Analysis of stress-strain state of bogie frame of PE2U and PE2M industrial traction unit

Sherzamin Abdurasulov*, *Nuriddin* Zayniddinov, *Abdulaziz* Yusufov and *Shuhrat* Jamilov

Tashkent State Transport University, Tashkent, Uzbekistan

Abstract. This article presents the results of the theoretical analysis of the stress-strain state of the industrial traction unit PE2U and PE2M frame. The stress-strain analysis was performed using the finite element method in SolidWorks Simulation software. The analysis results are necessary to estimate the residual resource of the traction units at the end of their service life and extend their service life. According to the requirements of the state standards, to extend the service life of the rolling stock load-bearing constructions, the stress-strain state of these constructions should be studied. A 3D model of the bogie frame was built using SolidWorks software to evaluate the strain-deformation state. Using the SolidWorks Simulation program, the stress-strain state of the bogie frame was evaluated using the finite element method based on the Palmgren–Miner–Mises theory. All static and dynamic loads in use affecting the bogie frame are taken into account.

1 Introduction

Several locomotives and traction units are used in metallurgical and coal mining enterprises in the Republic of Uzbekistan. These are TGM3, TGM4 type locomotives and PE2M, PE2U traction units. The main part of PE2M and PE2U traction units used in the Republic of Uzbekistan are traction units that are ending their service life. Determining the residual resource and extending the service life of these traction units is an important issue today. In assessing the residual resource, the frame structures of the rolling stock are the main object, and their reliability is the basis for determining the service life.

To date, most of these units have exhausted their designated service life, and therefore they all had to be re-informed about their suitability for further operation [8].

It's no secret: the fleet of domestic traction rolling stock is worn out to the limit, especially the one that belongs to industrial enterprises, since for more than 20 years, they have practically not purchased new locomotives [9].

The bogie is one of the main load-bearing elements of the railway rolling stock and is the main link that transfers the load from the body to the railway rail [2, 3, 17]. The strength of the bogie frame ensures the safety of the rolling stock, so its strength and durability must meet the requirements of the current regulatory documents [5].

* Corresponding author: sherzaminabdurasulov@gmail.com

One problem that needs to be solved is the insufficient strength of the load-bearing elements of the rolling stock, particularly the bogie frame.

During operation, technical objects, critical elements, and other responsible details are subject to static, quasi-static, and dynamic loads, elastic and elastic and plastic deformations, and individual zones and element details, working in thermal, atmospheric, low temperature, and corrosion conditions [10].

The load-bearing elements of the bogie must meet the following parameters and requirements [1, 4]:

• ensuring safety in the use of rolling stock;
• meet the requirements of strength and endurance;
• fulfill all usage requirements.

Most of these traction units are nearing the end of their service life, so they require an extension of their service life based on the current regulations, determining the residual resource for their reuse.

The importance of paying attention to the technical condition of the bogie frame is related to its significant impact on the safety of movement. In addition, over time, the fatigue indicators of the material decrease, and the load level increases, which affects the condition of the roads of industrial enterprises [19].

Basic element: An element of a complex technical system that meets one or more of the following criteria simultaneously [7]:

- performs a supporting function in the structure or the main function required by the consumer;
- is irreplaceable;
- has the most connections with other elements;
- has the highest cost of replacing an element about the cost of a complex technical system as a whole.

2 Methods

Methods of determining the residual resource of railway rolling stock are regulated by regulatory documents.

The assigned service life of locomotives should be determined by the resource of their base parts. The extension of the assigned service life of locomotives is carried out on the basis that the service life of the locomotive is determined by the resources of its basic parts (bogie frame, body frame, load-bearing elements of the body) [6, 15, 20].

To determine the stress-strain states, the following methods are used [7]:

a) analytical (strength of materials, theories of elasticity, plasticity, creep);
b) numerical (methods of finite elements, differences, boundary integral equations);
c) experimental:
1) thickness measurements (mechanical, optical, ultrasonic),
2) strain gauges (strain gauges, strain-sensitive coatings, holography, interferometry),
3) thermometry (thermocouples, thermal resistance, thermal imaging, pyrometers, thermal paints),
4) vibrometry (mechanical accelerometers, optical, electromechanical, laser, ultrasonic vibrometers);
5) combined (using computer simulation of elements and results of experimental studies).

Computational studies of stress-strain states should be performed by qualified personnel with appropriate confirmation, using the finite element method using proven software [6].

Bogie frames operate mainly under conditions of variable cyclic loads [11, 16]. The calculation of the bogie frame is carried out under the action of normative vertical and horizontal static and dynamic loads [6].

The static load on the bogie frame is determined based on the total mass of the traction unit. PE2U and PE2M traction units have an electric locomotive and two motor dump cars [12, 13, 14]. Electric locomotive mass P_E = 120 t., motor dump car mass P_{DC} = 124 t. The mass of the bogie is P_b = 24.5 t [13]. Each electric locomotive and motor dump car is mounted on 2 bogies. The bogie frame sits on the wheel pairs through 6 spring supports (fig. 1).

The total load acting on the bogie is calculated using the formula (1).

$$F = \frac{P_i - 2 \cdot P_b}{2} \tag{1}$$

The load acting on the bogie is distributed to the bogie frame by the central support and 2 conical supports and is calculated using the formula (2).

$$F_i = \frac{F}{3} \tag{2}$$

The bogie frame is made of 09G2 low-alloy steel sheets by welding. The properties of 09G2 steel are listed in Table 1.

Table 1. Mechanical properties of steel grade 09G2 [21].

Assortment	Size	S_B	S_T
	mm	MPa	MPa
Sheet, GOST 19282-73	10-20	440	305

The general appearance of the bogie frame is shown in Fig. 1.

Fig. 1. General view of bogie frame traction units PE2U and PE2M.

When evaluating fatigue resistance, it is required to evaluate the stress-strain state of the object under consideration to identify dangerous zones [22].

Programs based on the finite element method are used to determine the stress-strain state of structures, which allows for solving problems in linear and non-linear formulations and estimating the fatigue life of various variants of the same structure already at the design stage [18].

The object of research is the stress-strain state of the traction unit bogie frame. To study the stress-strain state of the bogie frame structural elements, the 3D modeling method, and the finite element method were used.

The finite element calculation of the constructed 3D model of the traction unit bogie frame was carried out under the action of standard loads. When calculating, it was assumed that the structure's material works in the zone of elastic deformations and has constant characteristics, modulus of elasticity $E = 2 \cdot 105$ MPa, and Poisson's ratio $\mu = 0.3$.

When calculating the stress-strain state of the bogie frame, the listed forces are taken as acting statically and are reduced to the following main application schemes:

vertical (gravity, vertical component of body inertia force);

longitudinal (traction force, longitudinal inertia forces);

lateral (centrifugal force, wind pressure force, horizontal frame forces);

skew-symmetric.

The bogie frame is supported on the wheel pairs in the design scheme by axle box suspension brackets.

As a result of the calculation analysis, the most loaded nodes of the bogie frame were determined, and for further research, a diagram of the placement of strain gauges for running dynamic tests was drawn up.

The endurance limit of the part, taking into account the asymmetry of the cycle according to [4], is determined by the formula:

$$\sigma_{-1Dm} = \sigma_{-1D} \cdot 1{,}035 \cdot \sqrt{1 - \frac{(\sigma_m + 0{,}35 \cdot \sigma_B)^2}{(1{,}35 \cdot \sigma_B)^2}} \quad (3)$$

where σ_{-1D} is the endurance limit of the part for a symmetrical cycle; σ_m is the average cycle stress; σ_B is the tensile strength.

The endurance limit of a part for a symmetrical cycle is determined by the formula:

$$\sigma_{-1D} = \frac{C(p) \cdot \sigma_{-1}}{K} \sigma_{-1Dm} \quad (4)$$

where σ_{-1} is the average value of the endurance limit of the sample (for steel 09G2 - 235 MPa); C(p) is a coefficient depending on the probability of failure of the part. The value is selected according to table 3.19 [4]; K is coefficient of reduction of the endurance limit, determined by the formula:

$$K = K_\sigma \cdot \eta \quad (5)$$

where η is a technological factor. The value of η depends on the method and control of welding (Table 3.20 [4]); K_σ is coefficient characterizing the decrease in the endurance limit:

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

where K_1 is coefficient that takes into account the heterogeneity of the part material; K_2 is coefficient taking into account the influence of internal stresses in the part; β_K is effective stress concentration factor in nodes with a complex shape, the stress concentration in which is determined only by their geometry; γ is coefficient taking into account the influence of the size factor; m is coefficient that takes into account the state of the surface of the part. Since the stress levels in the bogie frames are higher than σ_{-1Dm}, then, according to clause 3.6.3 [4], to assess the durability, we use the fatigue curve parameters of the standard sample and the distribution histograms of the bogie frame stress amplitude values. We describe the fatigue curve for the sample by equation (3.35) [4]:

$$N = \beta \cdot \frac{\sigma_B - \sigma}{\sigma - \sigma_{-1}} \tag{7}$$

where σ_{-1} is endurance limit of a standard sample for a symmetrical loading cycle; N is number of cycles until sample failure at stress amplitude σ of a symmetrical loading cycle; β is sample constant.

The parameters of the fatigue curve of the part σ_{-1D} and β_D for a symmetrical loading cycle are determined by the formulas:

$$\sigma_{-1D} = \frac{\sigma_{-1}}{K} \tag{8}$$

$$\beta_D = \frac{\beta}{K^2} \tag{9}$$

The parameters of the fatigue curve of a part for an asymmetric loading cycle are determined by the formula (3.37) [4]:

$$\beta_{Dm} = \beta_D \frac{\sigma_{-1Dm} + |\sigma_m|}{\sigma_{-1D}} \tag{10}$$

3 Results and Discussion

To analyze the stress-strain state of the bogie frame of PE2U and PE2M traction units using the finite element method, its 3D model was created in SolidWorks software (Fig. 2).

The method of supporting the bogie frame and the design loads are described in the research methodology.

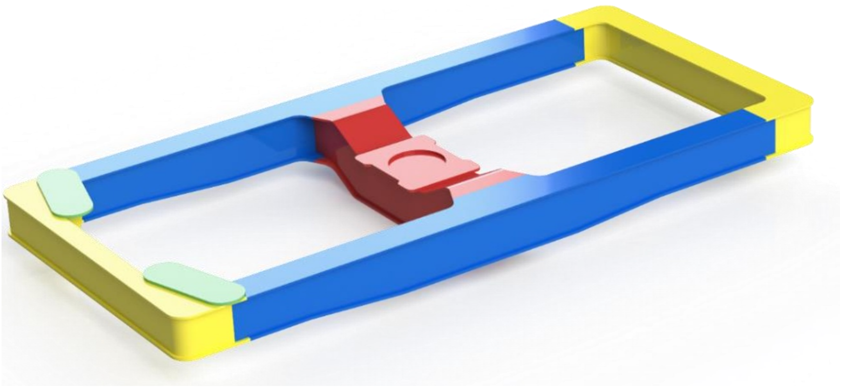

Fig. 2. 3D model of bogie frame of PE2U and PE2M traction units.

The finite element model of the bogie frame of PE2U and PE2M traction units is shown in Fig. 3.

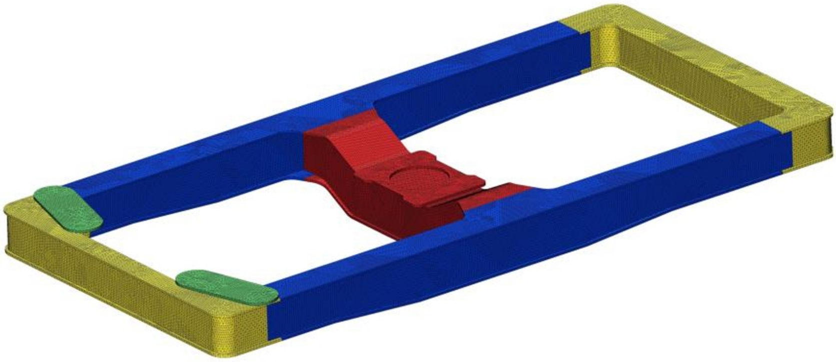

Fig. 3. Finite element model of bogie frame.

On fig. 4 shows the fields of equivalent stresses in the structural elements of the bogie frame. At the same time, a node is shown in which equivalent stresses reach values of 57 MPa.

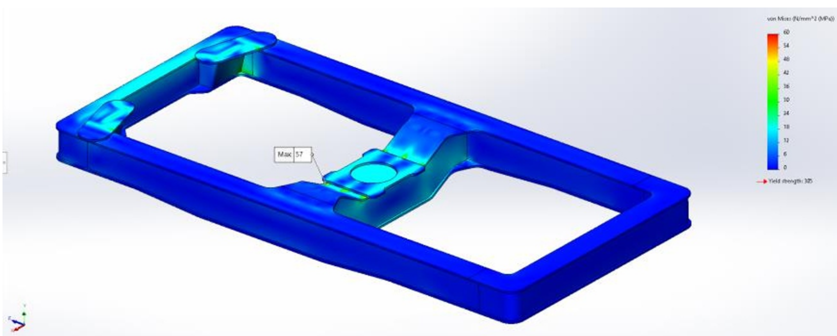

Fig. 4. Equivalent stress induced in bogie frame.

The maximum value of the displacement of the stroller frame due to loading was 0.254 mm. The maximum displacement occurred in the bolster beam (Fig. 5).

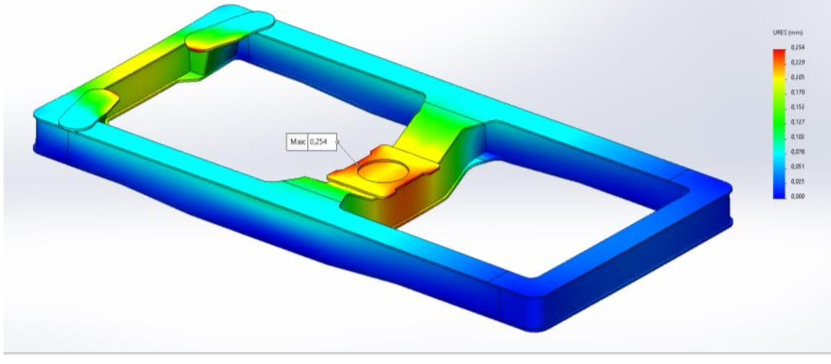

Fig. 5. The displacement diagram of bogie frame.

The minimum value of the safety factor of the bogie frame structure was 5.3 (Fig. 6), which is a sufficiently large value. The minimum value of the safety factor for the bogie frame should be 2.

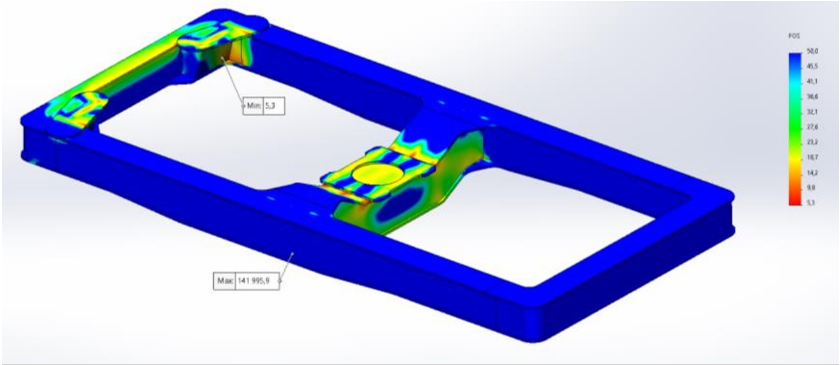

Fig. 6. Diagram of factor of safety of bogie frame.

Fatigue strength analysis of the bogie frame was performed in the SolidWorks Simulation program. The structure was tested for 10^8 cycles. As a result, no damage was observed in the structure even after 10^8 cycles, which means that the structure is sufficiently strong. Test results are shown in Fig. 7.

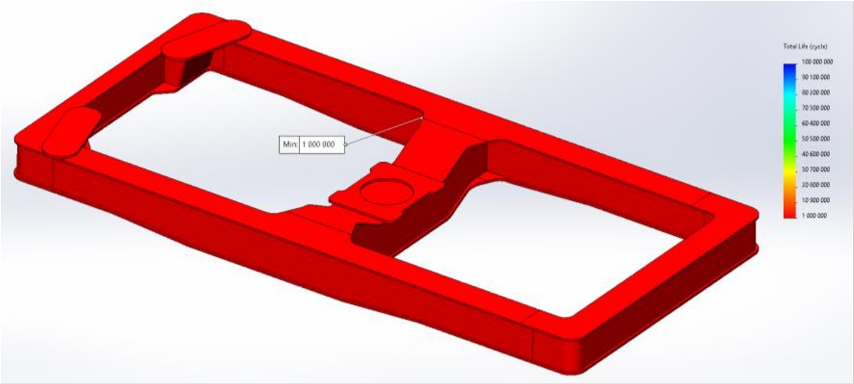

Fig. 7. Fatigue strength analysis of bogie frame.

Fig. 8 shows the S-N curve predicted by the fatigue strength analysis of the bogie frame in SolidWorks Simulation.

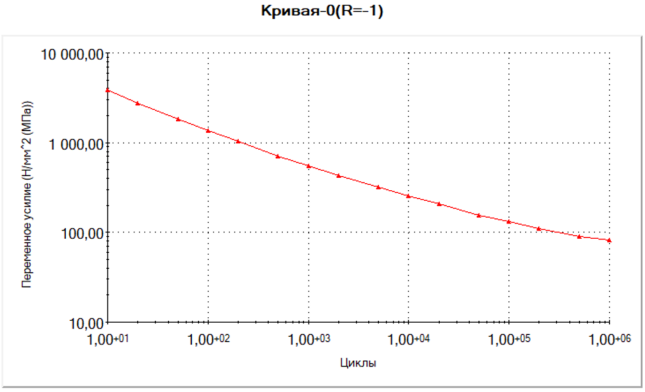

Fig. 8. Predicted S-N curve.

4 Conclusion

Analysis of the stress-strain state of cart frames using the finite element method gives us the necessary information and conclusions to extend the service life of PE2U and PE2M traction units. The results of this study will be used in further research to determine the residual resource of the traction units.

Using modern programs based on the finite element method, such as SolidWorks Simulation, has several advantages and is cost-effective. Using the finite element method is economically efficient because the creation of experimental samples is a cause of both time and costs. In addition, the accuracy of the finite element method is very high and has been proving itself over the years.

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References

1. Oganyan, E. S., & Voloxov, G. M. Raschety i ispytaniya na prochnost nesushix konstruksiy lokomotivov. (2013).
2. Kovalchuk, V., Kuzyshyn, A., Kostritsya, S., Sobolevska, Y., Batig, A., & Dovganyuk, S. Improving a methodology of theoretical determination of the frame and directing forces in modern diesel trains. *Eastern-European Journal of Enterprise Technologies*, *6*(7 (96), 19–26. (2018).
3. Kuzyshyn, A., Batig, A., Kostritsa, S., Sobolevska, J., Kovalchuk, V., Dovhanyuk, S., & Voznyak, O. Research of safety indicators of diesel train movement with two-stage spring suspension. In *MATEC Web of Conferences* (Vol. 234, p. 05003). EDP Sciences. (2018).
4. Normy dlya rascheta i otsenki prochnosti nesushchikh elementov i dinamicheskikh kachestv ekipazhnoy chasti motorvagonnogo podvizhnogo sostava zheleznykh dorog MPS RF kolei 1520 mm. Moscow: VNIIZhT.
5. Bolotin, V. V. (1984). *Prognozirovaniye resursa mashin i konstruktsiy*. Moscow: Nauka.
6. Polozheniye «Lokomotivy. Poryadok prodleniya naznachennogo sroka sluzhby» P.15.01.-2009 : [Utverzhdeno pyat'desyat tret'im Sovetom po zheleznodorozhnomu transportu gosudarstv-uchastnikov sodruzhestva. Protokol ot 20-21 oktyabrya 2010 g.]. – M.: 2010, – 24 s.
7. Obshie trebovaniya k metodam opredeleniya resursa. Railway technical means. General requirements for methods of life time estimation. GOST R 57445-2017.
8. Bondarev, O. M., Gorobets V. L., & Myamlin, S. V. Methods and research concerning service life extension of suporting structures of traction rolling stock for industrial transport. Science and Transport Progress, (2(50), 130–151. (2014).
9. Grishenko, A. V., Grachev, V. V., Bazilevskiy, F. Yu., Shrayber, M. A., Ganieva, Yu. M., & Melnikova, V. V. Otsenka ostatochnogo resursa nesushix konstruksiy

lokomotivov promyshlennogo transporta. *Byulleten rezultatov nauchnyx issledovaniy*, (3-4 (16-17)), 38-46. (2015).

10. Oganyan, E. S., Voloxov, G. M., & Gasyuk, A. S. Prognozirovanie resursa nesushix konstruksiy lokomotivov po usloviyam ekspluatatsii. *Izvestiya Transsiba*, (2 (38)), 47-54. (2019).
11. Gasyuk, A. S., & Oganyan, E. S. (2019). Raschetno-eksperimentalnye metody otsenki resursa bazovyx chastey podvizhnogo sostava. *Izvestiya Peterburgskogo universiteta putey soobsheniya*, *16*(2), 285-291.
12. V. A. Bratash, M. L. Bichuch, V. A. Volodarsky, L. F. Zholobov. I. V. Karlenko, D. A. Kurasov, S. B. Matusevich, E. A. Moskvichev, V. S. Potapov, V. N. Savisko. Electric locomotives and traction units of industrial transport. Ed. V. A. Bratasha. M., Transport, (1977).
13. Balon L.V., Bratash V.A., Bichuch M.L. Electric stock of industrial transport. Moscow, Transport Publ., (1987).
14. Rakov V. A. Locomotives and multiple unit rolling stock of the railways of the Soviet Union (1976-1985). — M.: Transport, (1990).
15. Khamidov, O., Yusufov, A., Jamilov, S., & Kudratov, S. Remaining life of main frame and extension of service life of shunting Locomotives on railways of Republic of Uzbekistan. In *E3S Web of Conferences*, Vol. 365, p. 05008. EDP Sciences. (2023).
16. Zayniddinov, N., & Abdurasulov, S. Durability analysis of locomotive load bearing welded structures. *Science and innovation*, *1*(A8), 176-181. (2022).
17. Deng, R., Zhai, W. M., & Xiao, S. N. Fatigue life prediction of a railway bogie frame. In *Advanced Materials Research* (Vol. 44, pp. 523-528). Trans Tech Publications Ltd. (2008).
18. Special rolling stock. Requirements for bearing structure strength and for dynamic properties. GOST 31846-2012.
19. Kostrytsia, S. A., Molchanov, S. Y., Kramarenko, M. V., Hrechkin, A. A., & Laktionov, D. V. Stress-strain state assessment of the bogie frame of dpkr-2 diesel train under action of design and operational loads. Science and Transport Progress, (1(79), 128–138. (2019).
20. Oganyan, E. S., Voloxov, G. M., Gasyuk, A. S., & Fazliaxmetov, D. M. Raschetno-eksperimentalnaya otsenka resursa bazovyx chastey lokomotivov dlya obespecheniya ix bezopasnoy ekspluatatsii. *Problemy mashinostroeniya i nadejnosti mashin*, (2), 39-43. (2018).
21. Stal nizkolegirovannaya tolstolistovaya i shirokopolosnaya universalnaya. Low-alloyed plate strip universal steel. Specifications. GOST 19282-73.
22. Xamidov, O. R., Yusufov, A. M., Abdurasulov, A. M., Jamilov, Sh. F., & Kudratov, Sh. I. Prodleniyu ostatochnogo resursa glavnoy ramy teplovoza serii TEM2 s metodom konechnyx elementov (MKE). *Innovatsionnыe podxody, problemy, predlojeniya i resheniya v nauke i obrazovanii*, *1*(1), 148-153. (2022).