

[23] S. Maksym, C. Colin, Q. S. Yan, M. Mitchell, S. Valentyn and M. Tim, Design and Simulation of Rail Vehicles, Boca Raton: CRC PressTaylor & Francis Group, 2014.

[24] W. Wei, H. Yang, W. Qing, Z. Xubao, Z. Jun and Z. Yuan, "An air brake model for longitudinal train dynamics studies," *Vehicle System Dynamics,* vol. 55, no. 4, pp. 517-533, 2016.

[25] O. E. Pudovikov and S.A. Murov, "Simulation of Regulating Braking Mode of Long Train," *World of Transport and Transportation,* vol. 13, no. 2, pp. 28-33, 2015.

[26] P. Luca, F. Duccio and R. Andrea, "Modelling the longitudinal dynamics of long freight trainsduring the braking phase," in *12th IFToMM World Congress*, Besançon, 2007.

[27] M. Vladislav, "Assessment of fatigue life of railway drawbar support according to UIC and TSI requirements.," in *PROCEEDINGS OF THE TECHNICAL UNIVERSITY OF SOFIA*, Sofia, 2025.

[28] "БДС EN 12663-2:2010 Railway applications - Structural requirements of railway vehicle bodies - Part 2: Freight wagons," 2010.

[29] W. Tiantian, Z. Zhikang, L. Zhiguo, X. Jingsong, W. Weifeng and Y. Jingsong, "Fatigue test and service performance evaluation of high-speed train hanging equipment bolts," *Structures,* p. 106202, 18 March 2024.