**Improving the Structural Reliability of Self-Propelled Railcar Frames Through Modernization Techniques**

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**Abstract.** This study explores methods for improving the structural durability of self-propelled rolling stock frames operating within Uzbekistan’s transport network. Through a combination of experimental strain gauge measurements and finite element modeling, zones with high stress concentrations were identified and reinforced. The integration of real-world loading data with numerical simulations enabled precise evaluation of stress distribution and informed reinforcement placement. The structural modifications led to a notable reduction in peak stress levels and promoted a more uniform force distribution across the frame. Enhanced resistance to cyclic loads was achieved without compromising safety or operational performance. These findings support the feasibility of significantly extending the service life of rolling stock frames through targeted structural improvements. The proposed approach can be adapted to other rail systems seeking to enhance vehicle reliability and operational efficiency.

**Keywords:** **s**elf-propelled railcar, stress analysis, modernization, strain gauges, structural reliability, frame.

# INTRODUCTION

Ensuring the reliability and safety of special self-propelled rolling stock is a priority for Uzbekistan's railway transport sector. Frames of such vehicles are exposed to significant dynamic and static loads, leading to structural fatigue and damage over time. Modernization and scientific reinforcement of these structures contribute to extending their operational lifespan and minimizing failures.

This paper focuses on the stress-strain state analysis of the ADM-1 self-propelled railcar frame, employing experimental and simulation techniques to determine the effectiveness of proposed modernization measures.

Today, the total number of special self-propelled rolling stock in operation in our republic exceeds 180. A large portion of these special self-propelled rolling stock units have exceeded their service life and require repair of their main components to extend their operational period. The existence of problems related to the expiration of service life of special self-propelled traction rolling stock in railways and other industrial enterprises of the Republic of Uzbekistan further emphasizes the relevance of this scientific research.

The ADM-1 railcar plays an important role in construction, installation, repair work, and maintenance of the contact network in railway transport. During the operation of ADM-1 motor trolleys, metal structures, especially the main frame, deform under the influence of dynamic and static loads. Fatigue or stress in the frame leads to the appearance of cracks over time and, consequently, to the failure of the entire structure. This problem currently needs to be addressed through repair and modernization. [5, 6, 7, 8, 9, 10].

# LITERATURE SURVEY

In recent years, the study of electromechanical systems and structural reliability in self-propelled rolling stock has become increasingly prominent, especially in efforts to optimize technical performance and extend operational lifespan. One research direction involves the evaluation of the working condition and failure likelihood of onboard electromechanical components. Authors such as Gafurdjanovna et al. [1] have highlighted the importance of systematically assessing equipment reliability in rail service vehicles to ensure safe and uninterrupted function.

Parallel to this, methods for regulating repair intervals based on the equipment's actual state have been developed. For instance, Fayzibaev et al. [2] suggested mathematical models that support condition-based maintenance strategies, thereby reducing unnecessary downtime and extending asset life.

The structural fatigue behavior of critical load-bearing parts in rolling stock has also received considerable attention. Mukhamedova et al. [3] investigated fatigue characteristics in special-purpose self-propelled units, noting the role of repetitive loads in structural degradation. Research in this field often includes proposals for reinforcement or processing technologies, such as the wheel bandage hardening method after mechanical treatment studied by Fayzibaev et al. [4], which aims to increase resistance to wear.

On a broader scale, modeling of stress distribution and material strength has been a core component in locomotive component analysis. Grishchenko et al. [6] emphasized predictive techniques for determining the remaining operational life of locomotive frames, especially in heavy-duty applications. Sładkowski and Ruban [5], meanwhile, provided a deeper understanding of machining tools used in maintenance operations, which indirectly impacts the precision and quality of locomotive servicing.

Finite element modeling (FEM) has become a key analytical tool in these studies. For example, Yusufov et al. [8] and Abdurasulov et al. [9] used FEM to simulate how bogie frame structures respond to loads under various conditions, identifying critical zones vulnerable to fatigue damage. Complementing these works, Khamidov et al. [10] conducted service life evaluations specifically for the main frames of shunting locomotives under local railway conditions, proposing engineering-based strategies to prolong their use.

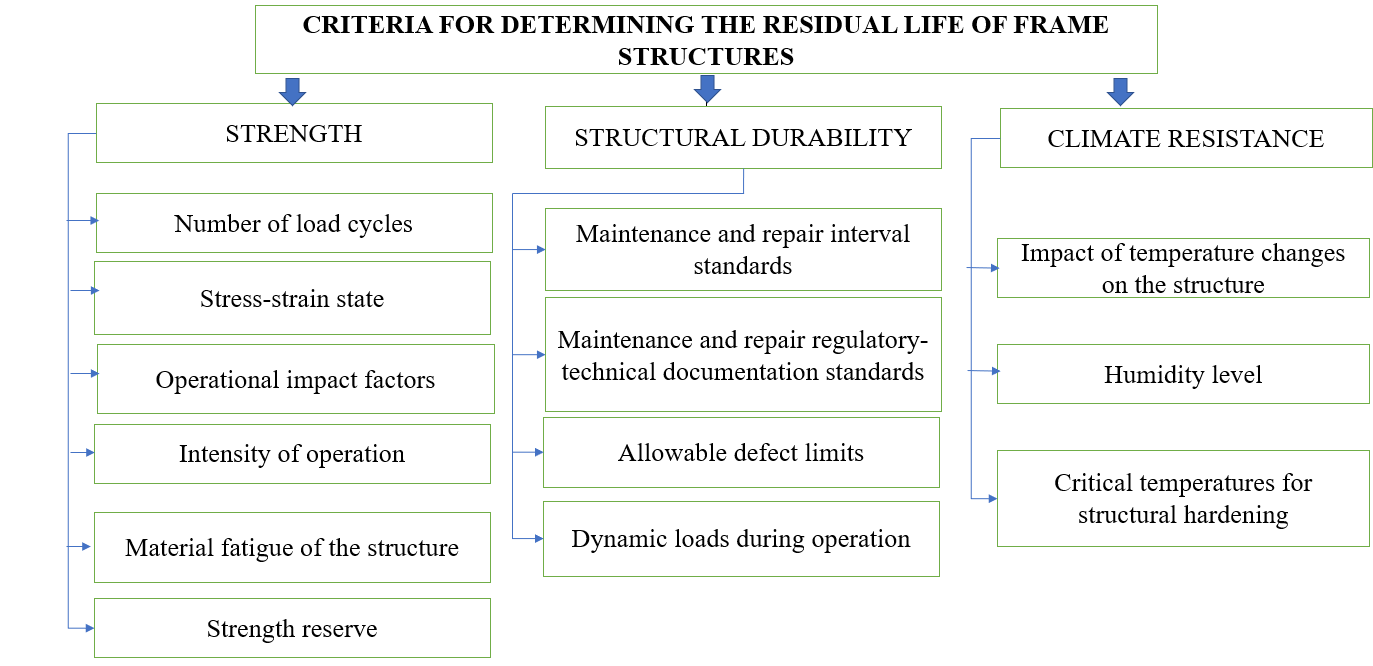
Modern diagnostic technologies are also playing an increasing role. Khamidov and co-authors [11] explored how advanced measurement tools can offer a clearer picture of locomotive health, aiding timely and cost-effective repairs. These efforts are aligned with international regulatory standards such as GOST 34939–2023 [12, 15] and GOST 31846–2012 [13], which define minimum criteria for structural integrity and dynamic stability in rolling stock.

Additionally, decision-making methods in repair planning were investigated by Puzyr et al. [16], who incorporated decision theory into the development of locomotive maintenance approaches. In the context of engineering design and digital modeling, the book by Chang [14] serves as a practical guide for using SolidWorks to virtually simulate structural enhancements.

**METHODS**

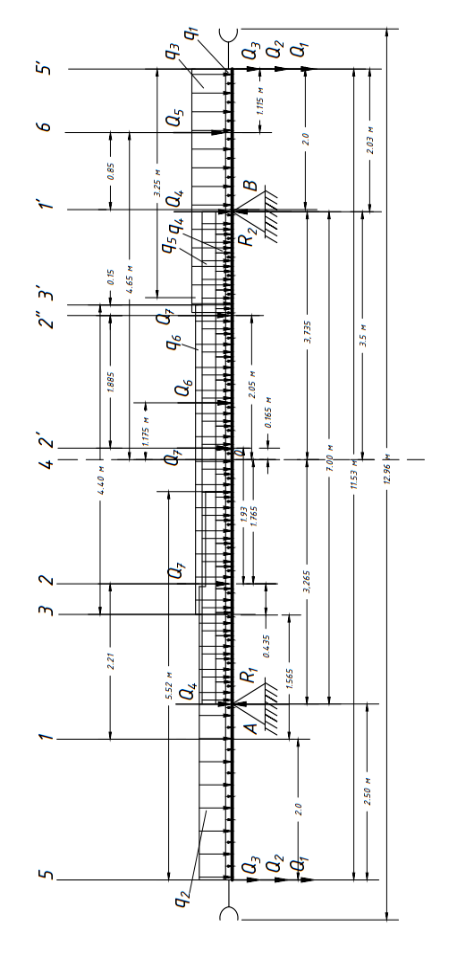
In the assessment of the residual life of special self-propelled rolling stock frame structures, analyzing the stress-strain state plays a crucial role. This method involves determining the distribution of stresses and deformations under operational loads using both experimental measurements and numerical simulations. In our research, we conducted strain gauge measurements on the frame of the ADM-1 self-propelled railcar under actual loading conditions. These measurements provided real-time data on stress concentrations and deformation behavior in critical zones of the frame [1, 2, 3].

Based on the obtained stress-strain data, the strength reserve of the structure was calculated. The strength reserve method evaluates the safety margin by comparing the maximum operational stresses with the allowable stress limits defined by regulatory standards. This analysis helps identify whether the current frame structure can continue safe operation or requires reinforcement. The criteria for determining the residual life of the frame structure of special self-propelled rolling stock are generally based on three main categories: strength, structural durability, and climate resistance (Fig. 1). These criteria include factors such as the number of load cycles, stress-strain state, operational conditions, allowable defect limits, and temperature effects according to GOST 57445–2017.



**FIGURE 1.** Determination criteria of the residual life of frame structures of special self-propelled rolling stock (according to GOST 57445—2017)

The combined use of these two methods allowed us to accurately assess the current technical condition of the frame, determine its remaining service life, and develop scientifically grounded modernization recommendations. By reducing stress concentrations and increasing the safety margin, we can extend the service life of the frame and improve its operational reliability [13].

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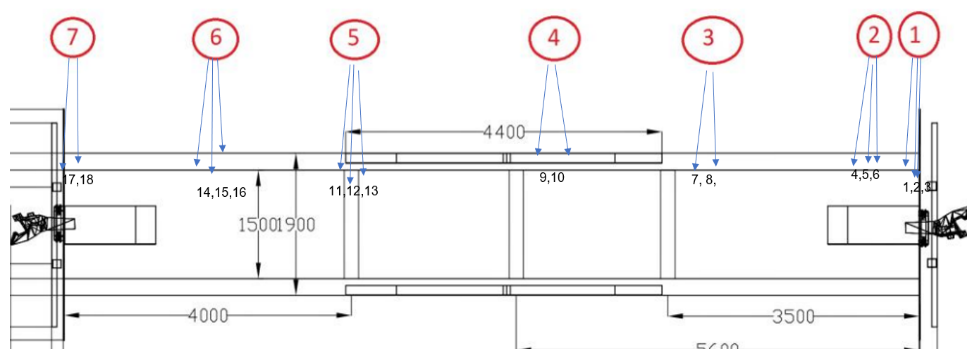
**FIGURE 2.** Static load of the frame

Figure 2 serves as a key reference for analyzing the static load-bearing behavior and overall durability of the railcar frame. The illustration offers a detailed view of the structural configuration, clearly marking the points of force application and their corresponding effects, which are critical for understanding stress distribution across the frame.

Detailed breakdowns of mass and static moments for the railcar frame itself, the brake system components (compressors, air reservoirs, distributors, etc.), the engine and power transmission units (engine, gearbox, cardan shafts), and various auxiliary and mounting equipment (cranes, rotating platforms, batteries, communication devices, etc.).

The total aggregated mass of the railcar, which is essential for comprehensive structural analysis.

This information is indispensable for engineering calculations, ensuring structural safety, determining the operational lifespan, and optimizing the design of the railcar frame. It serves as a fundamental technical reference for engineers and designers involved in the assessment and development of such railway rolling stock.

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**FIGURE 3.** Strain gauge placement scheme

In this project, a comprehensive monitoring system was implemented to ensure accurate evaluation of the stress–strain state of the engineering structure. The system comprises 18 channels distributed across 7 separate sections, with a total of 64 high-precision strain gauges installed for data acquisition, as shown in Figure 3.

Crucially, these strain gauges are connected using the Wheatstone bridge method. This configuration provides highly accurate and stable measurements, allowing for precise detection of even small changes in resistance caused by deformation, thereby ensuring reliable data acquisition for stress-strain analysis.

This strategic placement of strain gauges enables real-time monitoring of stresses and deformations occurring at various points within the structure. Each channel is responsible for collecting data from a specific zone, and the aggregated data from all 64 strain gauges provides a detailed and reliable representation of the structure's overall condition.

**RESULTS**

The experiment was conducted within a speed range of 10 to 60 km/h. This allowed the observation of the structure's dynamic response under different operating conditions. Table 1 summarizes the key results from this experiment. This network of strain gauges is designed to perform the following critical functions:

Continuous monitoring of the structure's behavior under various loads and dynamic conditions.

Identification of material fatigue and long-term deformations.

Early detection of potential defects or weakened areas.

**TABLE 1.** The maximum stress values determined on the frame of the railcar are in MPa. Corresponding to speeds of 10 km/h, 30 km/h, 55 km/h, and 60 km/h respectively

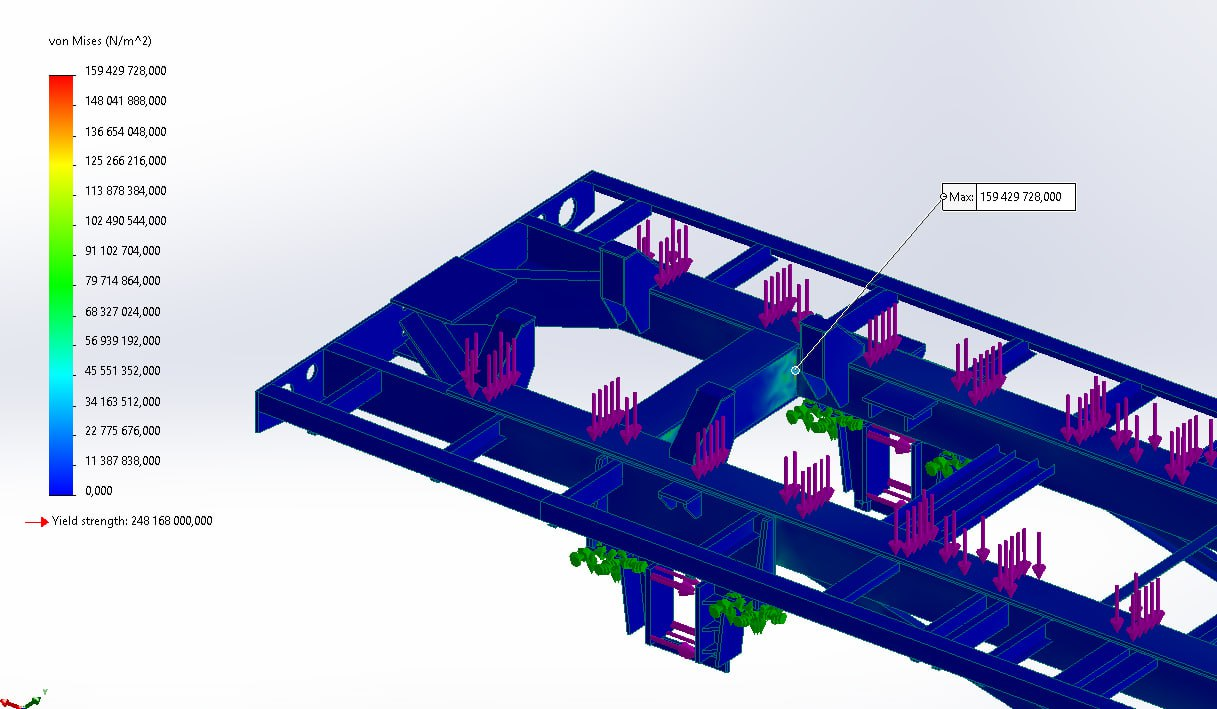
|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Sections | channels | 10 km/h | 30 km/h | 55 km/h |
| I | 1 | 0 | 0,3 | -14,7 |
|  | 2 | -1,2 | 1 | -1,2 |
|  | 3 | -1,1 | 1,4 | -0,9 |
| II | 4 | -0,5 | 1 | -1 |
|  | 5 | 0,1 | 0,3 | -0,2 |
|  | 6 | 0,8 | 6,1 | -1,9 |
| III | 7 | 0 | 0 | 0 |
|  | 8 | 0,3 | -0,2 | 0,3 |
| IV | 9 | -8,1 | -0,1 | -8,1 |
|  | 10 | -7,1 | 0,1 | -7 |
| V | 11 | -7,5 | 0,7 | -6,8 |
|  | 12 | 0,8 | -0,4 | 0,8 |
|  | 13 | 7,8 | 1,3 | 4,9 |
| VI | 14 | 0 | 0 | 0 |
|  | 15 | 0 | 0 | 0 |
|  | 16 | 14,6 | 88,5 | 109 |
| VII | 17 | 0,8 | -0,4 | 0,8 |
|  | 18 | 17,1 | 73,9 | 153,9 |

Collection of essential data for making informed decisions regarding safety assurance and optimization of operational lifespan.

This strain gauge system plays a vital role in enhancing the reliability and safety of the structure, while also building a valuable empirical data foundation for future projects.

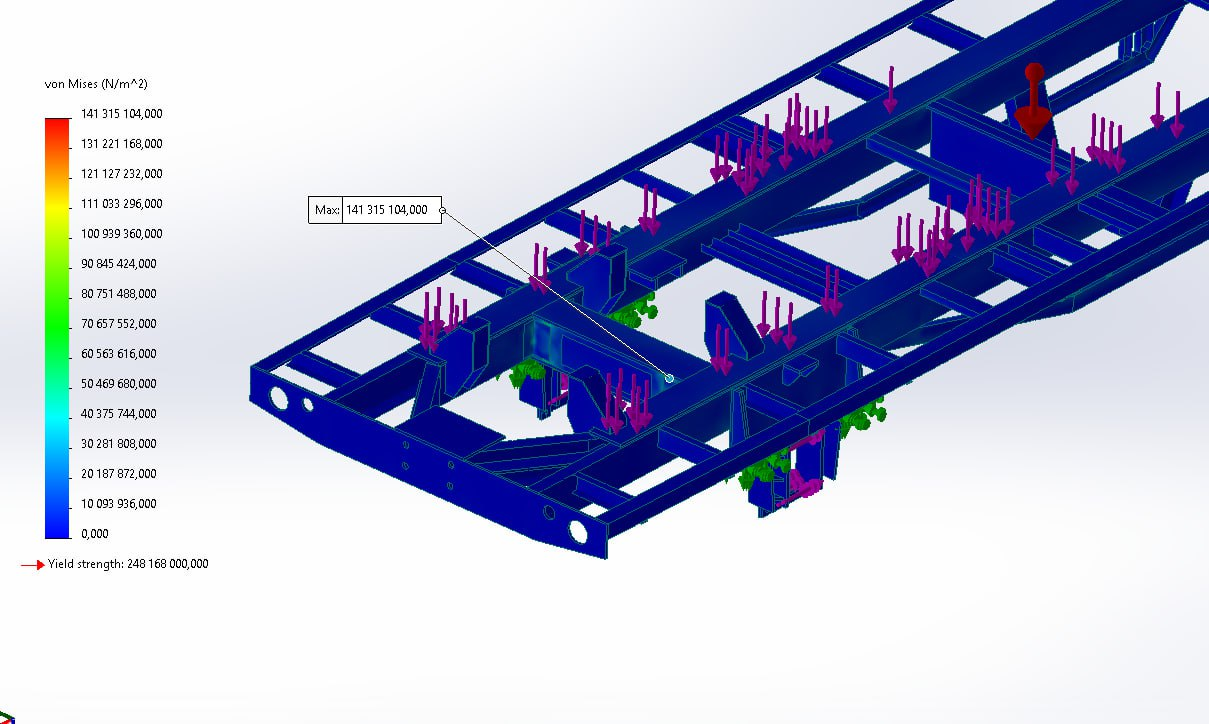
Structural Analysis: A Comparative Study of Frame Performance Before and After Modernization

The integrity and performance of critical structural components are paramount in engineering applications, particularly for heavy machinery like automotrice frames. This analysis presents a comparative study of the main frame structure's stress-strain behavior, leveraging Finite Element Analysis (FEA) results, to evaluate the impact of a recent modernization initiative.



**FIGURE 4.** Finite element model of the main frame structure before modernization

Pre-Modernization State: Prior to modernization, a comprehensive FEA was conducted on the original design of the main frame. The analysis, which simulated typical operational loads, revealed a maximum Von Mises stress of approximately 159.43 MPa (Figure 4). This stress concentration was identified in specific areas of the frame, visualized by red contours in the FEA output. While this maximum stress value was well within the material's yield strength of 240.16 MPa, indicating that the original design was safe from immediate plastic deformation under these loads, it served as a baseline for potential improvements. The identification of these higher stress zones also provided valuable insights for targeted design enhancements.



**FIGURE 5.** Finite element model of the main frame structure after modernization

Post-Modernization State: Following the implementation of modernization efforts, a new FEA was performed on the updated frame design under identical loading conditions [15]. The results from this analysis demonstrated a significant improvement in stress distribution. The maximum Von Mises stress recorded in the modernized frame was reduced to approximately 141.32 MPa (Figure 5). This represents a notable reduction of over 18 MPa compared to the pre-modernization state. The areas previously exhibiting the highest stress concentrations now show lower stress values, indicating a more optimized and balanced load distribution across the structure [10, 11].

**DISCUSSION**

Conclusion on Modernization Impact: The comparative FEA clearly demonstrates the success of the modernization efforts. The reduction in maximum Von Mises stress from 159.43 MPa to 141.32 MPa signifies several key benefits:

Enhanced Safety Factor: The modernized frame operates with an increased margin of safety against yielding, further mitigating the risk of permanent deformation under design loads.

Improved Fatigue Life: Lower peak stresses are generally conducive to a longer fatigue life for the material, potentially extending the operational lifespan of the frame by allowing it to withstand a greater number of load cycles before material fatigue becomes a concern.

Structural Optimization: The results suggest that the modernization involved effective design changes—such as material redistribution, localized reinforcement, or refined geometry—that optimized the structural integrity and efficiency of the frame.

In essence, the FEA validates that the modernization has not only maintained but significantly enhanced the structural robustness and long-term reliability of the main frame, ensuring safer and more durable performance.

|  |  |
| --- | --- |
|  | (1) |

where: - the fatigue life reserve coefficient; - endurance limit or fatigue limit; - stress amplitude (or amplitude of the stress cycle); -average stress; k- stress concentration factor; - ensitivity factor to mean stress.

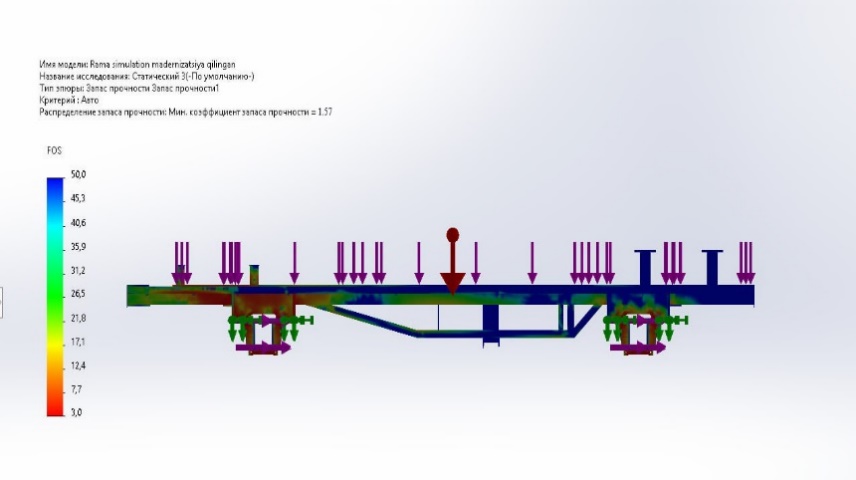
We determine the calculated value of the vertical dynamic coefficient for the car body frame using formula (2):

|  |  |
| --- | --- |
|  | (2) |

where**:** b — coefficient accounting for the influence of the number of axles in the bogie and the group of bogies under one half of the vehicle; fst — static deflection of the spring suspension, m.

This formula explains the methods for calculating the vertical dynamics coefficient , taking into account factors such as vehicle speed (V) and the static deflection of the spring suspension fst. Of particular importance is formula (2), used when the speed exceeds 55 km/h, which provides a precise methodology for determining this coefficient.

The fatigue life reserve coefficient, presented in formula (1), represents a key metric for assessing the fatigue strength of structural elements. It reflects the structure’s capacity to endure repeated loading cycles within its service life before fatigue failure becomes critical [14, 17, 18, 19]. In this research, modernization efforts led to a meaningful increase in the coefficient from 1.57 to 1.76—indicating enhanced structural resilience and reliability under cyclic loading conditions (see Fig. 6). These improvements are based on theoretical calculations derived using formula (1).



**FIGURE 6.** Strength reserve diagram of the main frame

**CONCLUSION**

The integrated application of stress-strain state analysis, strength reserve calculation, and structural modernization significantly improved the ADM-1 railcar frame's reliability and safety. The maximum values of the results obtained from theoretical and practical methods, namely strain gauging and finite element analysis, were determined with an accuracy of 80-90%. The modernization resulted in reduced stress concentrations, increased safety margins, and extended service life, contributing to the efficiency and safety of Uzbekistan's railway operations [15].

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