

# Prediction of the stress - strain state of the bogie frames of shunting locomotives using the finite element method

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**Abstract.** The article is dedicated to topical issues of control and calculation of residual life of the bogie frame of shunting locomotives operated on the railroad of Uzbekistan. Mathematical methods for calculating the residual life of locomotives are presented in the article and the expediency of extending the service life of shunting locomotives at the earliest stage of their development is substantiated. The outcomes were obtained with the help of the Solid works software environment which allows analyzing calculations and revealing forces acting on the bogie frame of locomotives. The mathematical description of forces acting during the bogie frame of locomotives is also presented. The methods of bogie frame residual life forecasting and service life extension of shunting locomotives are investigated.

## 1 Introduction

There are more than forty countries that do not have direct access to sea transport, which is the cheapest mode of transport in the world. Uzbekistan, bordering countries that do not have direct access to maritime transport in the Central Asian region, is one of two states in the world bordering not only landlocked countries, but also landlocked States. Therefore, a large share of cargo and passenger transportation in our republic falls on railways.

On September 14, 2022, in Uzbekistan, as part of the plan Shanghai Cooperation Organization (SCO) summit, a trilateral agreement was signed with representatives of the countries on the implementation of the Uzbekistan-Kyrgyzstan-China railway construction project. As a result of the construction of the new Uzbek-Kyrgyz-Chinese railway, additional types of locomotives will be required to be used for freight and passenger transportation on this new railway.

On the railway transport of JSC “Uzbekistan temir yullari” and industrial enterprises, shunting locomotives of types TEM2, CHME3, TEM18ДМ, TGM23B and TGM23B are used to sort freight and passenger cars, form rolling stock and perform maneuvering work on the road.

Table 1 below shows an analysis of the number of shunting locomotives at industrial enterprises of the Republic of Uzbekistan and table 2 shows an analysis of the number of

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TEM2 and CHME3 locomotives in the locomotive fleet of “Uzbekistan temir yullari” for 2020-2023.

**Table 1.** Analysis of industrial enterprises of the Republic of Uzbekistan by the number of shunting locomotives for 2019-2022

№	Locomotive type	Status of locomotive park in 2019	Status of locomotive park in 2020	Status of locomotive park in 2021	Status of locomotive park in 2022
1	Shunting locomotives and their types (TEM, TEM18DM, TGM23B and TGM23V)	89	99	102	107
2	Total locomotives	89	99	102	107

An analysis of the number of shunting locomotives in the locomotive fleet of industrial enterprises in Table 1 above shows that in 2018 there were 75 units, and by 2022 there were 107 units due to the acquisition of new locomotives.

**Table 2.** Analysis of JSC “Uzbekistan temir yullari” by the number of shunting locomotives of 2020-2023

№	Locomotive type	Status of locomotive park in 2020	Status of locomotive park in 2021	Status of locomotive park in 2022	Status of locomotive park in 2023
1	Shunting locomotives and their types (TEM, TEM18DM, TGM23B and TGM23V)	173	173	173	184
2	Total locomotives	173	173	173	184

The analysis of table 2 above for the period 2020-2022 amounted to 173 units, and in 2023, according to the plan, the number was to be 184 units due to the acquisition of a new shunting locomotive. But as of March 2023, the shunting locomotive will have 173 units due to lack of purchases [1].

The limited investment conditions for the purchase of new shunting locomotives, on the one hand, and the growth of operational failures of locomotives, on the other hand, forces the Republic of Uzbekistan to look for ways to increase the number of shunting locomotives due to the steady growth of freight and passenger transportation by rail.

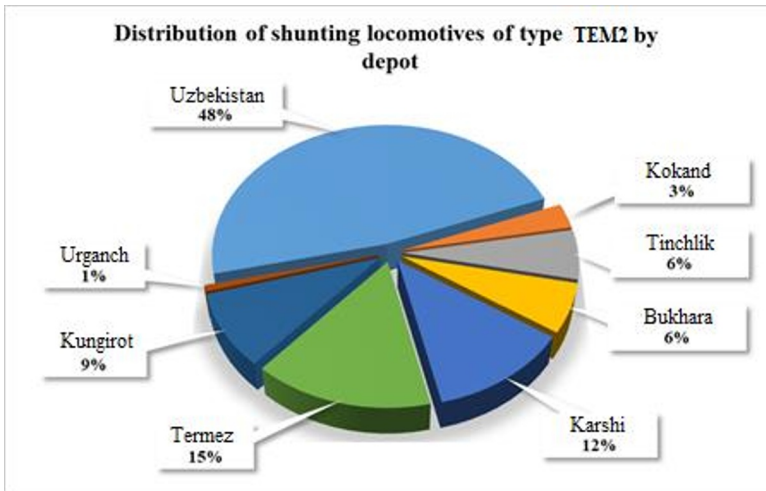
The number of shunting locomotives in the locomotive fleet of JSC “Uzbekistan temir yullari” is inextricably linked with their age. Based on this inextricable connection, the average age of the locomotive fleet is determined. Table 3 below shows an analysis of TEM2 shunting locomotives in operation in the locomotive depots of JSC “Uzbekistan temir yullari” by depot by year of production (age) [2].

**Table 3.** Analysis of TEM2 shunting locomotives of the locomotive fleet of JSC “Uzbekistan temir yullari” by age in locomotive depots is given

№	Locomotive depots as part of JSC “Uzbekistan temir yullari”	Age of shunting locomotives type TEM2 (as of 2023)				
		Up to 40 years old	41 to 45 years old	45 to 50 years old	over 50 years	Total
1	Uzbekistan	4	35	16	8	63
2	Kokand	-	4	-	-	4
3	Tinchlik	-	5	1	2	8
4	Bukhara	2	4	2	-	8
5	Karshi	1	9	4	2	16
6	Termez	2	9	7	2	20
7	Kungirost	-	8	1	3	12
8	Urganch	1	-	-	-	1
	Total locomotives	10	74	31	17	132

As a the consequence of the analysis table 3 above, Shunting locomotives of the locomotive fleet of JSC “Uzbekistan temir yullari” the service life has been exhausted for thirty years, new shunting locomotives have practically not been purchased from JSC “Uzbekistan temir yullari”.

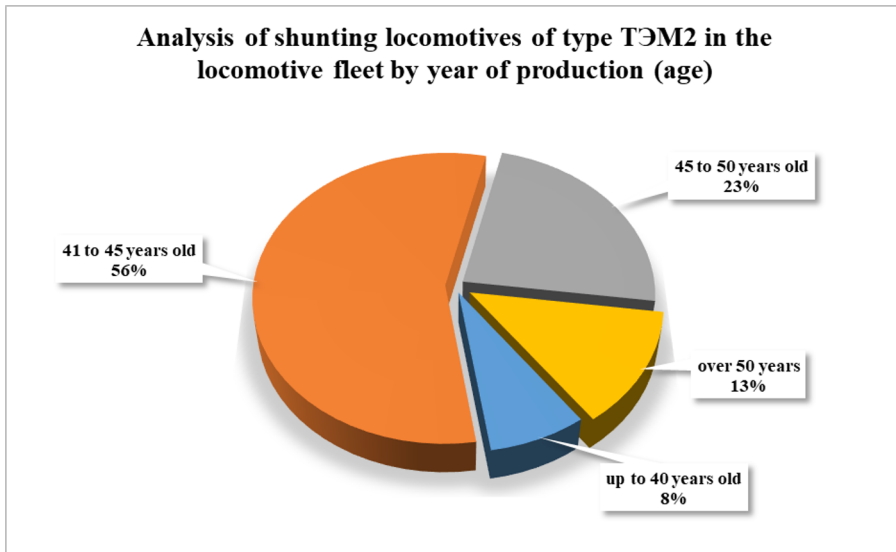
Analysis of the distribution of TEM2 shunting locomotives in the locomotive fleet of JSC “Uzbekistan temir yullari” by locomotive depots as of 2023 is shown in fig.1.



**Fig.1.** Distribution of TEM2 shunting locomotives by depot in the locomotive depots of JSC “Uzbekistan temir yullari”

Figure 1 shows that, the largest percentage in the distribution of TEM2 shunting locomotives in the locomotive depots of JSC “Uzbekistan temir yullari” belongs to the locomotive depot “Uzbekistan” and is 48%, the smallest depot “Urganch” and is 1%.

Figure 2 below shows an analysis of the age composition of shunting locomotives type TEM2 in locomotive fleet of JSC “Uzbekistan temir yullari”.



**Fig. 2.** Analysis by age of operated TEM2 shunting locomotives of the locomotive fleet of JSC “Uzbekistan temir yullari”

The extension of the assigned service life of shunting locomotives is carried out on the basis that the service life of the locomotive as a whole is determined by the resources of its basic parts (bogie frame, load-bearing elements of the body). The designated service life of locomotives (including additional ones) should be determined by the resource of their base parts. At the same time, the service life of mainline locomotives should not exceed 45 years, shunting locomotives and electric locomotives - 50 years.

Fig.3 shows that, 8% under the age of 40, 56% aged 41-45, 23% aged 45-50 and 13% over the age of 50, and these numbers are increasing from year to year.

## 2 Methods

One of the ways to solve this problem is to eliminate the extension of the useful life of locomotives by the manufacturer after the expiration of the established service life by conducting research to determine the residual life of the bogie frame of these locomotives and developing regulatory and technical documentation based on it [3-7].

Shunting locomotives undergo regular maintenance and repair during operation, while traction is not fully used during operation, despite the expiration of their service life, it can be assumed that their technical resource has not yet been fully exhausted. International practice shows that the actual service life of a shunting locomotive often significantly exceeds the service life set by the manufacturer. Based on the impossibility of simultaneous renewal of all shunting locomotives operated on the railways of the Republic of Uzbekistan, and the presence of their residual resource, it is advisable to check their technical condition to justify the possibility of extending the useful life by updating outdated equipment and strengthening load-bearing structures.

In these conditions, the diagnosis of a shunting locomotive, which is not officially provided for by the current regulatory documents, is the determination of its residual resource. This task is not easy, and it is not possible to determine the remaining resource using conventional diagnostic tools.

The residual service life of the supporting structures of shunting locomotives is largely determined at the time of inspection by the node having the smallest residual service life

[8-10]. Detection of such a node is possible only with the help of modern engineering software and diagnostic devices, otherwise it becomes even easier to make a mistake due to incorrect evaluation and incorrect evaluation of all defects present during the inspection. Since the evaluation of the residual life of the bogie frame is probabilistic in nature, for a more accurate assessment it is necessary to provide confirmation of the alleged defects in several ways. In order to take shunting locomotives out of service or send them for repair and determine the amount of repair, it is necessary to obtain scientifically based data on the minimum remaining service life of the supporting structure.

The greatest efficiency of a comprehensive survey of shunting locomotives can be achieved if there is a developed organizational and technological system for monitoring their technical condition, which allows obtaining maximum information about the technical condition without affecting the operation process [11].

These include:

- highly qualified specialists who own all types of modern technical means;
- organization of the laboratory of high-tech modern devices;
- regularly updated methodological base;
- a server with the ability to archive information about the system and its technical condition for remote monitoring of the functional parameters of shunting locomotives.

In order to extend the service life and ensure reliable operation of shunting locomotives, it is necessary to identify and eliminate defects in a timely manner. They are solved by preventing the accidental or irreversible destruction of their main components and assemblies. In combination with the elimination of identified defects, the best way to preserve the useful life is either to slow down the progression of the defect, or to completely stop its development.

A shunting locomotive of any type is a product that can be restored. Most of the parts of its components can be restored or replaced, and thus the service life is fully (rarely) or partially (usually) restored. A shunting locomotive has only one key component that determines the remaining service life, which is the bogie frame [12, 13].

Based on many years of experience in using methods for assessing the residual life of load-bearing structures, the identification and analysis of steadily changing trends in controlled parameters over a long regular observation period is based. The criteria for evaluating individual aspects of technical conditions are the threshold levels of individual parameters and trends in their determination and changes during technical expertise.

These studies can be carried out both experimentally and by calculation.

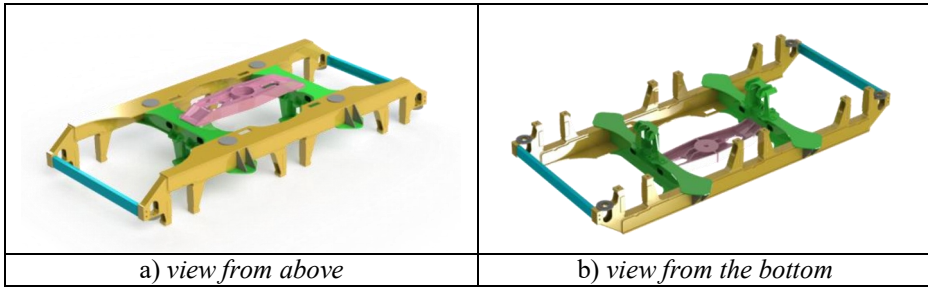
In recent years, analytical methods for studying the stress-strain state and fatigue bearing structures of locomotives using solid-state modeling methods have become widespread.

### **3 Results and discussion**

The bogie frame of a shunting locomotive absorbs and transmits vertical, traction, impact, braking, and inertial forces to the main assemblies of the crew part [14]. The design of the bogie frame must ensure reliability, functionality, and traffic safety during shunting locomotive operation by the requirements of technical operation rules [15].

We will provide a definition of the residual life of the bogie frame based on the TEM2 shunting locomotive [16].

A three-dimensional model of the shunting locomotive bogie frame in the Solidworks modeling environment is shown in Fig. 3.



**Fig. 3.** Three-dimensional model bogie frame of the TEM2 shunting locomotive

When calculating the complex tensioned elements of the bogie frame of the locomotive, the equivalent stresses are determined, which must not exceed the allowable values set for the corresponding design mode.

Calculation forces [17]

When calculating the strength of the bogie frame of the locomotive, the following forces are taken into account:

- its gravity (weight) and the gravity of the equipment placed on it;
- forces of inertia, friction, weight and resistance arising during the maneuvering movement of the locomotive;
- forces arising from the operation of traction motors and other basic mechanisms;
- forces acting during locomotive traction and related to the braking process;
- forces acting on the locomotive when it is connected;
- forces acting on locomotive elements during repairs and emergencies.

The forces listed above are assumed to act statically when calculating the stress-strain state of the bogie frame of the locomotive and are given the following basic diagrams of their application:

- vertical;
- side;
- longitudinal;
- asymmetrical.

Vertical forces consist of the locomotive crew's force of gravity, the force of gravity, equipment placed on it, and, the vertical components of dynamic loads.

The dynamic vertical force from body vibrations on a spring suspension is determined by multiplying the gravity of the body, including 1/3 of the gravity of the springs of the second stage of the spring suspension, using the indicator of the vertical dynamics of this stage.

The dynamic vertical force from bogie oscillation is determined by multiplying the gravity of its cushioned mass, including 1/3 of the gravity of the springs of both suspension stages, by the indicators of vertical dynamics.

The calculated indicators of vertical dynamics are determined by the formula:

$$K_D = \left( \frac{0,006}{f_{ct}} \pm 0.004 \right) \sqrt{V} \quad (1)$$

Where  $f_{ct}$  – total static deflection of the spring suspension;  $V$  – speed of motion.

Sign “-” for body parts; “+” for bogie springs and superstructure beams.

Under the intrinsic gravity of the locomotive, the crew is understood the total gravity of its parts, plus 2/3 of the fuel and sand.

The gravity of the equipment is the total gravity of the electrical, mechanical and other equipment placed inside the body, as well as on the wagons that load the structural element.

The vertical component (additive) on the bogie and the body from the longitudinal force of inertia of the body are determined by the formula:

$$\Delta P = P_{IK} \frac{h_k}{2L} \quad (2)$$

Where  $P_{IK}$  – the inertia of the gross body;  $h_k$  – the distance from the center of gravity of the body to the plane of the bogie supports;  $2L$  – body base.

Lateral forces are determined by the centrifugal force, the force of wind pressure, and the dynamic interaction between the locomotive and the track in the horizontal plane.

The centrifugal force is determined separately for the body and bogies, based on an unaccelerated acceleration of  $0.7 \text{ m/s}^2$ .

The wind pressure is determined by calculating the specific wind pressure on the side projection of the body (cart) equal to  $500 \text{ N/m}^2$ .

Horizontal transverse (frame) forces acting on the locomotive when it enters curves are determined from the condition of equilibrium of the crew when it moves in a circular curve with the unaccelerated acceleration of  $0.7$ . The coefficient of friction between the wheels and rail is assumed to be  $0.25$ .

The maximum frame forces must not exceed  $40\%$  of the locomotive's gravity.

Longitudinal forces represent the interaction forces between the locomotive and the cars that occur when driving in the train and performing maneuvers, traction and braking forces, and the outcomeing longitudinal forces of inertia.

Longitudinal forces act on the body.

The forces of interaction between the locomotive and cars are applied for Mode I – along the axes of couplers, for Mode II – to the tail coupler of the locomotive and are balanced by the forces of inertia of the locomotive masses.

The forces of inertia acting on individual assemblies and elements of the locomotive are applied in the centers of gravity of their masses and are determined for mode II by the formula:

$$P_{ni} = F_A \frac{m_i}{M} \quad (3)$$

Where  $F_A$  – longitudinal force determined by traction or braking forces;  $m_i$  – weight of a node or element;  $M$  – mass of the locomotive.

When determining the weight of the bogie, the inertia of the rotating parts is recommended to take into account by increasing the weight of the bogie by  $40\%$ . Inertial forces for the calculation of body-body connection details with the bogie are determined based on the acceleration of the bogie mass along the track axis equal to  $3g$ . Stresses in the calculated elements under the action of this force added to the static stresses from the gravity of the locomotive, must not exceed  $0,9$  of the yield strengths of the material. Asymmetric forces are a system of mutually balanced relative to the diagonal of the bogie frame vertical forces applied to the axles. Asymmetric forces are taken into account in calculations of bogies with a rigid frame or other structure capable of absorbing these forces, and are approximately assumed to be equal:

$$P_K = \Delta C_\delta \quad (4)$$

Where  $\Delta$  – the difference in the deflection of the axle springs of one-wheel pair;

$C_\delta$  – spring suspension stiffness in the vertical plane of a single axle box assembly.

The main vertical, lateral, and longitudinal forces when assessing the strength of the shunting locomotive crew part according to allowable stresses are taken into account by the design modes in combinations.

The forces from the operation of the equipment installed on the locomotive must be taken into account when calculating the elements of the crew part, in which stresses arise during the operation of the equipment. The outcomeing stresses are summed up with the stresses from the main design forces by the II design mode.

Assessment of fatigue resistance and durability.

In the absence of a histogram of the amplitude stress distribution characterizing the element loading during the assigned service life and in the absence of material fatigue curve parameters, the fatigue resistance evaluation shall be carried out according to the formula:

$$n = \frac{\sigma_{-1}}{K_{\sigma}\sigma_V + \psi\sigma_m} > [n] \quad (5)$$

Where  $\sigma_{-1}$  – the average value of the endurance limit of the standard specimen under a symmetrical loading cycle;  $\sigma_V$  – cycle stress amplitude;  $\sigma_m$  – average cycle voltage;  $\psi$  – coefficient characterizing the effect of cycle asymmetry;  $[n]$  – allowable coefficient of resistance to fatigue.

The value of the reduction coefficient of the endurance limit is determined from the expression:

$$K_{\sigma} = \frac{K_1 K_2}{\gamma m} \beta_K \quad (6)$$

Where  $K_1$  – a coefficient, which takes into account the effect of heterogeneity of the part material;  $K_2$  – a coefficient taking into account the influence of internal stresses of the part. Its value depends on the transverse dimensions of the part;  $\gamma$  – a coefficient which is taken into account influence of the dimensional factor;  $m$  – a coefficient which is taken into account state of the surface;  $\beta_K$  – effective stress concentration coefficient in the nodes of complex outline.

The critical stresses for the rods are determined by the Euler formula:

$$\sigma_{KP3} = \frac{\pi^2 E}{\lambda^2} \quad (7)$$

where  $E$  – flexural modulus;  $\lambda$  -rod flexibility for  $\lambda > \lambda_{CLP}$ ,

$$\lambda_{CLP} = \pi \sqrt{\frac{E}{\sigma_{CLP}}} \quad (8)$$

$\sigma_{CLP}$  – compressive limit of proportionality (for steel St3  $\sigma_{CLP} = 200$  mPa, for steel 09G2  $\sigma_{CLP} = 270$  mPa).

Materials subjected to pure shear in the elastic strain region have critical stresses defined by the formula:

$$\sigma_{KP} = k \frac{E}{1-\mu^2} \left(\frac{a}{b}\right)^2 \quad (9)$$

where  $k$  – is a coefficient that depends on the ratio of the plate sides ( $a/b$ ) and the conditions of its fastening.

In the combined action of compression, bending and shear, the critical stresses are calculated by the formulas:

$$\sigma_{KPC} = \sigma_{KP} \frac{c}{2\beta^2} \sqrt{c^2 + 4\beta^2} - c \quad (10)$$



$$\tau_{KPC} = \tau_{KP} \frac{1}{2\beta} \sqrt{c^2 + 4\beta^2} - c \quad (11)$$

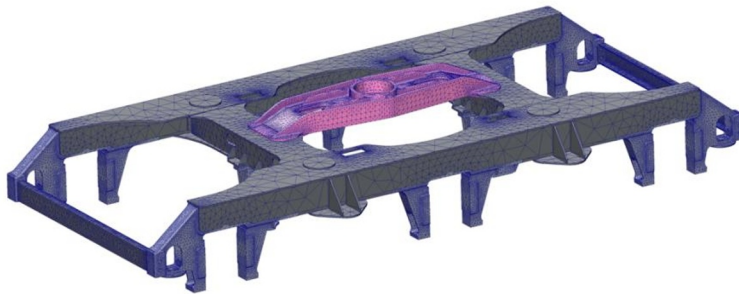
where  $c = \frac{\tau_{KP}}{\sigma_{KP}}$ ,  $\beta = \frac{\tau}{\sigma}$ .

The critical stresses are determined by the formula:

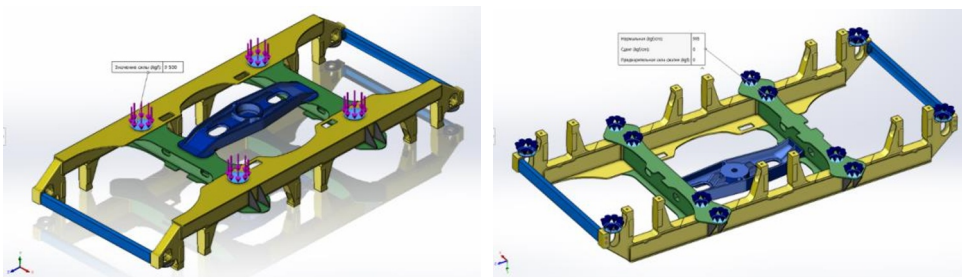
$$\sigma_{KP} = 0.18 \frac{E\delta_{CK}}{R_{CK}} \quad (12)$$

where  $\delta_{CK}$  and  $R_{CK}$  – thickness and radius of curvature cladding panel.

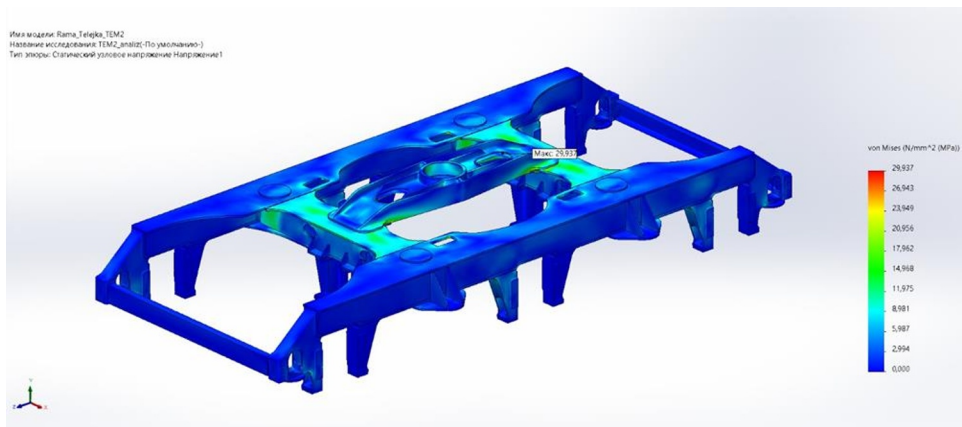
Figures 4-9 show the results of calculating the stress-strain state and fatigue of the bogie frame of a TEM2 shunting locomotive.



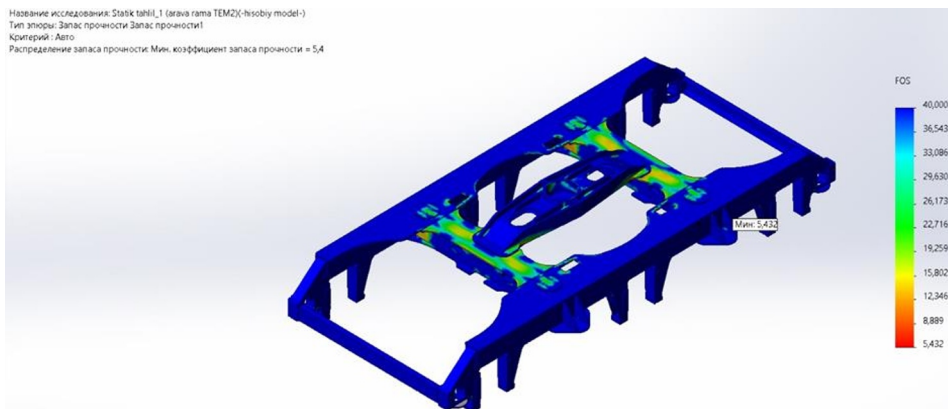
**Fig. 4.** Finite element mesh, applied load and geometric constraints.



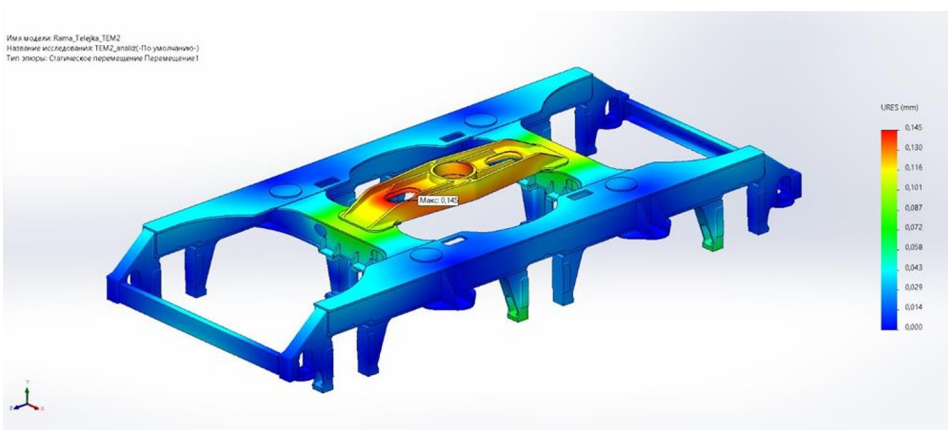
**Fig. 5.** Design scheme of the bogie frame of the locomotive TEM2



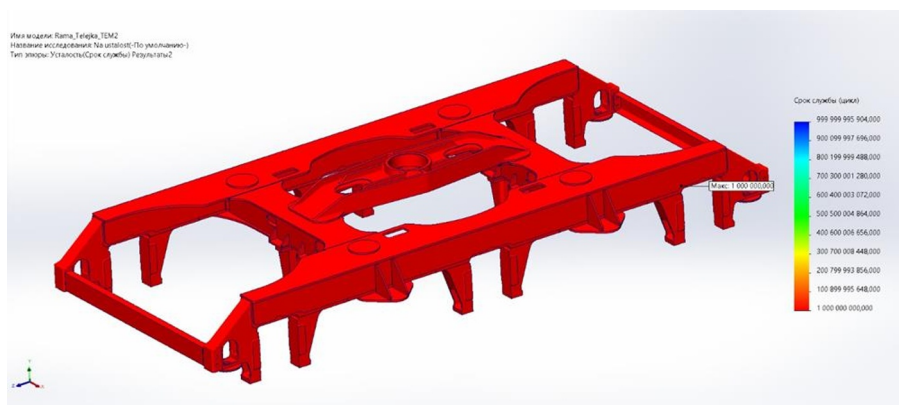
**Fig. 6.** Distribution of equivalent stresses in the bogie frame from the action of static loads



**Fig. 7.** Safety margin of the bogie frame shunting locomotive



**Fig. 8.** Moving the bogie frame shunting locomotive



**Fig. 9.** Bogie frame fatigue analysis

The obtained results of stress-strain state calculations and fatigue studies performed using application software packages must be verified by experimental methods (strain gauge, strain-sensitive coatings, acoustic emission, etc.), which in some cases (for example, in the

absence of sufficiently accurate results of stress-strain state calculations and fatigue studies, executed with the help of application software packages, they must be verified [18].

Determination of refined characteristics of materials is carried out on samples cut from the elements of the locomotive frame, or witness samples (in some cases, with sufficient experimental justification, on their imitators), by the research programs made about the detected damage and operating conditions of the structural element [19, 20].

Sample checks and determination of material parameters are carried out in accordance with scientific and technical documentation. According to the results of refined calculations and studies of the stress-strain state and parameters of materials, the mechanisms of destruction, indicators of technical condition are specified, defining characteristics of the technical condition and criteria of limit states are established.

## 4 Conclusions

The paper shows that timely detection of defects in locomotive assemblies is the basis for service life extension. It is shown that the locomotive bogie frame condition determines the intensity of locomotive operation, its durability, and serviceability. The presented mathematical model of calculating loads of locomotive bogie frames allows us describe the physical processes of damage and malfunctions as reliably as possible. The proposed model can be used during examination in the process of shunting locomotive service life extension.

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