Structural Strength Evaluation of the Main Frame in the PE2U Industrial Traction Unit Control Electric Locomotive

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**Abstract.** Objective: This study focuses on analyzing the stress–strain state (SSS) of the main frame of the PE2U industrial traction unit’s control electric locomotive when subjected to static loading. The aim is to determine whether the structural performance meets the criteria outlined in current strength regulations and engineering standards. Methods: To meet the research objectives, the SSS of the main frame was analyzed using the finite element method (FEM). The strength assessment was carried out by determining the allowable stress levels and evaluating the fatigue safety factor, in line with the requirements set by relevant engineering standards and regulations. Results: According to the results of the calculated SSS, the maximum stress in the frame structure was 59.23 MPa, which occurred in the zone of the vertical sheet and upper horizontal sheets of the cross-pivot beam. In this case, the fatigue safety factor was n = 5.1. Conclusion: The SSS of the main frame structure, calculated using the FEM, allowed for the assessment of its load distribution throughout the entire volume and identification of potentially hazardous zones. This information will serve as essential data for further research in developing recommendations to extend the service life of long-used traction units.

**Keywords:** Industrial electric locomotive, static strength, fatigue safety factor, FEA, FEM.

# Introduction

Currently, a total of 75 PE2U industrial traction units are being utilized for ore transportation at enterprises such as JSC “Uzbekcoal” and JSC “Almalyk Mining and Metallurgical Combine” in the Republic of Uzbekistan [1, 2, 3]. Over 70% of the traction units in operation have exceeded their designated service life, with many having been in use for more than 30-40 years. The PE2U traction unit is considered an industrial electric locomotive, consisting of one control electric locomotive and two motor dump cars, designed for operation on mining railways electrified with a direct current of 1500V or 3000V [2].

It is well known that for each manufactured vehicle, a warranty period is established by the manufacturer. During the specified warranty period, vehicles must meet the requirements for parameters such as safety, reliability, and quality. The manufacturer's warranty service life for traction units of PE2M, PE2U, and MPE2U types is 24 years [2]. Experience shows that the total service life of railway rolling stock can exceed the warranty period established by the manufacturer. This can be determined through the development of diagnostic systems for railway transport vehicles and continuous monitoring of their technical condition [4, 5, 6].

Frame structures of locomotives are continuously subjected to periodically varying loads during operation [7, 8, 9, 10, 11]. Depending on the operating conditions and intensity of use of traction units, the material of their frame structures undergoes degradation to varying degrees. Calculating the SSS of frame structures, identifying highly loaded zones, and assessing fatigue strength can serve as a foundation for ensuring safety during the subsequent operation of long-used traction units.

The operational safety and reliability of industrial traction units, particularly when exposed to high-intensity loads, are closely linked to the structural integrity of their main frame elements. A thorough strength evaluation of the control locomotive’s main frame is crucial for ensuring stable performance and extended service life. As outlined in regulations concerning the lifespan extension of traction rolling stock, one of the primary strength assessment approaches involves analyzing the static resistance of the frame structure.

A scientifically grounded assessment of the residual resource of traction units in use and extending their service life will allow for their continued effective utilization during the period leading up to the renewal of the traction unit fleet. This, in turn, enables industrial enterprises to conserve their foreign currency funds for a certain period of time.

# Literature review

The SSS assessment of frame structures can be carried out using strain gauge or FEA methods. Today, FEA or FEM is considered the primary tool for strength calculations among millions of engineers [12]. According to the requirements of standards regulating locomotive strength and various regulatory documents on strength calculations, it is recommended to perform structural analysis of their load-bearing structures using FEM [13]. European standards such as EN 12663-1 and EN 13749 explicitly mandate the application of the finite element method (FEM) in the structural strength analysis of complex load-bearing frames in locomotives. These standards emphasize the importance of advanced computational methods to ensure accurate and reliable assessment of mechanical performance. Considering this, FEM is a widely used digital calculation method in modern locomotive manufacturing and is actively used by the broader scientific community for analyzing complex load-bearing frame structures of locomotives. Specifically, Kassner [14] and Chen et al. [15] evaluated the bogie frame strength according to EN 13749 requirements using various methods, including FEM. In their studies on extending the operational lifespan of TEM2 shunting locomotives, Yusufov et al. [16, 17, 18] analyzed the structural strength of key load-bearing components – such as the main frame and bogie frames – using SolidWorks Simulation tools. Their approach focused on evaluating residual life through numerical modelling techniques. Fomin et al. [19] used FEM to determine dynamic loads on the frame of a composite tank car. Koshel et al. [20] conducted a strength analysis of the load-bearing structures of specialized rolling stock by employing SolidWorks Simulation software, enabling the evaluation of their mechanical performance under operational loads. Seo et al. [21] applied FEM to calculate potential residual stresses in various repair options for weld seams of welded bogie frames. Mukhamedova et al. [22] investigated the strength characteristics of the support structures in the ADM-1 specialized self-propelled rolling stock. Their study involved finite element analysis performed in Ansys, enabling detailed assessment of structural behavior under loading conditions. According to research by Miao et al. [23], the difference in values obtained by FEM and strain gauging methods did not exceed an average of 7.2%. This is considered an acceptable relative error for engineering calculations.

Bondarev et al. [24, 25] addressed issues of assessing strength, determining residual life, and extending the service life of traction units used in the mining industry. They substantiated the possibility of extending the service life of OPE1A type traction unit frame structures based on strength indicators. Bannikov et al. [26] worked on modernizing PE2U traction units by improving the strength indicators of the control electric locomotive’s main frame. They developed modernization proposals to increase the strength of the main frame buffer beam and the automatic coupler assembly against longitudinal collision forces. However, they calculated the SSS of only the buffer beam using SCAD software, not the full-scale model of the main frame structure. This approach does not allow for a comprehensive assessment of the full-scale model’s strength indicators. In this study, we assess the static strength of the full-scale frame structure in accordance with GOST 34939 requirements, which is a regulatory document, and thereby evaluate the main frame’s strength indicators based on the fatigue safety factor.

# Materials and Methods

## Object of Research

This study focuses on the main frame of the PE2U control electric locomotive, a key structural component of the traction unit. The frame is assembled using welded steel profiles and constructed from low-alloy structural rolled steel, specifically grade 09G2. The mechanical and physical properties of the material are summarized in Table 1.

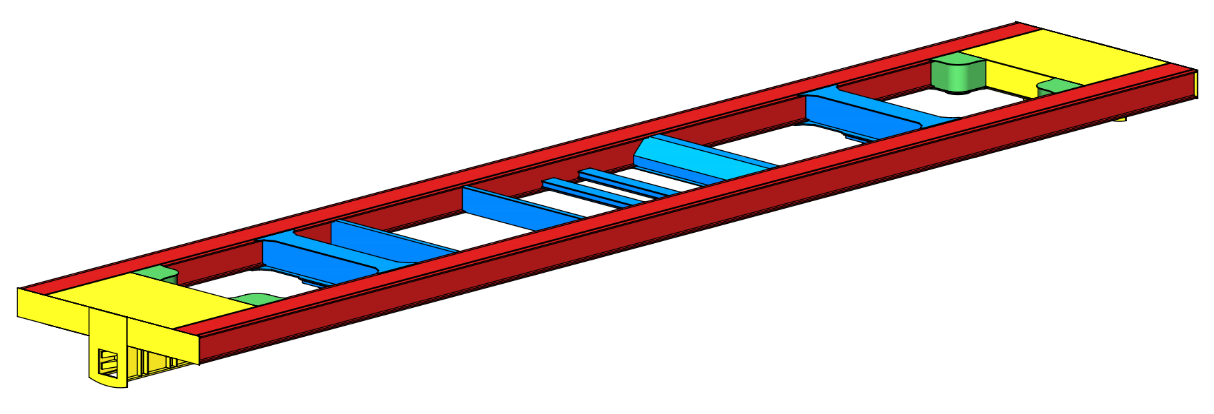
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| --- | --- | --- | --- | --- | --- | --- |
| **TABLE 1.** Materials properties | | | | | | |
| **Thickness [mm]** | **Yield strength [MPa]** | **Tensile strength [MPa]** | **Relative elongation [%]** | **Endurance limit [MPa]** | **Young’s modulus [GPa]** | **Poisson’s ratio** |
| < 20 | 305 | 440 | 21 | 210 | 210 | 0,3 |
| 20-32 | 295 | 430 |

The main frame (Figure 1) consists of two longitudinal beams (side beams), two transverse beams, buffer beams located at both ends of the frame, under-cabin beams, and other elements used for mounting equipment. The frame rests on two two-axle bogies through two central supports and four rubber conical side supports.

The longitudinal beams consist of box-shaped structures made of two 36M I-beams, connected from above and below by 10 mm thick sheets.

Box-shaped cross-section pivot beams are made of sheet steel of varying thicknesses (top sheet - 12 mm, bottom sheet - 16 mm, 2 vertical sheets - 12 mm). A flange with a mounting hole for the central support and limiting brackets are welded to the bottom sheet of the pivot beam, preventing excessive rotation of the bogies when they derail.

Buffer beams consist of sheets of varying thickness (8-15 mm), which are connected to each other by four diaphragms that are 8 mm thick. In the middle part of the lower sheet (15 mm), there is an automatic coupler box with a shock-absorbing apparatus for installing a traction yoke.



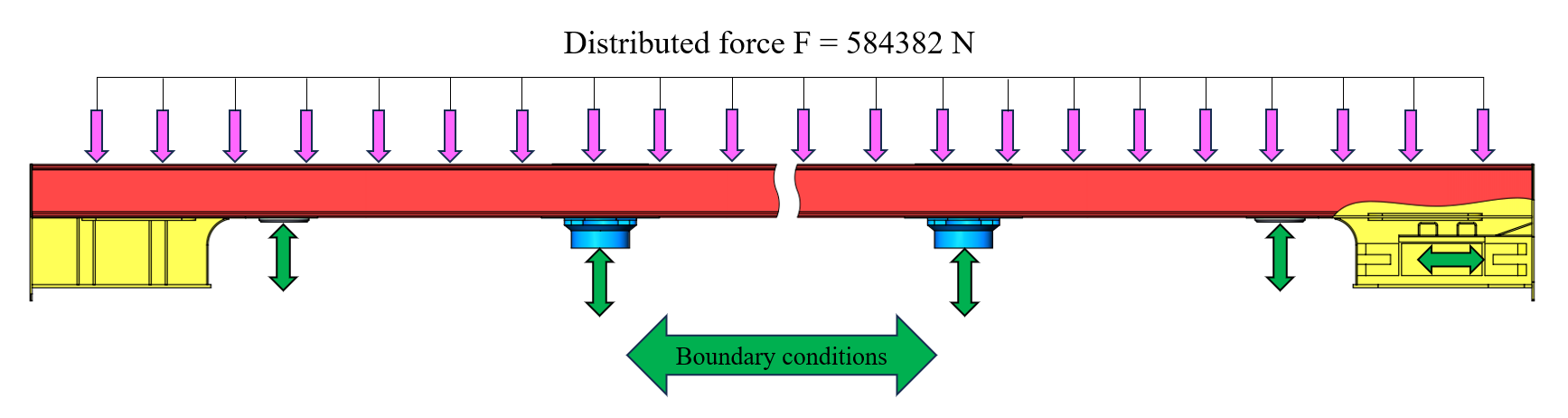
**FIGURE 1.** Main frame of the PE2U traction unit control electric locomotive

## Modeling Approach and Loading Conditions

A three-dimensional model of the main frame was developed using SolidWorks software, utilizing detailed technical drawings and dimensional data obtained from real-world locomotive components. The model was then imported into ANSYS Workbench, where material properties were specified. Welded joints were modeled as rigid connections, and constraints were applied to reflect the real boundary conditions.

As the acting force, in accordance with the requirements of GOST 34939, the vertical static gravitational forces from the equipment and devices installed on the control electric locomotive, as well as the frame's own weight, were applied as a distributed force on the upper surfaces of the frame. The applied load was determined using Equation (1), with input parameters derived from the data presented in Table 2.

For boundary conditions, the displacement of 6 frame supports was restricted in the vertical and transverse directions, and the displacement of the supporting surface of one external auto-coupler support was limited in the longitudinal direction. The loading diagram of the main frame is shown in Figure 2.



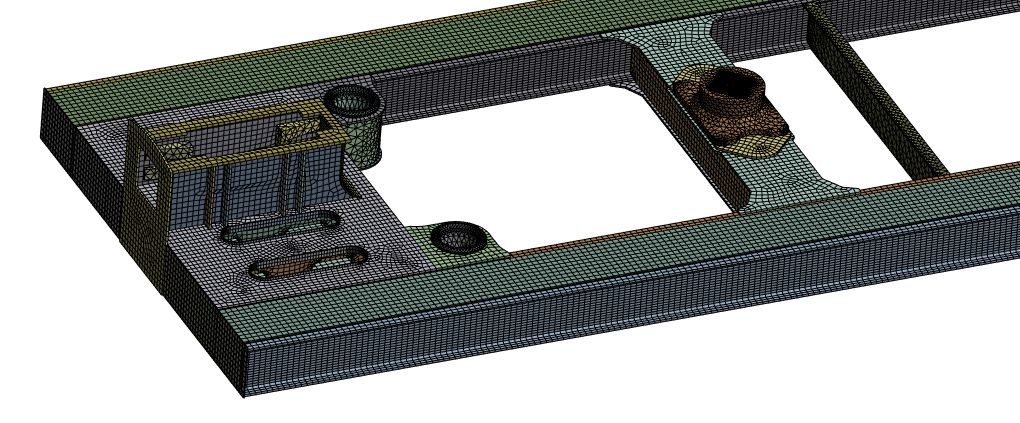
**FIGURE 2.** Loading diagram of the main frame

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| **TABLE 2.** Properties of frame structure materials | |
| **Parameter** | **Value** |
| Control electric locomotive mass, *MCEL*,t. | 120 |
| Bogie mass, *MB*, t. | 24,5 |
| Mass of the control electric locomotive’s main frame, *MMF*, t. | 11,43 |
| Design speed, *V*, km/h | 65 |
| Vertical dynamics coefficient, *KD* | 0,238 |

## Finite Element Analysis

Finite Element Analysis (FEA) was performed using the Ansys software package to evaluate the SSS of the main frame under the specified loading conditions. Through this, the mean stress value in the frame structure was determined. To ensure convergence, mesh sensitivity was investigated and linear static structural analysis was conducted. The stress distribution was determined according to von Mises criterion. A portion of the finite element (FE) model of the main frame is illustrated in Figure 3. The mesh consists of elements with an average size of 40 mm and a minimum edge length of 6 mm. The overall model includes 904,277 nodes and 175,494 finite elements.



**FIGURE 3.** Fragment of the main frame’s FE model

## Strength Assessment

The strength of the main frame is evaluated by calculating the allowable stress and fatigue safety factor according to the requirements of GOST 34939 [27, 28]. The load-bearing capacity of the main frame is assessed in calculation modes I, II, III, and IV based on allowable stresses relative to the material’s yield strength. Fatigue resistance is calculated based on the results of calculation mode III. In calculation mode III, the stress value should not exceed 60% of the yield strength. The fatigue safety factor must be n ≥ 2. The fatigue safety factor is calculated using formula (2) or (3) depending on the operating conditions of the structural elements. If the element operates under tensile stress, we use formula (2), and if it operates under bending stress, we use formula (3).

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The concentration coefficient *Kσ* is calculated based on the following formula (4):

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The amplitude value of the cycle stress is determined by the following formula (5):

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The maximum and minimum stress values of the cycle occurring during the movement of the traction unit are determined by formulas (6) and (7):

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We determine the calculated value of the vertical dynamic coefficient for the car body frame using formula (8):

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We accept the stresses resulting from constant vertical static loads as the mean stress *σm* of the cycle, determined by the FEA. The initial data for calculations are presented in Table 3.

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| **TABLE 3.** Initial data for assessing the fatigue resistance of the main frame in accordance with regulatory requirements. | | |
| **Notation** | **Parameter** | **Value** |
| 𝜎-1*r* | The endurance limit of the standard sample in the symmetrical tension-compression cycle (the use of the empirical dependence *σ-*1*r* = 0.7σ-1 is permitted), MPa | 147 |
| 𝜎-1 | Endurance limit of a standard sample in a bending symmetrical load cycle, MPa | 210 |
| *ψ*𝜎 | Coefficient characterizing the effect of cycle asymmetry | 0,3 |
| *α*𝜎 | Theoretical coefficient of stress concentration (for concentration zones at the boundaries of welded joints) | 1,4 |
| *K*1 | Coefficient accounting for material heterogeneity (for rolled steel) | 1,1 |
| *K*2 | Coefficient that takes into account the effect of internal stresses based on the maximum cross-sectional dimension of the part (ranging from 1.0 to 1.2 proportionally for dimensions from 250 mm to 1000 mm) | 1,152 |
| *Km* | Coefficient adopted based on the surface treatment method for the part (for surfaces initially processed on the machine) | 0,8 |
| *γ* | Coefficient selected based on the maximum cross-sectional dimension h of the part and accounting for the influence of the size factor (for dimensions above 250 mm) | 0,7 |
| *K*3 | Correction coefficient applied in welded load-bearing structures for low-alloy rolled steel of grade 09G2, according to GOST 19281 | 1,2 |
| *K*𝜎 | The stress concentration factor is a coefficient that quantifies the decrease in fatigue strength of an actual structure relative to the fatigue limit of a standard test specimen | 2,715 |
| *fst* | Overall static deflection of the spring suspension, m | 0,1 |

# Results and Discussion

According to the FEA results, the highest stress concentration occurs at the junction of the vertical and upper horizontal plates of two transverse kingpin beams, specifically in the zone of the T-shaped weld. The stress in this concentration zone was 47.845 MPa (Figure 4). Although this value is lower than both the yield strength of the material and the allowable stress, its location in the weld zone makes it a potentially dangerous area for crack formation after prolonged use from the perspective of multi-cycle fatigue.

According to the FEA and calculation results, the fatigue safety factor of the main frame was determined to be n = 5.1. The calculation was carried out using formula (3), as the zone of maximum stress concentration operates in the bending cycle. The fact that this value is significantly higher than the permissible value demonstrates the high fatigue strength of the control electric locomotive and substantiates the possibility of its long-term use.

The results of the calculations are shown in Table 4.

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| **TABLE 4.** Results of calculations. | | | | | |
| **Mean stress, 𝜎*m* [MPa]** | **Vertical dynamics coefficient, *KD*** | **Maximum stress, 𝜎*max* [MPa]** | **Minimum stress, 𝜎*min* [MPa]** | **Stress amplitude, 𝜎*a* [MPa]** | **Fatigue safety factor, *n*** |
| 47,85 | 0,238 | 59,23 | 36,46 | 11,39 | 5,1 |

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**FIGURE 4.** Distribution of equivalent stresses in the main frame.

# Conclusion

The research results fully comply with the requirements of GOST 34939, which serves as a regulatory document. Specifically, according to the data presented in Table 4, it was determined that the maximum stress in the concentration zone (59.23 MPa) is significantly lower than the permissible stress (183 MPa), and the fatigue safety factor (n = 5.1) is considerably higher than its permissible value (n = 2).

According to the calculation results, the main frame demonstrates sufficient rigidity and strength under static loads. However, to ensure long-term reliability, it is recommended to inspect and reinforce areas subjected to high stress during major repairs without causing additional damage. During scheduled periodic overhauls, the reliability and service life of the main frame can be extended through mechanical and thermal treatment of elements and welded joints in its hazardous zones, allowing for long-term use.

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